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4 authors, including:

Swastika Chatterjee
JIS COLLEGE OF ENGINEERING

Soumyajit Das
Medical College, Kolkata

Dibyendu Mandal
JIS COLLEGE OF ENGINEERING

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REVIEW

Advancements in robotic surgery: innovations, challenges and future prospects

Swastika Chatterjee[1] · Soumyajit Das[2] · Karabi Ganguly[1] · Dibyendu Mandal[1]

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Abstract

The use of robots has revolutionized healthcare, wherein further innovations have led to improved precision and accuracy. Conceived in the late 1960s, robot-assisted surgeries have evolved to become an integral part of various surgical specialties. Modern robotic surgical systems are equipped with highly dexterous arms and miniaturized instruments that reduce tremors and enable delicate maneuvers. Implementation of advanced materials and designs along with the integration of imaging and visualization technologies have enhanced surgical accuracy and made robots safer and more adaptable to various procedures. Further, the haptic feedback system allows surgeons to determine the consistency of the tissues they are operating upon, without physical contact, thereby preventing injuries due to the application of excess force. With the implementation of teleoperation, surgeons can now overcome geographical limitations and provide specialized healthcare remotely. The use of artificial intelligence (AI) and machine learning (ML) aids in surgical decision-making by improving the recognition of minute and complex anatomical structures. All these advancements have led to faster recovery and fewer complications in patients. However, the substantial cost of robotic systems, their maintenance, the size of the systems and proper surgeon training pose major challenges. Nevertheless, with future advancements such as AI-driven automation, nanorobots, microscopic incision surgeries, semi-automated telerobotic systems, and the impact of 5G connectivity on remote surgery, the growth curve of robotic surgery points to innovation and stands as a testament to the persistent pursuit of progress in healthcare.

Keywords Robots · Robotic surgery · Innovation · Challenges · Future prospects

Introduction

Brief overview

Robotic surgery, also known as robot-assisted surgery, is a revolutionary and promising technology in medical science that has both real and potential advantages. The evolution of robotic surgery stands as the exemplification of human innovation and the pursuit of advancement in healthcare technologies. This rapidly evolving technology has captivated the attention of the medical community as well as researchers due to its enhancement in precision, reduction in invasiveness, and improvement in patient outcomes, thereby gaining acceptance, especially across various specialties, such as urology, general surgery, cardiothoracic surgery, gynecology, otolaryngology, neurosurgery, orthopedic surgery and surgical oncology [1].

Background and history

The idea of robot-assisted surgery can be traced back to 1967; however, it was the US Department of Defense, along with various stakeholders, who brought into existence the first fully functional surgical robot, to reduce war casualties [2]. In 1985, Kwoh conducted the first robotic surgery using Puma 560, an industrial robot arm, in a CT-guided brain biopsy which was then used as a stereotactic frame in neurosurgery, but later the robot's manufacturer, Westinghouse Limited, cited that it was unsafe to use the robot for surgical purposes as it was designed for industrial environments, thereby, not allowing its use in surgical procedures [3].

The actual implementation began in the late 1980s with the use of Robodoc in prosthetic hip replacement by Hap

✉ Dibyendu Mandal
dibyendu.biomech@gmail.com

[1] Department of Biomedical Engineering, JIS College of Engineering, Kalyani, West Bengal, India

[2] Medical College, Kolkata, West Bengal, India

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Paul, DVM, and William Bargar, MD along with the development of a urologic robot for prostate surgery by Brian Davies and John Wickham [4, 5]. Furthermore, researchers at the National Aeronautical and Space Administration (NASA) Ames Research Center, while working on virtual reality, were keen to develop telepresence surgery, which set a landmark for the development of surgical robots [6]. In the early 1990s, several scientists from the NASA-Ames Research Center, along with roboticists and virtual reality experts from the Stanford Research Institute (SRI), developed a dexterous telemanipulator for hand surgery [7].

General surgeons and endoscopists also joined the development teams and later teamed with the engineers working on this project to form commercial ventures that led to the introduction of robotic surgery for civilian causes [6]. Computer Motion developed a robotic arm, Automated Endoscopic System for Optimal Positioning (AESOP), which utilized the surgeon's voice commands to guide an endoscopic camera. This was soon followed by the licensing of the SRI Green Telepresence Surgery system, by Integrated Surgical Systems (now Intuitive Surgical), which was reintroduced as the Da Vinci surgical system [7].

Pros and cons

Robot-assisted surgery has now become an integral part of modern surgical practice with surgeons having access to highly sophisticated robotic platforms offering greater precision, 3D visualization, and dexterity in performing intricate procedures, developing the scope for minimally invasive surgery. However, robotic surgery has its shortcomings, including the substantial cost of robotic systems, their maintenance, the size of the systems as well as surgeon training, and the acquisition of robotic skills. Moreover, competent integration of robotic technology with surgical curricula demands time and resources and is paramount to its success [8] (see Table 1).

Methodology

We initiated this review by conducting a comprehensive survey across reputable academic databases, including PubMed, IEEE Xplore, Google Scholar, and CrossRef. Keywords and phrases, such as "robotic surgery," "surgical

Table 1 Comparing the pros and cons of open surgery, minimal invasive surgery and minimally invasive robotic surgery [8]

	Open Surgery	Minimally invasive Surgery	Minimally Invasive Robotic Surgery
Shorter operative time	✗	✓	✓
Shorter post op stay	✗	✓	✓
Shorter recovery time	✗	✓	✓
Less blood loss	✗	✓	✓
Less post op pain	✗	✓	✓
Less scarring	✗	✓	✓
Less complications	✗	✓	✓
Less infection risk	✗	✓	✓
Less transfusion requirement	✗	✓	✓
Less fatigue (surgeon)	✗	✗	✓
Less expensive equipement	✓	✓	✗
Less specialized training	✓	✓	✗
Compensate for hand tremors	✗	✗	✓
Enhanced view	✗	✓	✓
Small incisions	✗	✓	✓
Less anesthesia required	✗	✓	✓
Fewer doctors in OR	✗	✗	✓
Motion scaling	✗	✗	✓
Improved dexterity	✓	✗	✓
Fulcrum effect	✗	✓	✗
Longer setup time	✗	✗	✓
Significant haptic-feedback	✓	✗	✗

robots," "innovations," "challenges," and "future prospects," were utilized to identify pertinent research articles, reviews, and conference papers. We also included variations of these terms to capture a wide spectrum of literature. Articles were included if they focused on the history, advancements, challenges, or future prospects of robotic surgery, and were written or translated in English. Studies that primarily discussed non-robotic surgical techniques or were not peer-reviewed were excluded. Two independent reviewers screened the titles and abstracts of identified articles to assess their relevance. Entire articles were then reviewed based on the inclusion criteria. Any discrepancies were resolved through discussion involving all the authors.

Data extraction was performed systematically, including information on the publication date, study objectives, methodologies, key findings, and areas of innovation or challenge discussed in each article. The extracted data were then synthesized to provide a comprehensive overview of the advancements in robotic surgery, the challenges faced by the field, and the anticipated future prospects. Key themes and trends were identified and discussed. Since this review is based solely on publicly available literature, ethical approval was not required. Proper citation and referencing of all sources were ensured throughout the review process. The review article is structured to provide an introduction to robotic surgery, followed by sections on innovations in robot-assisted surgical techniques, clinical application of robotic surgery and their outcomes and finally a conclusion discussing the future prospects. Each section incorporates the findings from the literature review and offers insights into the respective aspects of robotic surgery.

Innovations in robot-assisted surgical techniques

Robot-assisted surgery has witnessed a wide range of advancements in robotic platforms, implementation of imaging and visualization technologies, application of augmented reality (AR), artificial intelligence (AI), machine learning, and use of haptic feedback and teleoperation in surgical settings, all of which have led to improved precision, flexibility, minimal invasiveness, followed by faster recovery and fewer risks.

Improved precision and dexterity

Enhanced precision and dexterity are one of the key features that robotic surgical systems offer to healthcare. Implementation of highly articulated robotic arms with miniaturized surgical instruments, which not only imitate the movements of a surgeon's hand but also significantly reduce tremors, allows delicate and precise maneuvers during surgery [9]. These highly dexterous instruments allow minimal invasiveness into the body of the patient aiding in faster recovery followed by reduced costs per patient [10, 11]. Furthermore, the use of robot arms for positioning and holding surgical tools not only relieves the surgical assistants from the tedious task of physically holding instruments but also mentally relieves the surgeon due to enhanced positioning and working accuracy, leading to increased patient safety and better postoperative outcomes [12].

Advancement in materials and design

Construction of robots using biocompatible soft materials, superelastic materials, and 3D-printed soft plastics such as silicon elastomers allows changes in robotic shape and mechanical properties in response to touch, thus enhancing their greater intrinsic safety [13]. Recent advancements involve bendability and stiffness controllability as key aspects that allow elongation to tune the exact position of the robot and greater flexibility of the instrument neck. The force applied by shape reconstruction is sensed, with the stiffness of the advancing tip being controlled by the tension, thereby allowing active adjustment of the payload [14]. Flexible surgical robotics, therefore, is a highly promising research area and has been deployed in the operating room for single port surgery, endoscopic surgery, bronchoscopy intervention, and vascular catheterization, thereby aiding in designing cost-effective, minimally invasive, and patient-specific surgical procedures [15].

Integration of imaging and visualization technologies

The accuracy of robotic surgeries has improved with the integration of imaging and visualization technologies. For instance, traditional laparoscopic surgery involves a 2-dimensional (2D) field of view, narrow space, lack of depth perception, and prolonged procedures which lead to fatigue among surgeons [16], whereas the robot-assisted surgical system offers a stable camera platform, a high-definition 3-dimensional (3D) surgical field of view and visual magnification, all of which results in better surgical outcomes as well as reduced surgical fatigue among surgeons [9].

Further, the application of real-time augmented reality (AR) aids in highlighting critical anatomical structures, thereby providing in-situ visualization of preoperative or intraoperative information about the patient. It can also be used for proper port placement, sensory substitution, supervised robot motion, advanced visualization, bedside assistance, and surgical training along with hand-gesture-based interaction for adjusting the surgery plan which helps the surgical team to remain sterilized for a longer duration [17] (see Fig. 1).

Haptic feedback and sensory enhancement

Haptic feedback systems help surgeons to determine the consistency of the tissues they are operating upon, without physical contact, thereby preventing surgeons from accidentally applying excessive force and damaging them [18]. Virtual sensations, also known as visual haptics, provide an alternative for sensations generated during surgery such as tissue palpation, needle insertion, the sensation of using a tool on human tissue, and needle slippage. Although there are technical challenges in introducing haptics in telesurgery, including instrumentation, transparency, stability, and modalities for force reflection, there is a necessity to develop sensitized minimally invasive surgical tools that bio-mimic the human finger's ability to detect normal and shear forces, tissues' softness, and other physical properties [18, 19]

Teleoperation and remote surgery

The advancement of technology and communication in recent years has revolutionized the field of medicine, with telemedicine and teleoperation becoming popular among patients and physicians. Teleoperation technology, also known as master–slave technology, aids in remote operation by a surgical robot, actively controlled by a distant operator. This promotes the surgeons to perform procedures on patients located remotely, thereby reducing geographical limitations and providing access to specialized healthcare [20], additionally aiding in improving surgical accuracy, surgical collaborations and minimizing the risk of infections. However, zero-latency time and improvement in haptic feedback technology are required for precise and accurate surgeries [21]. Despite these major shortcomings, this technology has been valuable in emergencies and in rural or underserved environments [20]. Technologies such as 5G network, IoT, and tactile robotics should be incorporated in telesurgery to overcome these barriers [21] (see Fig. 2).

Artificial intelligence (AI) and machine learning (ML) in surgical decision-making

Artificial intelligence (AI) refers to the study of algorithms that give machines the ability to reason and perform cognitive functions such as decision-making, problem solving, as well as object and word recognition, which can help analyze vast amounts of patient data, including medical images and patient histories, thereby assisting in real-time decisions during procedures. [23]

Machine learning (ML), a subfield of AI, enables machines to learn and make decisions based on pattern recognition. It allows a computer to learn, not only, from human labeled data fed to the ML algorithm (known as supervised learning) but also from unlabeled data fed to the algorithm, thereby making the machine attempt to find a

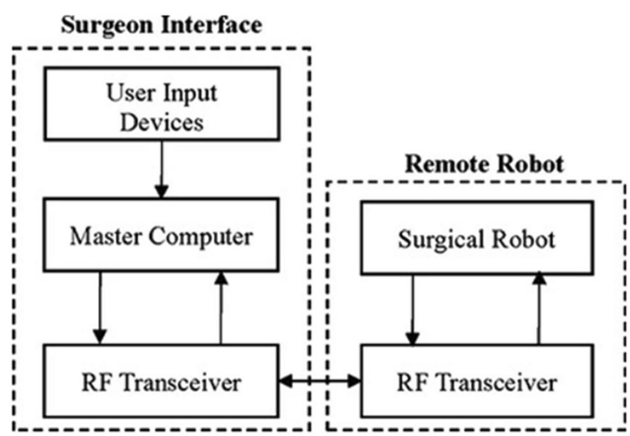

Fig. 2 Block diagram of remote surgical platform [22]

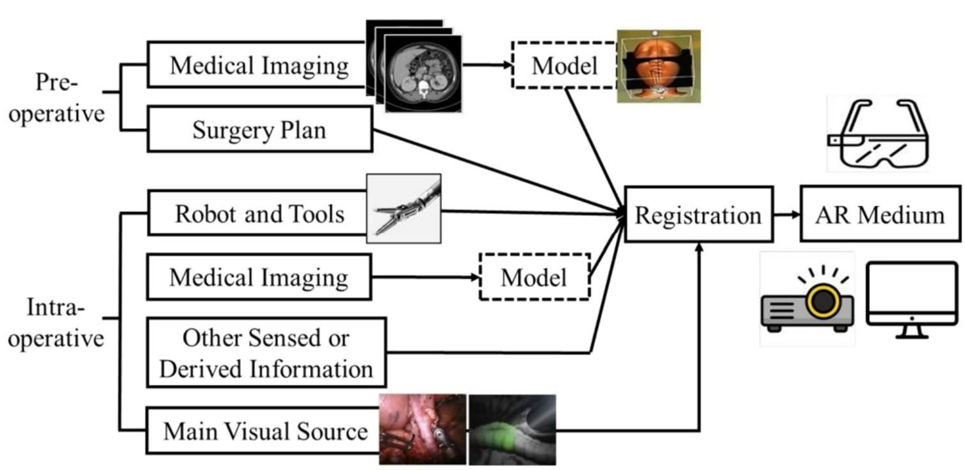

Fig. 1 Diagram showing the components of a typical AR-based intraoperative guidance application [17]

hidden structure to the data (called unsupervised learning). This helps to train the computer to make predictions about the data without explicit programming [24]. In addition, a system can undergo reinforcement learning, another category of ML, where a program attempts to accomplish a task and learn from its own successes and mistakes [25]. While supervised learning is useful for training a ML algorithm to predict a known outcome, unsupervised learning is useful in searching for patterns within data [24]. Reinforcement learning, on the other hand, can be useful for auto-tuning of actions, which can find its application in cases such as controlling an artificial pancreas system to fine tune the measurement and delivery of insulin to diabetic patients [26].

For enhancement of precision and decision-making in robotic surgical systems, artificial intelligence (AI) and machine learning (ML) has been implemented. For instance, ML can be used to train the robotic surgical systems for accurate recognition of a gallbladder in an image and differentiate a bleeding tissue from a non-bleeding one [23]. Moreover, attempts have been made to use AI for technical skills augmentation focused on simple tasks such as suturing and knot-tying, which laid the foundation for more complex AI tasks, as demonstrated by the autonomous ex-vivo and in-vivo bowel anastomosis in animal models by the Smart Tissue Autonomous Robot (STAR) developed by Johns Hopkins University [27–30]. While fully autonomous robotic surgery is a distant dream as of now, amalgamation across fields will likely accelerate the capabilities of AI and its application in robot-assisted surgery [23].

Clinical applications of robotic surgery and their outcomes

Many medical specialties have brought in revolution with the implementation of robotic surgery, which has improved precision, enabled minimally invasive procedures, and enhanced patient outcomes. This technology incorporates the skill of surgeons with robotic systems, enabling intricate procedures with greater ease.

Otolaryngology

The da Vinci surgical robot system is the only FDA-approved robotic surgical system for head and neck surgery [31]. The transoral robotic surgery (TORS) technique has wide application in the field of Otolaryngology including robotic resection of the tongue, robotic tonsillectomy, as well as surgery for oropharyngeal squamous cell carcinoma [32, 33]. A study on patients with t1–t3 tonsillar cancer noted that the TORS method did not provide any significant improvement in survival rate, but when the rate of margin negativity was improved, recovery to normal swallowing was observed to be faster [34]. The major advantage of the TORS is reducing average operating times by almost half and lesser blood loss, thereby enhancing better patient outcomes [31, 35].

In addition, robotic surgery finds its application in thyroidectomy, where it uses the nonvascularized area near the branches of sternocleidomastoid muscle and below the infrahyoid muscles, leading to fewer complications, lowering postoperative discomfort and bettering cosmetic outcome, although operative time is higher [36, 37].

Neurosurgery

With the increase in demand for minimally invasive approaches to the brain and spine, robotic surgery finds its application in neurosurgery through localization of the lesion, surgical planning for access to deeper areas of the brain and postural stability to the surgeon's hand. This is aided by the intuitive haptic feedback, which allows fine positioning of the robotic arm with minimal exertion. Currently, there are three categories of robotic systems in the market for application in neurosurgery. These include the telesurgical robot, the supervisory surgeon controlled robot and the handheld shared/ controlled systems [38, 39]. Neuromate (the first FDA-approved robotic device), Pathfinder, NeuroArm, SpineAssist, and Renaissance are among the robotic systems commonly used in neurosurgery [39]. They are extremely useful for stereotactic procedures such as insertion of DBS electrodes, biopsy of deep-seated complex tumors, insertion of multiple depth electrodes for stereo encephalography (SEEG) and placement of microcatheters for targeted chemotherapy in gliomas. Assistance of this technology can be taken in conjunction with neuroendoscopy to help in navigating narrow corridors of access without any deviation [38].

Gastrointestinal surgery

The field of gastrointestinal (GI) surgery has also started to implement therapeutic robotic surgery in cases ranging from stomach, liver, gallbladder, pancreas, small bowel, adrenal, colon and others [40]. Various case reports portray the use of the daVinci or ZEUS robotic surgical systems in GI surgeries. One such application is gastrectomy for gastric cancer, although initially the complexity of the D2 lymph node dissection hindered the utilization of robotics for this procedure. Another type of robotic GI surgery is the robot-assisted silicone-gastric banding as a treatment for obesity [41]. Moreover, robot-assisted gastric bypass surgery showed better outcomes with no postoperative leaks or anastomotic failure [42]. In addition, Nissen fundoplication was performed using surgical robots; however, no clear clinical benefit was noticed. Therefore, it can be inferred that the currently used precise robotic systems allows for dissection in congested abdominal cavities with minimum blood loss, resulting in improved clinical outcomes [43].

Gynecology

It has been demonstrated that the use of the daVinci surgical robotic system in complicated gynecological surgeries like hysterectomy with bilateral salpingo-oophorectomy was superior than the conventional procedure because it allowed for a better operative field visualization, better manipulation, easier dissection and faster recovery [44]. Similar advantages have been seen in robotic myomectomy, which offers a high level of hand dexterity to carry out a more precise surgery and extend their capabilities in terms of the size and number of myomas that can be removed in a minimally invasive way, thereby proving to be an alternative to the traditional approach [45–47]. Furthermore, use of robotics has been implemented for endometriosis [40]. Robot-assisted laparoscopic sacrocolpopexy, the treatment of post-hysterectomy vaginal vault prolapse in obese patients, offers better visualization and dexterity, especially during the pre-sacral space dissection, positioning of the mesh and intracorporeal suturing, better postoperative sexual function and improved pelvic support [48–50]. Robot-assisted tubal re-anastomosis, cervical cerclage, vesicovaginal repair, recto-vaginopexy and Burch colposuspension are few other applications of the technology in this field [51–56].

Cardiothoracic surgery

Robotic surgery has widespread application in the field of cardiothoracic surgery. Using the daVinci surgical system, surgeons can now perform coronary revascularization which includes totally endoscopic coronary artery bypass (TECAB), wherein a graft from the left internal thoracic artery (LITA) is harvested using a robot and grafted onto the left anterior descending (LAD) artery, both on beating as well as arrested heart. [57] Use of robotic surgical systems such as da Vinci and AESOP in mitral valve surgery has proven to significantly reduce mortality and morbidity, lower risk of atrial fibrillation and pleural effusion and significantly reduce the length of hospital stay [58–61]. In addition, robotic surgery can also be used for treating the atrial septum defect, resection of primary cardiac tumors and guided left ventricular lead implantation [62–64].

Orthopedic surgery

Use of robotics in orthopedic surgery has evolved over the years. Robotic total hip arthroplasty (THA) has been successful in precise restoration of the hip joint with better recovery than manual procedure [65]. Further, robot-assisted total knee arthroplasty (TKA) aids in better positioning of implants and successful preservation of bone and soft tissues [66]. It also finds its application in pedicle screw placement during spine surgery in patients with spinal metastasis and low-grade spondylolisthesis where it reduces the need for revision surgery [67, 68]. The use of robotics in shoulder surgery and percutaneous reduction of fractures are still in the experimental stage, however, the results are promising [69, 70]. Robots have also been used to identify the entry point of intramedullary nailing, apply distal locking bolts in cadavers and safely identify, dissect and repair nerves in Brachial plexus injuries [71–74].

Urologic surgery

The depth of the pelvis and the small anatomical structure makes it difficult for the surgeon to access the target area [75]. Thus, robotic surgical systems are useful in surgeries prostatectomies, nephrectomies and adrenalectomies [76]. In addition, a minimally invasive approach for treatment of utero-pelvic junction obstruction has been made possible by the application of this technology [77]. Robotic radical cystoprostatectomy has shown decreased blood loss, shorter postoperative catheterization period, faster restoration of urinary continence, faster mean return time of erection and lower rate of complications [78]. Other procedures carried out by robotic assistance include vasectomy reversals, sub-inguinal removal of a varicocele, and removal of innervations of the spermatic cord [79].

Surgical oncology

The use of robotics in cancer surgery is different as it tackles unique challenges in the form of early advantages that have compromised long-term benefits or higher cost of surgery, both being detrimental to the treatment of cancer. Currently, studies have shown that robotic surgery in cases such as carcinoma rectum and esophagus has short-term outcome, less conversion rate, and marginal benefit in comparison to traditional surgery; however, poor long-term outcomes were observed in carcinoma cervix and carcinoma bladder [80–83]. Procedures such as anterior resection in carcinoma rectum, metastasectomy in the lung, wedge resection, and lobectomy in carcinoma lung have shown definitive advantages in terms of ease of surgery when carried out with robotic assistance [80, 84]. It should be noted that evidence-based advantages for many other robotic procedures performed in the field of surgical oncology is still unknown and further research is required for exploring new possibilities in this field [85].

Pediatric surgery

As far as robotic general surgery in pediatrics is concerned, fundoplication is one of the most widely performed procedures [86]. Frequently performed pediatric robotic cardiothoracic procedures includes diaphragmatic hernia repair, lobectomy, bronchogenic cyst excision, Heller's cardiomyotomy for achalasia, esophagoplasty, and esophageal atresia repair [87]. Robot-assisted pediatric urology procedures include ureteroureterostomy, Mitrofanoff appendicovesicostomy (APV), bladder augmentation, bladder neck reconstruction, and augmentation ileocystoplasty (AI). Robotic surgery also finds its application in neonatal diseases, such as the repair of duodenal atresia, duodenojejunostomy for SMA syndrome, and Kasai operation for biliary atresia. Further, procedures involving robotic spleen-preserving distal pancreatectomy, robotic pancreatic enucleation, robotic lateral pancreaticojejunostomy, robotic pancreaticoduodenectomy and partial pancreatectomy are used as a treatment of pediatric pancreatic conditions. Although the usage of robots in the fields of head and neck surgery and surgical oncology for children is in its infancy, better feasibility and increasing usage will be beneficial in development of robotic surgery in these fields [88].

Ophthalmology

In the field of ophthalmology, robotic surgery is in its initial phase. Use of surgical robots aids in reduction of physiologic tremors and helps to guide surgical movement appropriately in procedures like placement of a microcannula tip into a retinal blood vessel and maintain it in the blood vessel in order to deliver a drug [89, 90]. Systems like da Vinci finds its application in repair of corneal laceration, retinal vascular microsurgery, pars plana vitrectomy, intraocular foreign body removal, anterior capsulorhexis, penetrating keratoplasty, and pterygium surgery [91–93].

However, robotic surgery, in the field of ophthalmology, faces certain challenges. The presence of high remote center of motion (RCM) in the robot right above the wrist and at a long distance from the tip of the instrument makes the intraocular movements less controllable and promotes unnecessary tension of the surface of the external eye which compels the surgeon to utilize another RCM in procedures like ocular penetration [92]. Another limitation is the achievement of optimal and detailed images as the video capture system of the robot is designed for endoscopic use only [93]. Development and research are still going on, which would catalyze the usage of robots in this specialty.

Conclusion

According to a study conducted by a reputed publisher of strategic business and related economics, AI has an enormous impact on the Indian healthcare ecosystem by bringing cutting-edge tools for diagnosis, treatment and patient care. The study suggests that the market share of AI in healthcare is projected to grow from \$14.6 billion in 2023 to \$102.7 billion by 2028, enabling further research and its application in geriatric care, drug discovery, clinical trials, telemonitoring, prediction and management of epidemics and pandemics, and so on [94].

Looking ahead, the future prospects of robotic surgery are nothing but intriguing. At present, the robots used in surgery are mostly manual, but attempts are being made to train the robot using AI, which will allow the surgeons to identify the two boundaries of the location of interest as input to the system and the system will automatically suture the area. This would aid in reducing errors and increase the accuracy of the system [95]. As a short-term goal, the idea is to train the robot to safely perform actions in the risk-prone regions of the body along with the development of nanorobots which are small enough to enter the bloodstream and then identify and treat the target site.

In addition, robotic systems are being developed that allow surgery to be done through microscopic incisions [40, 96]. Presently, robotic systems that can perform surgeries through smaller incisions are being developed for application in fields like neurosurgery where the size of incision is directly proportional to the amount of tissue lost [88]. In addition, a semi-automated telerobotic surgical system called Trauma Pod, capable of performing the tasks of circulating and scrub nurses as well as keep a track of supplies, is being developed to save the lives of critically injured patients on the battlefield [97]. Furthermore, the potential for remote surgery, enabled by 5G connectivity, opening up new frontiers in global healthcare delivery [98]. In addition, development of various new robotic platforms, such as Senhance Surgical Robotic System, Flex Robotic System, SurgiBot, and many others will surely boost the usage of robotic surgery in fields were its use is still in nascent stage [99–102].

In conclusion, robotic surgery has emerged to be a revolutionary force in the field of surgery and healthcare, transforming various surgical specialties with the integration of human capabilities and technology. Despite the challenges which exist in the form of cost and training requirements, the growth curve of robotic surgery points to innovation and stands as a testament to the persistent pursuit of progress in healthcare.

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