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Review Article

Current surgical practices of robotic-assisted tissue repair and reconstruction

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ABSTRACT

This paper systematically reviewed and analyzed the recent publications of robotic-assisted surgeries in the field of tissue repair and reconstruction. Surgical robots can elevate skin flap more accurately and shorten the time of tissue harvest. In addition, robotic-assisted surgery has the advantage of minimal tissue trauma and thus forms minimal scar. The utilization of surgical robots reduces the occurrence of complications after oral radical tumor resection while achieving cosmetic sutures. Robotic-assisted radical mastectomy could radically remove invasive breast cancer lesions and achieve breast reconstruction in the first stage through the small incisions in the operation areas. Surgical robots enable precise microvascular anastomosis and reduce tissue edema in the surgical field. Robotic-assisted technology can help appropriately locate the target tissues at different angles during sinus and skull base surgeries and accurately place tissues during urethroplasty. The robotic-assisted technology provides a new platform for surgical innovation in the field of tissue repair and reconstruction. However, the uncertainty in the survival rate after tumor radical surgery, the increase of operating time, and the high costs are barriers for its clinical application in tissue repair and reconstructive surgery. Nevertheless, robotic-assisted technology has already demonstrated an impact on the field of tissue repair and reconstruction in a meaningful way.

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Introduction

The concept of “robotic-assisted surgery” originated from military hospitals and was proposed by the military doctors during World War II aiming to develop a machine-operated system that supports a remote control surgery. Such surgical robots would perform surgeries on the wounded in time to achieve the purposes of initial tissue repairing. However, the robotic-assisted surgery only stayed around fanciful conception because of the difficulties in implementation at that time.

In 1994, Phil Green et al. designed a visual remote surgery operating system that consisted of a console and a wireless remote control arm. The system allowed a surgeon to perform surgical wound repair and plastic surgery on injured soldiers who were located at 35 km away.¹ In the 1980s, minimally invasive laparoscopic surgery was put into service and became popular rapidly because of some obvious advantages including small skin incisions, short operative time, rapid postoperative recovery, and the small and

unconspicuous incisional scars. However, laparoscopic surgery has some intrinsic disadvantages. There is no stereoscopic sense in two-dimensional imaging, the operation lacks flexibility and the vision field has blind areas. With the popularity of minimally invasive surgery, more patients have a growing demand for precise surgical operations in the repair of tissue and organ functions, particularly, in the facial area. In 2000, the da Vinci Surgical Robot No. 1 was approved by the US FDA for clinical use.² It consists of three portions: (1) The console, (2) the rotating arms, and (3) the display. It has 3–4 rotating arms, which can fulfill the requirements of minimal trauma, precise repair, quick recovery, and slight scarring. In 2014, the improved version of the da Vinci 1 Xi™ was officially launched and equipped in several major hospitals around the world. As of 2017, a total of 62 surgical robots have been settled in major hospitals in the mainland of China signifying an era in which the surgical robots will become the leading technology in modern surgery.

Advantages of surgical robot operating system

Surgical robotic surgery has the following advantages over traditional surgical procedures (Table 1). Firstly, surgeons do not have to have a direct contact with the patients and the procedures can be completed through a three-dimensional vision system and

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Table 1
Technical characteristics of three generations of surgery.

Technical characteristics	Traditional operation	Endoscopic surgery	Robotic surgery
Surgical manipulation	Direct control; Topical operation is not accurate and the space is narrow and limited	Need to cooperate with the assistant to locate the field of view. Disadvantages: reverse operation of the device	Lens and instruments can be adjusted by operating surgeons. There is no space restrictions
Imaging technology & coordination	Naturally direct, but the fine structure is difficult to see	2D planar imaging, general resolution; but easy to be distorted, low coordination	3D stereo HD image, good coordination
Flexibility & precision	Intuitive, flexible, and poorly accurate	Not as flexible as a hand; Accuracy is average	The operating arm has seven pre-set positions. More flexible and precise
Stability & safety	There is physiological jitter, and safety depends on the experience and skill of the doctor	Operation to amplify physiological jitter, depending on the experience and skill of the doctor	Filtering the tremors facilitates the separation of tissues, nerves, and blood vessels in deep and narrow spaces. High security
Trauma	Traumatic, slow recovery after surgery	Minimally invasive, quick recovery after surgery	Minimally invasive, quick recovery after surgery
Operating posture	Standing to complete surgery	Standing to complete surgery, not suitable for complex surgeries	Surgeon in sitting position; suitable for complex surgeries

an action calibration system. Secondly, the movements of the surgeon's arms, wrists, and fingers are recorded by the sensors in the computer and simultaneously translated to the robotic arms. The front ends of the robotic arms simulate the surgeon's technical movements and accurately complete the surgical procedures.

Compared with laparoscopic surgery, surgical robots not only inherit the advantages in laparoscopic surgery, but also have other merits. Firstly, a surgical robot wrist joint is much more flexible and is able to take multiple positions in a 360° dimension in order to readily match the surgeon's personal style during the operation. Secondly, the operating arm can intelligently filter out human hand vibration. Additionally, the operating arm has the functions of traction, cutting, suturing, etc., and is especially capable of operating fine surgery in a small space.³ Thirdly, the display can provide a high-definition 3D view of the operating area. It can magnify the surgical field by 40 times and the surgical action by 10 times. The display features high-resolution 3D image processing technology that allows the surgeon to position and manipulate tissues confidently and accurately.^{4,5} Lastly, the surgeon can take a sitting posture for the operation, which is obviously a benefit during a long time and complicated operation. The screens can display the real time images of the surgeon's hand movement and the operation details will provide a teaching platform for young physicians.⁶

Application of surgical robot in tissue repair and reconstruction surgery (Table 2)

Surgical robotic-assisted flap or tissue harvesting

Skin flaps and various tissues (such as nerves, cartilage, bone, tendons, etc.) are commonly used in plastic surgery. At present, incisions have to be planned in concealed areas, such as axilla, in order to avoid apparent scarring when harvesting tissues. Even with minimally invasive endoscopic techniques, some surgical procedures cannot be performed due to poor flexibility and precision of the endoscope (e.g., breast reconstruction with rectus abdominis after mastectomy). When a surgeon uses minimally invasive endoscopic techniques for surgery, the entire surgical procedure is completely dependent on the surgeon, and his assistant provides no substantial help. This type of operation relies entirely on the surgeon skill levels, therefore complications often occur, such as secondary malformations and localized scar formation after mastectomy. Clemens et al.⁷ and Selber et al.⁸ pioneered in the use of surgical robots to perform a mastectomy that preserved the nipple and areola, while completely cutting a piece of latissimus dorsi muscle tissue for the procedure of either the

Immediate Breast Reconstruction or Delayed Breast Reconstruction. Postoperative results confirmed that surgical robotic mastectomy significantly reduced scar formation. Selber et al.⁸ used surgical robots to perform breast-conserving resection and reconstruction with latissimus dorsi tissue. They skillfully designed the two surgical incisions together, and this improvement significantly shortened the operation time. In the case of traditional rectus abdominis surgery, the anterior sheath of the rectus abdominis is often damaged, which is likely to cause postoperative abdominal hernia. Similarly, when an endoscope is used to remove or take nerves and their branches, the nerves and their innervated areas are often damaged due to factors such as their deep position that making nerve taking difficult. However, robotic-assisted surgery can overcome the above shortcomings. Louis et al.⁹ used a surgical robot to perform rectus abdominis tissue excision followed by pelvic tissue reconstruction. The postoperative results were satisfactory and the operation time was less than 1 h. The use of surgical robot for surgeries on rectus abdominis and reconstruction can completely preserve the anterior rectus sheath, reduce abdominal wall spasm, and avoid the postoperative intestinal dysfunction and postoperative sexual dysfunction.¹⁰ Porto et al.¹¹ used a surgical robot in

Table 2
Application of surgical robot in tissue repair and reconstruction surgery.

Repair & reconstruction surgery	Surgeon	Advantages
Assisted flap or tissue cutting	Clemens MW, Selber JC, Louis V	Selection of the flap or tissue is accurate, the operation time is short, the surgical trauma is minimal, and the postoperative scar is small.
Oral facial repair surgery	Nam, Weinstein GS, Selber JC	Reduce postoperative complications, achieve a cosmetic suture in the incision
Breast-conserving and breast augmentation	Toesca	Minimally invasive, postoperative reconstruction can be completed in one stage
Microsurgery	Katz RD	Microvascular anastomosis, reducing tissue edema
Sinus and skull base surgery	Friedrich DT, Schneider	Expanding the field of small space
Urethroplasty	Unterberg SH, Dinerman BF	Making visualization and accurate placement

assisting nerve tissue removal which quickly and completely stripped deep nerve tissues.

Surgical robotic-assisted oral and facial repair

Nam et al.¹² performed a retrospective analysis of 103 patients with oral tumors and summarized the incidence rate of postoperative complications that was as high as 18.4% with the traditional surgical approach. Among the rates of these complications, the mandibular pseudoarticular formation was 6.7%, the bone radioactive necrosis was 4.9%, and the intraoral ostomy was 2.9%. Meanwhile, some other complications such as scar healing and long incision were often seen. In order to improve this situation, Hatten et al.¹³ based on the experiences gained in the traditional surgery and *trans*-oral laser surgery, first proposed the concept of *Trans*-oral robotic surgery (TORS). TORS can remove these tumors directly through the oropharynx. Using an oral occlusion device and a cheek retractor to retract the oropharynx and then extend the endoscope into the pharynx, the field could be clearly visualized. Finally, the surgeon performed tumor resection with a CO₂ laser robotic arm. The early T1/T2 oropharyngeal tumor could be completely removed. The trachea was not cut during the entire operation, thus avoiding the damage to the internal structure of the trachea.¹⁴ Postoperative swallowing function and vocal cord function were almost unaffected, achieving the goal of initial cosmetic restoration.^{15,16}

Surgical robotic-assisted breast-conserving surgery and breast augmentation

At present, breast resection with nipple preservation is a hot spot in breast cancer surgery. Studies have shown that inadequate exposure of the mammary lesion tissues due to the concern of postoperative aesthetics may lead to incomplete tumor resection.¹⁷ The operation of the breast site inevitably damages the blood vessels and their surrounding flaps, thereby increasing the probability of nipple-areola complex (NAC) necrosis.¹⁸ Lateral radial incisions and hemispherical incisions may lead to postoperative breast deformation or secondary NAC necrosis.^{19–21} For the first time, Toesca et al.²² successfully performed a breast-conserving resection using a surgical robot. The advantages are summarized as follows: the surgical robot is capable of avoiding the damage of the blood supply of the breast and the surrounding flap tissues while achieving minimally invasive radical mastectomy and breast reconstruction with reduced risk of NAC necrosis. Postoperatively, only 3–4 cm of minimally invasive scars were left on the axillary lines.

Surgical robotic-assisted microsurgery

Katz et al.²³ used a robotic-assisted microsurgery (RAMS) robot to align the anterior tibia artery and the anterior tibia vein of a pig. By comparison, it is found that the surgical robot is more accurate than the traditional microsurgery procedure for anastomosis of vessels with diameters of less than 1.5 mm. Karamanoukian et al.²⁴ used RAMS robots in porcine coronary artery bypass grafting and demonstrated that surgical robots have significant advantages for millimeter-scale vascular anastomoses. Lower extremity edema often occurs in patients with cancer because of the poor lymphatic drainage. Surgeons at the University of Maastricht Hospital in the Netherlands completed the world's first ultramicroscopic surgery - "Lymphatic Vein Anastomosis" with the assistance of surgical robots. They successfully sutured a blood vessel with a diameter of 0.3–0.8 mm, and the patient's lower extremity pain and edema were significantly improved after the surgery.²⁵

Robotic surgery for the sinuses and skull bases

Currently, robotic surgery for the sinuses and skull bases is still very challenging. Due to the irregularity of the bones of the sinus and the skull base, the endoscopic surgery has the several disadvantages including blind vision field and inconvenient maneuver that makes it difficult to completely remove the lesions. Friedrich et al.²⁶ and Schneider et al.²⁷ applied the modified surgical robots to the sinus and skull base surgery to make the procedure more flexible. Compared to traditional endoscopic surgery, the parameters for robotic surgery can be intelligently set to fit the sinuses and skull base environment and the operative angle of view can be adjusted easily, thus avoiding errors caused by inadequate operation by surgeons. The surgical robot is capable of intelligently assisting anatomical positioning, allowing the surgeon to clearly see each tissue structures. In addition, the surgical robot can evaluate the size, location, and adjacency of the tumors of the sinus and skull base, and recommend surgical access and operation options to the surgeons.

Robotic surgery for urethroplasty

Making visualization and accurate placement of perineal urethroplasty in the posterior and proximal anterior urethra is a challenge for urologist. Unterberg et al.²⁸ reviewed the cases of ten patients who underwent robotic-assisted urethroplasty at a single institution by a single surgeon in a period of one year. All patients underwent a standard perineal dissection with robotic-assisted placement of proximal sutures. They concluded that robotic-assisted urethroplasty provides excellent visualization and ergonomics for posterior and proximal bulbar urethral reconstruction. This is particularly helpful in patients with narrow pelvic anatomy and long distance from the perineal skin to the proximal urethral edge. Obviously, with more clearer visualization by using robotic assistance versus conventional standard approach, surgeons feel more comfortable in the control of operative procedures and the post-operative outcomes. Dinerman et al.²⁹ used surgical robots to assist with bladder urethra anastomosis. Intraperitoneal robotic-assisted mobilization of the bladder and urethra perineum mobilization allow for tension-free bladder urethral anastomosis while avoiding resection. The side docking of the da Vinci Xi robot allows for simultaneous access to the perineum during minimally invasive pelvic surgery, enabling a new approach to complex bladder neck reconstruction.

Existing problems and prospects

Problems

The surgical robot has the advantages of minimal incision and precise operation, and usually results in quick recovery after surgery. However, there are still some problems that need to be resolved. Recent studies have shown that the total postoperative survival time of surgical robotic-assisted tumor surgery is shorter than that of traditional surgery. Ramirez et al.³⁰ and Melamed et al.³¹ have performed a cohort study involving women diagnosed of early-stage cervical cancer and underwent either traditional or robotic-assisted radical hysterectomy. The results showed that minimally invasive radical hysterectomy was associated with lower rates of both disease-free survival and overall survival than that with open abdominal radical hysterectomy. The above data indicated that surgical robotic-assisted tumor surgery may have some defects possibly because the scope of tumor resection cannot be effectively expanded to avoid the negative impact on the early recovery after surgery. On the other hand, the average age of patients

who chose surgical robotic-assisted radical mastectomy was relatively high in developed countries. It is worth mentioning that He et al.³² performed the surgical robotic-assisted lymphadenectomy for 13 patients with suspected internal mammary lymph node metastasis. All patients were followed up (average, 16.5 months; range, 2–33 months) on a regular basis. However, the local recurrence, distant metastasis, or obvious discomfort was not reported. Therefore, the further improvement of the application of surgical robots in the field of tumor resection will be the focus of future research and development of surgical robots.

According to the US FDA reports, from 2000 to 2013, the number of accidental deaths caused by the use of surgical robots was 144, with 550 adverse events per 100,000 treatments. The incidence of accidents in some areas is significantly higher than that of traditional operations. For example, the surgical risk of head and neck and cardiothoracic surgery is significantly higher than that of traditional surgery. Adverse events such as machine parts failure, internal ignition of the machine, and video jam of the display were also reported during the operations. Especially during a remote surgery, a lag in image transmission would delay the real time hemostasis for a bleeding. In addition, surgical robots are extremely expensive and cannot be popularized. Alemzadeh et al.³³ counted about 10,000 reports related to surgical robot applications, of which more than 1500 cases reported negative effects on patients. Moreover, there is currently no available robot technology that can be applied to burn treatment. Nevertheless, surgeons at the University of Manchester have developed a new robot technology for skin wound remodeling. The robot firstly estimated the missing area and depth of the wound according to a 3D modeling technology, and then sprayed the human cells in the nutrient solution on the wound surface through the operating rod for repairing the burn wounds. It is highly expected that such technologies will be translated from the laboratory to bedside soon.

Prospects

Currently, 3D plastic surgery robots are in the research and development stage. The common concerns of the patients who choose plastic surgeries include whether the outcome of plastic surgery satisfactory and whether the postoperative appearances can be predicted in advance. Now, these questions can be answered by a 3D plastic surgery robot that has a three-dimensional plastic scanning design system and can perform three-dimensional scanning on human faces and other body parts, and then quickly generates accurate three-dimensional models of the human body. Under the joint communication and editing with plastic surgeons, a surgical robot can design a plastic surgery program. Patients can sneak peek the virtual images immediately and judge whether “I may become more beautiful?” Now, the device can design a rhinoplasty solution in 90 s and demonstrate the full-face plastic surgery in 10 min. Plastic surgeons can develop surgical robot-based “Design drawing”, combined with clinical experiences and surgical techniques, then, the 3D plastic surgery robot transmits the “Design drawing” to the operating system to ensure that the design can be accurately fulfilled. The future of 3D plastic surgery robots is highly expected.

At present, the treatment of complex refractory wounds and chronic sinus is still difficult, and there is no consensus protocol and standardized treatment plan, resulting in a slow treatment process. The traditional view advocates expanding the removal of the sinus. This method has a certain effect, but due to the high risk of surgery and large local wounds, the expected effect after surgery is not promising. Therefore, the application of surgical robots in the complex refractory wounds and chronic sinus surgery, so as to

optimize the scope of resection would be a new direction for future research.

Summary

How to better apply surgical robots to the field of reconstructive surgery requires further exploration and experimentation. Meanwhile, the development of intelligent, miniaturized, portable and mobile surgical robots will also be the future development trends. In addition, further improve the cost-effectiveness would also be conducive to the promotion and application of surgical robots.

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Ethical statement

The study was performed in accordance with the Declaration of Helsinki and approved by the institutional committee on research ethics.

Conflicts of interest

There are no conflicts of interest.

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