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Emerging trends in robotic breast surgery in the era of artificial intelligence

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Abstract

The advent of artificial intelligence (AI) heralds a new era in the field of robotic surgery. This article discusses recent trends in the integration of AI technology with robotic surgical procedures, highlighting the latest advancements in robotic breast surgery. The application of AI in robotic surgery ranges from preoperative planning to intraoperative assistance. Machine learning algorithms are now utilized to analyze medical imaging data, enabling surgeons to devise detailed surgical plans tailored to the unique characteristics of each patient's tumor. This approach leads to more precise tumor excision and better preservation of healthy tissue. Robotic systems equipped with advanced visualization and sensor technologies can provide real-time feedback during surgery and training. Additionally, AI algorithms can predict the occurrence of postoperative complications, allowing for early intervention. With the ongoing development of AI and robotic technologies, significant progress has been made in robotic automation. The future of robotic breast surgery holds the promise of even greater accuracy, and the quality of life for breast cancer patients may be significantly improved.

Keywords: Artificial intelligence, robotic breast surgery, convolutional neural network, automation, deep learning

INTRODUCTION

Minimally invasive breast surgery is a popular surgical treatment method at present, which enables improved cosmetic outcomes[1,2]. Although endoscopic breast surgery is safe and technically feasible, it remains hindered by limited degrees of freedom, insufficient anatomical angles, and interference between instruments at a single axillary access point[3]. The robotic-assisted surgical system has obvious advantages in breast surgery due to the 3D visualization, enhanced flexibility, and reduction of intraoperative tremor, and the safety and feasibility of its adoption are currently under investigation in the surgical field[4,5]. However, robotic surgery also has disadvantages such as high training requirements for medical staff, lack of tactile feedback, long surgical preparation times, and technological limitations in complex surgeries[6]. The integration of artificial intelligence (AI) with robotic platforms could refine robotic surgery further. AI can combine computational power with human intelligence, thereby enabling deep learning[7]. AI technology can provide personalized treatment recommendations based on the individual health data of patients, and it can also serve as a platform to deliver remote care through telemedicine technology[8-11]. The data analysis and deep learning functions of AI are essential to achieve semi-automation and automation of robotic surgery, including preoperative planning and precision surgical planning, as well as real-time intraoperative decision support. The combination of AI and robotic surgery is constantly pushing surgical procedures in a more accurate and efficient direction and it could also lead to further advances in robotic breast surgery. This review highlights more recent technological advancements in robotic breast surgery in the era of AI.

ROBOT-ASSISTED SURGERY

The concept of using robots to operate remotely was first proposed by the US Army and the National Aeronautics and Space Administration (NASA)[12]. In the 1990s, the first master-slave system was developed, which consisted of a robot with remote manipulators controlled by a surgeon at a surgical workstation. A widely used platform is the da Vinci robot, a master-slave device developed by Intuitive Surgical Inc[13]. The da Vinci device in human abdominal surgeries was approved by the Food and Drug Administration (FDA) in 2000, and its approval for breast surgery still requires more evaluation of oncological safety[14]. The technical advantages of robotic surgery, such as 3D vision, stable and magnified images, physiological tremor filtration, and motion scaling, were able to overcome many limitations of laparoscopic surgery[15,16]. Robotic surgery has been rapidly adopted and now plays a significant role in gastrointestinal, hepatobiliary, pancreatic, urological, and gynecological procedures[17-24]. In 2015, the Da Vinci robot surgical system was first reported to be used in breast surgery[25]. Other robotic surgical systems developed in recent years include the MUSA Surgical System and the Symani Surgical System, which have more operational flexibility due to the high degree of freedom in their wrist tools, primarily benefiting the field of microsurgery[26,27]. With the development of fifth-generation (5G) networks and AI, robotic surgery may offer new frontiers, such as enabling remote surgeries and the potential for the future to herald an era of autonomous robot-delivered surgeries[28,29].

ROBOTIC BREAST SURGERY

Robotic nipple-sparing mastectomy

Both nipple-sparing mastectomy (NSM) and skin-sparing mastectomy (SSM) are considered standard modalities of performing a mastectomy[30-33]. A devastating complication associated with NSM is nipple-areolar complex (NAC) necrosis, and the rate of NAC necrosis ranges from 7.4% to 11% after NSM[34,35]. Intraoperative frozen section of subareolar tissue is commonly used to confirm negative margins, with atypical or positive frozen results leading to SSM, occurring in 2.5%-12% of cases[36,37]. NSM with immediate reconstruction is associated with enhanced patient satisfaction[38]. Endoscopic NSM has been proven feasible and is associated with high patient satisfaction[39]. The robot-assisted nipple-sparing mastectomy (RNSM) was first described by Toesca *et al*. in 2015, and they performed NSM through a single axillary incision, followed by immediate implant reconstruction[25]. In Toesca's initial series of 29 cases with RNSM, only two cases required conversion to open surgery due to technical problems. The total surgery duration did not exceed 3 h, and there were no cases of hematoma, skin or NAC injury/necrosis, or infection[40]. To achieve a safe and efficient RNSM, it is essential to provide training in robotic surgery not only to the surgical staff but also to the entire team. A meta-analysis shows that compared to traditional NSM, RNSM does not show a significant difference in the incidence of postoperative complications[41]. Although the RNSM takes longer and is more costly, the clinical outcomes of RNSM were comparable to those of traditional NSM, and RNSM showed favorable satisfaction with esthetic results[42]. RNSM is a safe option in terms of complications, particularly with improved wound healing, and the advantage of the minimal access group in RNSM is the higher satisfaction than conventional NSM related to wound esthetics[43]. Although there is a paucity of data to make definitive conclusions, one study suggested that compared to endoscopic nipple-sparing mastectomy (ENSM), RNSM offers higher satisfaction with wound esthetic, less bleeding, and a shorter learning curve[44]. The cost of RNSM is significantly higher than ENSM, which is one of the limitations of RNSM at present, and more research is needed to evaluate its cost-effectiveness[43,44]. Relevant comparative studies are shown in Table 1. The inherent limitations of the multi-arm surgical platform restrict the ergonomic use of the mechanical arms and the mobility of the robotic camera. In 2018, the FDA approved the da Vinci SP® surgical system for urological surgery, marking another significant step forward in the evolution of robotic surgery[45]. The SP® surgical system, designed specifically for single-port (SP) procedures, utilizes a single 25 mm multi-channel port (which includes a 3D robotic camera and three instrument slots), offering more flexible operation and superior camera control. The SP® surgical system is equipped with a fully hinged elbow joint that enables complex operations in confined spaces with greater precision and adaptability. In 2018, two surgeons with experience in robotic mastectomy conducted a preclinical cadaver study using the SP surgical system in Berlin, Germany, and then applied the system to patients[46]. Park *et al*. performed the first clinical case using the SP® surgical system for RNSM with minimal incision[46]. Go *et al*. assessed the safety of the SP® surgical system for RNSM, reporting a nipple necrosis rate of 2.5% (one case), with no cases requiring conversion to open mastectomy[47]. A prospective study on the da Vinci SP® surgical system for robotic nipple-sparing mastectomy (SPrNSM) found that the overall postoperative complication rate was 7.5%, which included one case of postoperative expander infection and one case of skin necrosis[48]. The study also demonstrated that SPrNSM had higher rates of intact NAC and skin sensation than open NSM. Currently, there is a lack of data on the oncological safety of the SP® surgical system for RNSM, as well as data comparing it with multi-arm RNSM. Moreover, whether it is single-arm or multi-arm RNSM, there is a lack of long-term oncological safety data with big data, which requires multicenter collaboration for research. Of course, technological advances in the Da Vinci robotic surgical system have made our breast surgery incisions smaller, and the operation more flexible, which may be associated with better quality of life and improved esthetic, potentially offering benefits to patients.

Robotic latissimus dorsi breast reconstruction

The latissimus dorsi flap has been used for breast reconstruction since the 1970s[49]. Traditional latissimus dorsi muscle flap harvest techniques require an incision on the back that ranges from 15 to 45 cm, in addition to an axillary incision to transfer the pedicle[50]. The pursuit of minimally invasive techniques for harvesting the latissimus dorsi muscle flap has always been a goal. Endoscopic harvesting has been reported by numerous studies[51,52]. However, due to technical challenges such as line of sight around the curvature of the back and other limitations of endoscopic instrumentation, some centers have abandoned this technique[53]. Selber first described the robotic harvest of the latissimus dorsi muscle in the cadaver model[54]. Subsequently, robotic latissimus dorsi harvest was performed on seven patients, and it was found to be a novel and effective method for muscle procurement, with technical advantages over endoscopic harvesting and esthetic advantages over open techniques[55]. None of the seven patients experienced donor

Table 1. Comparative study of robotic breast surgery

Author (year)	Research type	Group (number)	Operation time	Complication (*P* value)	Reference
Filipe *et al*. (2022)	Meta analysis	R-NSM *vs*. C-NSM	-	0.07	[41]
Lai *et al*. (2020)	Retrospective study	R-NSM (51) *vs*. C-NSM (62)	0.01	0.98	[42]
Lai *et al*. (2020)	Retrospective study	R-NSM (40) *vs*. E-NSM (91)	0.01	0.284	[44]
Lai *et al*. (2024)	Prospectively study	R-NSM (76) *vs*. C-NSM (46) *vs*. E-NSM (84)	< 0.01 (unilateral mastectomy)	-	[43]
Winocour *et al*. (2020)	Retrospective study	R-LD (25) *vs*. C-LD (27)	0.002	0.034	[56]
Eo *et al*. (2023)	Prospective study	R-LD (20) *vs*. E-LD (17) *vs*. C-LD (20)	< 0.001	> 0.90	[57]
Lee *et al*. (2022)	Retrospective study	R-DIEP (21) *vs*. C-DIEP (186)	< 0.001	≥ 0.085	[69]
Tsai *et al*. (2023)	Retrospective study	R-DIEP (13) *vs*. C-DIEP (86)	0.006	0.348	[70]
Moreira *et al*. (2024)	Retrospective study	R-DIEP (46) *vs*. C-DIEP (48)	0.013	0.624	[71]
Elameen *et al*. (2024)	Meta analysis	R-ABR (263) *vs*. C-ABR (520)	< 0.001	≥ 0.150	[73]

R-NSM: Robot-assisted nipple-sparing mastectomy; C-NSM: conventional nipple-sparing mastectomy; E-NSM: endoscopic nipple-sparing mastectomy; R-LD: robot-assisted latissimus dorsi muscle harvest; E-LD: endoscopic latissimus dorsi muscle harvest; C-LD: conventional latissimus dorsi muscle harvest; R-DIEP: robot-assisted deep inferior epigastric perforator flap harvest; C-DIEP: conventional deep inferior epigastric perforator flap harvest; R-ABR: robotic autologous breast reconstruction; C-ABR: conventional autologous breast reconstruction.

site hematomas, seroma, or skin injuries, and the surgery time was reduced from over 2 h to approximately 1 h. Despite longer operative times and higher seroma rates, robotic-assisted latissimus dorsi muscle harvest remains an effective alternative to traditional open surgery, offering the benefits of no back scars and lower opioid requirements[56]. Patient satisfaction with robotic-assisted latissimus dorsi flap breast reconstruction after partial mastectomy is higher than with traditional open methods, particularly regarding donor site scarring[57]. Chen *et al*. conducted a study on robotic NSM followed by immediate breast reconstruction using the latissimus dorsi muscle without island flap[58]. They found that compared to reconstruction with latissimus dorsi muscle with skin island, the technique without island flap saved surgical time and reduced intraoperative blood loss, but also included the disadvantage of lacking a skin paddle for monitoring. Robotic breast reconstruction using the latissimus dorsi muscle without island flap shows potential for application in the future. A prospective, single-arm study on robotic-assisted latissimus dorsi muscle harvest has been approved by the U.S. FDA[59]. The primary safety endpoint is adverse events caused by the harvest, and the primary efficacy endpoints include muscle viability after the harvest and the conversion rate to open surgery. This study will further explore the feasibility and safety of robotic-assisted latissimus dorsi harvest.

Robotic deep inferior epigastric perforator flap

Some patients are satisfied with autologous breast reconstruction[60]. The initial autologous breast reconstruction was based on abdominal tissue, relying on the pedicled transverse rectus abdominis myocutaneous (TRAM) flap, followed by the free TRAM flap. Currently, the deep inferior epigastric perforator (DIEP) flap has become the standard for autologous breast reconstruction[61-63]. Both pedicled and free TRAM flaps sacrifice the rectus abdominis muscle, which can lead to serious abdominal wall complications. In contrast, DIEP flaps, which preserve the rectus abdominis muscle, can significantly reduce the occurrence of abdominal wall complications[64]. Even with technical advancements, harvesting the DIEP flap through the traditional open approach still requires a long incision. Since the DIEP pedicle extends along the deep layer of the rectus abdominis muscle, dissecting it often necessitates splitting the muscle, leading to direct muscle damage. This may damage the motor nerves of the rectus abdominis, resulting in muscle dysfunction and increased postoperative pain[1]. Robot-assisted DIEP can significantly reduce the fascial incision and perform the resection through a posterior approach, minimizing the occurrence of muscle and nerve damage[65]. Robotic-assisted DIEP flap harvest has been shown to be feasible in cadaveric models, and a totally extraperitoneal approach may further reduce donor site morbidity[66,67]. Preoperative computed tomography angiography (CTA) imaging is crucial for determining whether patients are suitable for a robotic approach[68]. Patients with a single perforator or two closely grouped perforators are better suited for a robotic DIEP. A retrospective study found that compared to the open DIEP, a robotic DIEP can improve postoperative recovery while reducing postoperative pain and shortening hospital stays[69]. Robotic bilateral DIEP flaps are also feasible without the need for port adjustments, thanks to novel port placement techniques[70]. Compared to open bilateral DIEP, robotic bilateral DIEP flap harvest can reduce the length of fascial incisions, decrease abdominal wall disruption, and avoid the need for fascial reinforcement with mesh[71]. Indocyanine green-guided near-infrared fluorescence aids in vascular dissection during robotic-assisted DIEP[72]. The successful harvest of robotic DIEP flaps also confirms the feasibility and safety of robotic autologous breast reconstruction[73]. The da Vinci SP® surgical system requires only a 2.5 cm diameter port, which allows surgeons to operate in confined space, such as DIEP surgery. Jung *et al.* successfully used the SP® surgical system for the first time to perform dissection of vascular pedicle through minimal fascial incisions[74].

Robotic microsurgery

The complete elimination of tremor and 10x magnification advantages of the robotic system make it an appealing choice for super-microsurgery. Robotic microsurgery can be used to treat upper limb lymphedema. In 2010, Selber *et al.* reported cases of oral robotic reconstruction of oropharyngeal defects, including the use of robotic microvascular anastomosis[75]. O'Brien first described the technique of lymphovenous bypass in dogs in 1977 as a means of improving lymphedema[76]. In the field of supermicrosurgery, the renowned surgeon Koshima made it possible to treat lymphedema with lymphovenous bypass surgery by performing anastomoses on vessels and lymphatics with diameters ranging from 0.3 to 0.6 mm[77]. In the first human study of robotic-assisted supermicrosurgery lymphovenous anastomosis (LVA), van Mulken *et al.* compared robotic-assisted anastomosis with manual anastomosis and demonstrated the feasibility of robotic LVA[78]. Robotic omentum lymph node flap harvest for the treatment of extremity lymphedema has also been shown to be safe and feasible[79]. Lindenblatt *et al.* reported the first use of the Symani surgical system for LVA and arterial anastomosis in lymphatic reconstruction in humans[26]. However, the learning curve for robotic-assisted LVA is very steep, as the procedure takes significantly longer than manual suturing techniques at the beginning[80], but once surgeons become familiar with the technology, the time required for robotic-assisted LVA becomes comparable to that of manual suturing techniques. van Mulken *et al.* reported the application of the MUSA in humans for treating breast cancer-related lymphedema[27]. The advantages of the MUSA surgical system are also stability, scaling movements, and filtering vibration. The robotic arms of this system are equipped with true microsurgical instruments. Robotic-assisted techniques allow novice and intermediate surgeons to perform at a level comparable to experts, enabling novice learners to train early on in microsurgical anastomosis with the assistance of robotics[81]. The studies conducted thus far have demonstrated that the application of robotic-assisted anastomosis techniques in clinical settings is both safe and feasible. Overall, despite the limitation of a steep learning curve, prolonged operative time, and high costs, these advanced robotic systems are critical to the development of microsurgery.

NEW TRENDS IN ROBOTIC BREAST SURGERY IN THE ERA OF AI

AI in robotic surgery

AI was coined by John McCarthy in 1955 at Stanford University[82]. AI is the use of computer science and related technologies to enable machines to simulate human intelligent behavior[83]. From manufacturing to education and other industries, AI is gradually changing the way humans live and work. AI, in particular the deep-learning subtype, has been applied in various healthcare fields, and in some cases, it has even outperformed experienced doctors[84]. However, in surgical procedures, AI has not yet fully realized its potential due to some challenges such as safety and efficacy in the discipline[85].

In the field of surgery, AI has a broad range of applications, such as simulation, intraoperative decision making, event and outcome prediction, postoperative progression, complication management, and re-credentialing of surgeons. In this context, the term "surgical data science" has recently been coined[85]. AI-based systems can predict future acute kidney injury based on data from hundreds of thousands of patients[86]. Similarly, AI can also be used to predict circulatory failure in intensive care units[87].

With regard to surgery, digital surgical methods, such as master-slave manipulators used in robotic-assisted surgery, stand to benefit significantly from the advancements in AI. The most distant goal of the application of AI in robotic surgery is to achieve independent and autonomous completion of advanced surgery. To achieve this goal, robotic systems need to start with conventional anatomical structure recognition, and gradually intelligent learning to complete the long-term goal[88-91]. The automation level of robotic surgery ranges from the non-automated "master-slave" method to the fully automated level where the robot makes all surgical decisions without human involvement, divided into six levels[92,93].

Wang *et al.* reported that a convolutional neural network (CNN) can assist in creating a smoke-free intraoperative view during surgery, thus enabling a clearer intraoperative field of view[94]. Eslamian *et al.* created a model that combines intraoperative visual field tracking, intraoperative image, and robotic kinematic data, enabling autonomous view transformation and determination of the best surgical visualization[95]. These combinations of AI with robotics can enhance the surgical field of view for surgeons during procedures. Kumazu *et al.* created a model by analyzing surgical videos of robot-assisted surgeries[96]. This model is capable of automatically segmenting loose connective tissue, demonstrating strong performance in identifying the safety plane. Marsden *et al.* proposed an AI model based on integrating fiber fluorescence imaging with robotic surgical platform cameras, and the model has the potential to assess intraoperative edges[97]. The sensitivity and specificity for identifying different anatomical structures of the oral cavity and oropharynx were 86% and 87%, respectively. Bianchi *et al.* used preoperative multi-parametric magnetic resonance imaging (MRI) images to generate a 3D model in order to accurately cut the lesion and identify the tumor margin, which could be combined with the robot field of view during the operation and instruct the intraoperative tumor margin cutting[98]. In this study, there were no significant differences between the model group and the control group in terms of operation time and postoperative complications. However, the rate of positive surgical margins in the model group (5%) was significantly lower than that in the control group (20%). These methods may also guide surgeons in identifying tumor boundaries during surgery to facilitate complete cancer resection in the future. In the age of AI, automated system performance indicators can be used for objective, real-time surgical performance assessment tools through dynamic and video analysis. The learning curve of robotic-assisted surgery is very long, and its training is mainly carried out through training courses, virtual reality, etc. Training in robotic surgical systems is extremely valuable, and machine learning and video feedback can enhance education in robotic-assisted surgery[99]. By predicting surgical proficiency based on the training intervals of key surgical tasks and video segments, it is possible to differentiate the performance of expert and novice surgeons[100].

Together, these studies lay the foundation for the future automation of robotic surgery.

AI in robotic breast surgery

Machine learning is a facet of AI and deep learning is a facet of machine learning. Deep learning has the ability to automatically extract features and process large amounts of data. It works by establishing an artificial neural network system capable of classifying and recognizing images. The role of deep learning in assisting image analysis for the early detection of cancer is gradually growing[101]. Liao *et al*. developed an ensemble deep learning model, EDL-BC, based on deep CNN. This model can extract morphological features of early breast lesions, perform effective and objective image analysis, improve the accuracy of differential diagnosis of breast nodules, and provide an accurate prognosis for early breast cancer[102]. Yoon *et al*. conducted a meta-analysis on the use of AI for breast cancer detection in screening digital mammography and digital breast tomosynthesis, finding that the performance of standalone AI in digital mammography is as good as that of radiologists[103]. Radiomics can analyze medical images and transform them into quantitative data. By using machine learning to extract quantitative imaging features at high throughput, it can further assess the tumor microenvironment and heterogeneity[104]. Zhao *et al*. developed a machine-learning-based radiomics model that can accurately predict the response to immune checkpoint inhibitors (ICIs)-based therapy in patients with advanced breast cancer[105].

AI is more accurate and faster than humans in diagnosis and treatment decision making. IBM Watson for Oncology (WFO) is one of the most advanced AI decision-making systems, with a consistency rate of 56% between its intelligent decisions and those of doctors. It has shown excellent feasibility and standardization in the application of breast cancer treatment[106]. A retrospective multicenter study integrated MRI radiomics features, axillary lymph node (ALN), clinicopathological characteristics, and molecular subtypes through machine learning to propose a multi-omic signature. This signature can conveniently identify patients with ALN metastasis among different molecular subtypes in early-stage breast cancer, potentially guiding future surgery[107]. Existing postoperative pain assessments require extensive questionnaires and interaction with patients, while machine learning in breast surgery can predict postoperative pain immediately after surgery[108,109]. Machine learning models also indicate that artificial neural networks achieve superior predictive performance and are significantly better than other predictive models, which could predict breast cancer recurrence up to 10 years after surgery[110]. In a preliminary study, Mavioso *et al*. utilized machine learning to assess the vascular CT imaging of patients planned for DIEP breast reconstruction, discovering that this technology could reduce the preoperative planning time for DIEP flaps[111]. O'Neill *et al*. developed a machine learning algorithm to establish a clinical predictive model capable of identifying the risk of flap failure in patients undergoing DIEP flap reconstruction. The results indicated that age ≥ 40 years, BMI ≥ 40, unilateral or bilateral reconstruction, and the presence of complications may contribute to flap failure[112].

The application of AI in breast surgery is still largely conceptual, but computer vision technology can support surgical techniques, and be used in anatomical visualization and surgical navigation[113]. AI, involving machine learning and supported by deep learning, offers opportunities for real-time decision making in breast surgery and can also enhance the realism of robotic breast surgery. Anatomical visualization and surgical navigation are crucial for visualization and completely removing tumor tissue during robotic breast surgery, as well as predicting and resecting axillary positive lymph nodes during surgery. Matrix metalloproteinase-9 (MMP-9) and fibronectin are biomarkers for breast cancer. Cheng *et al*. have developed a new imaging probe, CREKA-GK8-QC, targeted at fibronectin and MMP-9 activation, for detecting *in situ* and metastatic breast cancer[114]. This probe can facilitate complete tumor resection and reduce iatrogenic damage during surgery under the guidance of fluorescence imaging. The probe may also be applicable to robotic breast surgery and even robotic breast-conserving surgery. Robotic ultrasound-assisted biopsy technology enables the integration of robotics and AI with MRI and ultrasound (US) imaging, offering a high degree of precision in needle placement for breast cancer imaging and biopsy[115].

Duarte *et al.* proposed an innovative deep learning technology that integrates CNN, long short-term memory networks (LSTM), and multilayer perceptrons (MLP) to generate depth maps from RGB images, which are then converted in real time into 3D meshes for the three-dimensional reconstruction of the breast[116]. This method can be used for robotic-guided breast biopsy. Additionally, this technology could be further utilized to predict breast size and volume for the calculation of the amount of prosthesis or tissue needed to extend to the field of breast reconstruction, and even for 3D printed breast reconstruction. Peng *et al.* conducted a study on a lesion morphology aware network, LMA-Net, segmenting breast tumors in MRI images, which includes two stages: breast segmentation and tumor segmentation[117]. Alqaoud *et al.* utilized deep learning based on nnU-Net to segment MRI images of the fatty, fibroglandular, and tumor tissues, thereby laying the foundation for robotic surgery planning and image-guided navigation[118]. The study also proposed a simulated breast phantom created from these segmentation results, introducing a polyvinyl alcohol cryogel (PVA-C) breast model for experimental evaluation and validation of the research. The 3D-printed PVA-C mold was produced according to the surfaces extracted from the segmentation outcomes. Although still in the research phase, these developments provide a solid foundation for future clinical applications in robotic breast surgery.

The future

Although current surgical robots are fully remotely operated devices, the “semi-automation” and “automation” of robotic systems are advancing. Researchers are addressing the technical challenges of surgical process automation through the development of real-world task demonstrations, such as the da Vinci Research Kit (dVRK), KUKA LBR Med collaborative robot, and RAVEN robot[119]. Surgical intelligent vision is a challenging task, but if applied to robotic surgery, such as intraoperative decision support and image-guided surgery, it will lead to advancements in future surgical procedures[120]. One of the main differences between robotic-assisted surgery and open surgery is the sense of touch. Developing an intelligent robot with a complete tactile feedback loop requires high-resolution sensor skin, algorithms to interpret sensor information, and reliable feedback control that corresponds to the skin, nerves, and the brain. Bao *et al.* have integrated robotics with AI to study an integrated intelligent tactile system based on touch, achieving real-time tactile perception and grasp control of a humanoid robot’s intelligent robotic hand[121]. Guo *et al.* have developed a tailored wearable haptic controller for robot-assisted microsurgery systems. This haptic glove is designed to capture hand movements for remote operation of robot-assisted microsurgery, and enhance the user’s depth perception to reduce depth errors in microsurgical tasks[122]. The integration of AI with robotic breast surgery may also promote the improvement of medical materials. In the future, appropriate reconstruction materials can be selected through preoperative AI and imaging data modeling to evaluate breast size and density. Robotic remote breast surgery is an important direction for the future, particularly in addressing the surgical needs of patients in areas with limited medical resources or in dangerous regions. In robotic remote surgery, signal latency can cause image interference and oscillation of robotic instruments, thereby affecting surgical safety. Motion scaling may be a solution, and the issue of signal delay can be further resolved by improving motion scaling algorithms and customizing them for specific surgical tasks and conditions in the future[123]. Moreover, the automation of robotic breast surgery will inevitably face ethical constraints. Therefore, it is necessary to standardize autonomous robots in terms of ethics, standards, and regulations to establish public confidence in autonomous robotic systems. In the near future, the task of automating robotic surgery, enabling autonomous robotic programs to adapt to real environments and their resilience, will be the true challenge ahead.

CONCLUSION

The integration of AI with robotic breast surgery represents a significant leap forward in the evolution of surgical procedures. With continued advancements, breast surgery is likely to become more precise, less invasive, and increasingly tailored to individual patients. Ultimately, this progress promises to improve the survival rates and enhance the quality of life for those affected by breast cancer.

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Authors' contributions

Made substantial contributions to the conception and design of the study: Li C
Manuscript writing: Li X, Li C

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