

# Current Status and Trends in Surgical Robot Development Across Different Operating Environments

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**Abstract.** The application of surgical robots has enhanced surgical precision and resolved previously challenging issues in operations, making it one of the most researched topics worldwide. This paper elucidates the significance of selecting surgical robots tailored to the characteristics of different surgical environments. This paper introduces that the application of surgical robots in the abdominal surgery environment can make up for the shortcomings of traditional surgery and perform long-distance surgery. The application of a frameless stereotactic surgery robot in neurosurgery has high precision, and the controllability of the operation process is effectively enhanced through the dynamic calibration mechanism. The surgical robot applied in the microsurgery environment can improve the operation accuracy of the surgery through the functions of motion scaling and tremor filtering. However, the current surgical robot still has the limitations of low penetration, limited tactile feedback, and a long user training cycle. In the future, the rational application of AI and the targeted development of the functions of surgical robots according to the characteristics of the corresponding surgical environment are the key to expanding the application of surgical robots.

**Keywords:** Surgical Robot; Surgical Environment; Precision.

## 1. Introduction

With the advancement of science and technology, the application of robots in surgery is becoming more and more common. This phenomenon has gradually become a social hot spot of widespread concern in recent years. The application of 5G has accelerated the speed of data transmission, and the development of AI has enabled surgical robots equipped with fully trained AI to perform some surgeries autonomously. The application of these new technologies in surgical robots is more conducive to doctors using surgical robots to perform surgical work on patients. In the field of global surgical robots, there is a trend of accelerating the iteration of technology and expanding the application scenarios of robots. In September, China's Jingfeng laparoscopic surgery robot and Jingfengyun remote surgery system successfully implemented 12035 kilometers of transcontinental and trans-oceanic ultra-remote surgery between Kuwait and Brazil, and obtained Guinness World Record certification [1]. The US SRT-H robot has a 100 % success rate in experimental surgery after being trained through an artificial intelligence framework [2].

With the development of surgical robots in recent years, surgeons can solve some problems that cannot be solved by traditional surgery, such as hand tremor and insufficient precision of human eyes. Surgical robots are gradually being integrated into surgical operations, such as the Da Vinci surgical system, which covers surgical operations in the fields of urology, gynecology, and cardiothoracic surgery. This phenomenon has led to public curiosity about surgical robots and concerns about whether their safety and functionality are sufficient for surgery.

Therefore, based on the environmental characteristics of some surgeries, this paper introduces the characteristics of some existing surgical robots, and puts forward suggestions based on the development trend of surgical robots, aiming to provide some reference materials for relevant surgical staff.

## 2. Characteristics of the Surgical Robot

As a new tool in surgery, the surgical robot not only acts as a suture tool to simply suture the wound during the operation. Its characteristics revolve around the four core areas of precision improvement, trauma reduction, operation optimization, and process control. In terms of accuracy improvement, surgical robots can solve the shortcomings of traditional surgery, such as slight hand tremor and a limited range of motion. In terms of trauma reduction, the small holes required for minimally invasive surgery by surgical robots are much smaller than those of traditional surgery. In the process of suture, the traction and extrusion of surrounding tissues are less, which can significantly reduce the amount of intraoperative blood loss. In terms of operation optimization and process controllability, the surgical lens, robotic arm, ergonomic chair, and other tools equipped with the robot can greatly reduce the doctor's operating load, save the doctor's physical strength, and improve the controllability of the surgical process. Surgery is often used in acute trauma repair, tissue reconstruction, and other scenarios. A successful surgery requires efficient and accurate tools, and surgical robots meet this requirement.

## 3. The Development Status of Surgical Robots in Different Surgical Environments

In abdominal surgery, the technical requirements for the robot are to be able to adapt to the CO<sub>2</sub> pneumoperitoneum environment in the abdominal cavity and have a mechanical arm anti-collision design. In neurosurgery, the technical requirements for the robot are sub-millimeter-level accuracy and can support image fusion (CT/MRI+ultrasound) during surgery. In microsurgery, the technical requirement of the robot is micron precision. The environment for surgical operations is diverse, and the robots that need to be applied are also different. Therefore, in the surgery that requires the application of surgical robots, it is particularly critical to select the appropriate surgical robot to cooperate with the doctor for surgical operations according to the actual situation.

### 3.1. Surgical Robot for Abdominal Surgery

Abdominal surgery is a routine surgical procedure, ranging from appendectomy to complex visceral transplantation. With the assistance of robots, the problem of physiological tremor of human hands and insufficient accuracy of human eyes can be effectively solved, and even remote surgery can be performed through robots to break the limitations of space. Each manipulator of the Da Vinci surgical robot is equipped with a total of 7 degrees of freedom, which can make precise operations that human hands cannot make [3]. And the mechanical arm system equipped with vibration elimination and action positioning system can filter out the jitter of the hand and reduce the action range according to a certain proportion [3]. The workflow of the Da Vinci surgical robot is shown in Fig. 1.

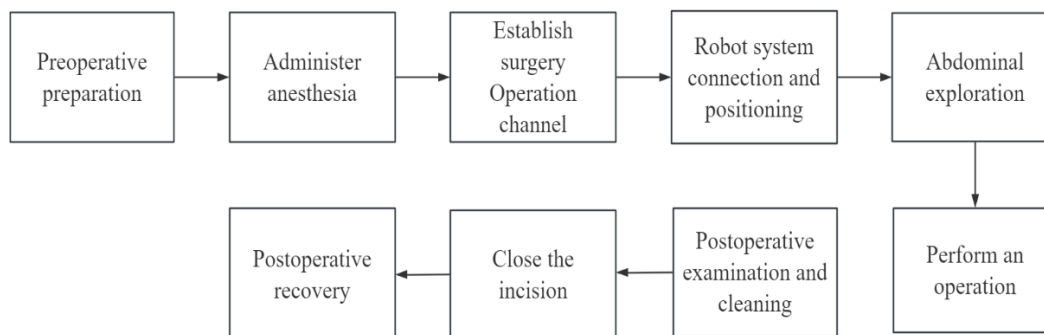
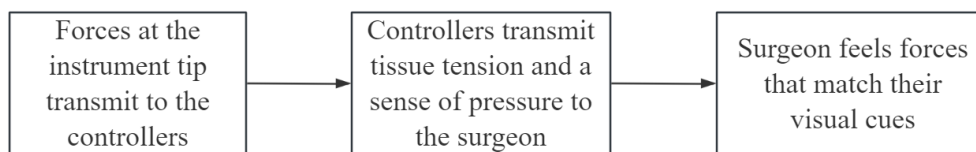


Fig. 1 Da Vinci robot surgery process (Original)

The fifth-generation Da Vinci robot, equipped with force feedback technology, allows doctors to complete the suture task with less force on the tissue to avoid intraoperative organ damage that may

be caused by excessive force, and helps novice robot-assisted surgeons adapt to robotic surgery [4]. Its force feedback-related process is shown in Fig. 2.

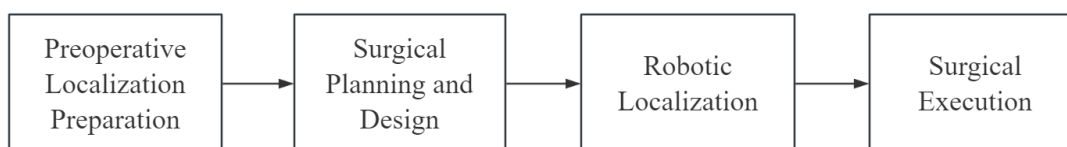


**Fig. 2** Force feedback related process of Da Vinci Robot [5]

Compared with the traditional laparoscopic technique, the operation time can be saved by about 20 minutes when the robot system is used to cure the choledochal cyst [6]. The detection rate is about 50 % higher, the secondary injury of biliary anatomy is less, the distal opening of the cyst is more reliable, and the postoperative recovery is faster [6]. The Toumai Robot adopts 5G technology, which has the advantages of real vision, low maintenance, and low use cost, and the farthest surgical distance can reach about 780 km [7]. In the clinical experiment, the cholecystectomy of 6 animal subjects was successful [7]. In 20 cases of urological surgery, all operations were successfully completed [8]. The success rate of upper urinary tract reconstruction was 100 % at 3 months, and the positive surgical margin rate of radical prostatectomy was 25 % [8]. No biochemical recurrence was observed during the 3-month follow-up period [8]. The application of surgical robots in abdominal surgery has significant advantages. The Da Vinci surgical robot manipulator is precise, and the fifth generation is equipped with force feedback technology. Compared with traditional laparoscopic surgery, it is more efficient in choledochal cyst surgery. The Toumai robot adopts 5G, with real vision, low cost, long operation distance, and good clinical performance.

### 3.2. Surgical Robot for Neurosurgery Application

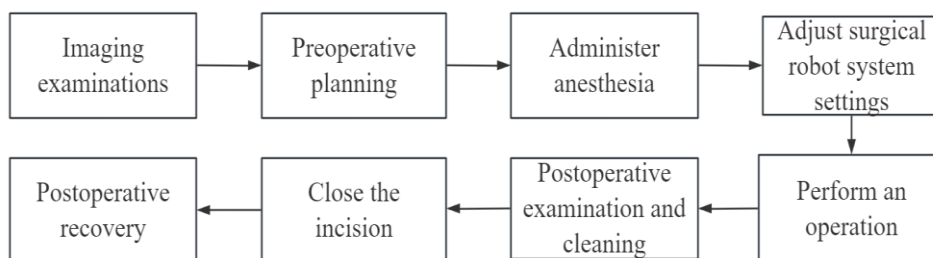
Neurosurgery is a surgical intervention for the treatment of the central nervous system, the peripheral nervous system, and related accessory structures. Its technical requirements are high, the risk of surgery is high, and the operation should be carried out on the premise of not destroying the nerve function to the greatest extent. Traditional stereotactic surgery relies on a frame system, and it is easy to affect the operation due to small displacements caused by respiratory / anesthesia fluctuations. Nowadays, the frameless stereotactic surgical robot used in neurosurgery has higher accuracy and dynamic calibration, which can effectively improve the controllability of the surgical process. Using the Remebot surgical robot, doctors can use CT or MRI images to reconstruct three-dimensional images of intracranial tissues and lesions through the computer surgical planning platform, which is conducive to doctors' preoperative planning and surgical simulation [9]. The coordinate relationship between the unified medical image and the robot surgery space can be completed through its visual surgery navigation platform [9]. Finally, the surgical operation platform is used to control the only mechanical arm to complete the surgical positioning and operation [9]. Remebot frameless brain stereotactic surgery steps as shown in Fig. 3.



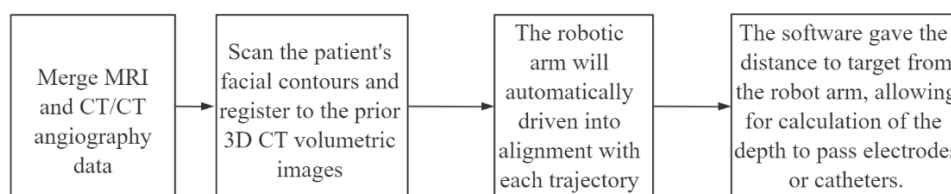
**Fig. 3** Related steps of Remebot frameless brain stereotactic surgery [9]

The Remebot surgical robot had accurate positioning, and the overall target accuracy error of the biopsy was  $(1.510 \pm 0.636)$  mm [10]. The target accuracy error of the experimental group was  $(1.207 \pm 0.470)$  mm, and the target accuracy error of the control group was  $(1.899 \pm 0.614)$  mm [10]. The ROSA surgical robot is mainly composed of a robotic arm, a touch screen, a special instrument, etc [11]. It is equipped with a six-degree-of-freedom robotic arm sensing technology, a marker-free automatic registration technology, and a patient position dynamic tracking technology [11]. The

target position can be accurately positioned, and the error does not exceed 1mm [11]. The operation process is shown in Fig. 4. In the operation, the laser scanning technology of the ROSA surgical robot is helpful to the precise operation of the manipulator. The related process is shown in Fig. 5.



**Fig. 4** Surgical procedure of ROSA surgical robot (Original)

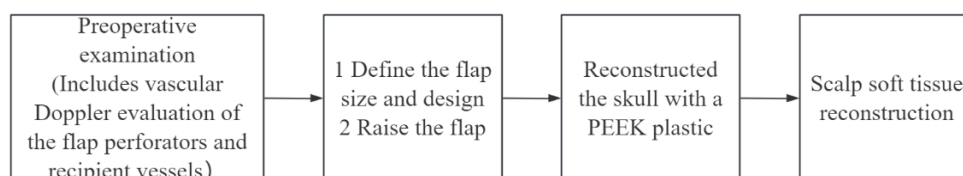


**Fig. 5** The related process of laser scanning technology and mechanical arm in the operation of the ROSA surgical robot [12]

Stereotactic biopsy was performed in 76 patients with intracranial lesions with the assistance of the ROSA robot [13]. The positive rate of biopsy was 98.7%, and only 1 case was not diagnosed [13]. The application of a frameless stereotactic surgical robot in neurosurgery has higher accuracy and dynamic calibration, which improves the controllability of surgery. The doctor can use the CT / MRI of the Remebot surgical robot to reconstruct the intracranial three-dimensional image for preoperative planning simulation, and match the coordinates through visual navigation to make the positioning more accurate. The target positioning error of the ROSA surgical robot is less than 1mm, and the positive rate of lesion biopsy is high.

### 3.3. Surgical Robots for Microsurgical Surgery Applications

Microsurgery is inseparable from optical amplification equipment and special precision instruments. Its operation accuracy needs to reach the millimeter or even micron level to achieve accurate repair and reconstruction of small blood vessels, lymphatic vessels, and other structures. The application of the robot can help the surgeon to save physical strength, and its equipped instruments can also improve the operation accuracy during the operation, thereby improving the success rate of the operation. The Symani surgical system has a high degree of availability and accuracy in the application of microsurgery technology [14]. It consists of two robotic arms equipped with expanders and needle holders with cutting functions, respectively, and a console connected to an ergonomic conditional chair equipped with a pedal controller and two joysticks [14]. The motion scaling ratio can be up to 7 to 10 times [14]. The working process of it in assisting scalp free flap reconstruction surgery is shown in Fig. 6.



**Fig. 6** Symani surgical system used in the free flap reconstruction of the scalp [14]

Even if there is a lack of tactile feedback, the patency rate of robot-assisted anastomosis is 100 % in 6 suture operations [14]. MUSA is composed of a main manipulator, a suspension ring, a slave manipulator, and a pedal [15]. Thanks to its light and small size, it can be installed on the operating

table and microscope without too much adjustment to the layout and organization planning of the operating room [15]. MUSA applied motion scaling and tremor filtering technology to improve the operation effect of microsurgery [15]. The anastomosis time of the robot-assisted group was 16-33 minutes, but compared with the manual group, the time required for the robot-assisted group to complete the anastomosis was significantly shortened [15]. The Symani surgical system has high availability and accuracy, and a high proportion of motion scaling. MUSA is light and small, and motion scaling and tremor filtering techniques are used to improve the effect of microsurgery. The application of surgical robots in microsurgery can help doctors save physical strength, improve operation accuracy, and thus improve the success rate of surgery.

#### 4. Conclusion

The use of surgical robot-assisted surgery can make up for the shortcomings of traditional surgery. For example, in abdominal surgery, the robot can provide the function of filtering out the jitter of the hand and reducing the amplitude of the action in a certain proportion. In neurosurgery, the robot can provide frameless stereotactic surgery with higher accuracy and dynamic calibration. In microsurgery, the robot can provide functions such as motion scaling.

At present, surgical robots still have problems such as low penetration, limited tactile feedback, and long user training cycles. In response to the above problems, the tactile feedback of surgical robots can be improved in the future, such as lower-latency real-time feedback on the original basis. Special training and simulation experiments can be carried out for relevant personnel. Applying AI to surgical robots enables them to learn from past surgical cases, allowing them to make automated judgments in routine situations during operations and thereby reduce the cost of human training to a certain extent.

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This paper provides a clear and comprehensive overview of the application of surgical robots in various surgical environments. It elucidates the advantages of abdominal surgical robots in compensating for the shortcomings of traditional surgery and supporting remote operation; the value of frameless stereotactic neurosurgery robots in high precision and dynamic calibration mechanisms; and the role of microsurgical robots in improving operational accuracy through motion scaling and tremor filtering. Simultaneously, the authors objectively point out the current system's shortcomings in terms of adoption rate, tactile feedback, and training cycle, and propose a reasonable development direction for the future: combining AI with functional customization for specific surgical scenarios. The paper is well-structured, features typical cases, and provides insightful evaluations, making it a valuable reference and recommended for direct acceptance.						