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Remote Vascular Interventional Surgery Robotics: A Review

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Abstract—Interventional doctors are exposed to radiation hazards during the operation and endure high work intensity. Remote vascular interventional surgery robotics is a hot research field that can not only protect the health of interventional doctors, but also improve accuracy and efficiency of surgeries. However, the current vascular interventional robots still have many shortcomings to be improved. This article introduces the mechanical structure characteristics of various fields of vascular interventional therapy surgical robots, discusses the current key features of vascular interventional surgical robotics in force sensing, haptic feedback, and control methods, summarizes current frontiers about autonomous surgery, long geographic distances remote surgery and MRI-compatible structures. Finally, combined with the current research status of vascular interventional surgery robots, this article analyzes the development directions and puts forward a vision for the future vascular interventional surgery robots.

Index Terms—Haptic feedback, Medical robotics, Vascular Interventional.

I. INTRODUCTION

INTERVENTIONAL radiology has developed over the last several decades, becoming one of the three main effective therapies besides Internal Medicine and Surgery [1]. The benefits of interventional radiology to patients are both extensive and beyond dispute, but many of these procedures also can produce patient radiation doses high enough to cause radiation effects and occupational doses to interventional radiologists high enough to cause concern. To limit occupational radiation dose to an acceptable level, radiologists usually use personal protective devices, such as aprons, thyroid shields, eyewear, and gloves [2]. Those devices are heavy and are a burden to radiologists when performing interventional surgery. This situation makes interventional surgeons face two major health risks: fluorescent radiation and musculoskeletal strain [3].

To protect radiologists from potential health problems caused by fluoroscopy radiation and to minimize the patient radiation doses, in recent decades, many institutes have been working to develop robotic systems aimed to precisely steer and

position interventional tools for catheter-based interventional surgeries, such as guidewires, microcatheters, balloons, and stents. Those robotic systems are supposed to shorten procedure time and reduce patient exposure to contrast agents and radiation, allowing operators to perform surgery by a remote console behind a radiation shield. The main advantages of using robotic technology are the increased levels of speed, precision, reproducibility, and endurance of these machines compared with human performance. In medicine, robotic technology has been used since the mid-1990s, primarily in surgery and radiation therapy [4].

Vascular interventional surgical robotics has been developing for many years, but this has been complicated by the challenging therapy methods and surgical procedures and various surgical equipment involved. Common vascular interventional surgical robots are designed for angioplasty, vascular embolization, or radiofrequency ablation. The interventional instruments operated by surgical robots are also different in different surgical scenarios [5-8]. Related commercial products in various fields have been certified and put into clinical use. According to clinical reports, the application of vascular interventional robots has significantly reduced the amount of radiation received by interventional doctors and reduces the work intensity of interventional doctors [9]. The high-precision manipulation characteristics of the robot system shorten the operation time and greatly increase the success rate of the operation.

This review will briefly start from vascular interventional surgery, discuss the structural design of interventional surgery robots in combination with existing research institutions and commercial systems. We discuss the key features of vascular interventional surgery robot technology and the frontiers that are currently being developed and combined.

II. STRUCTURES OF VASCULAR INTERVENTIONAL ROBOTS

Interventional surgery robot systems can be roughly divided into general vascular interventional robots and electrophysiological interventional therapy robots from the application field. General vascular interventional includes angioplasty and intravascular infusion. Electrophysiological

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interventional therapy includes interventional radiofrequency ablation. The two types of interventional surgery are very different in terms of treatment methods, treatment purposes, interventional instruments, etc. Therefore, the structures of the two types of surgical robots are very different.

A. General Vasculature Interventional Surgeries

General vasculature interventional surgeries in interventional robotics can be roughly divided into angioplasty and intravascular infusion.

Fig. 1. The main difference between surgical robots designed for angioplasty and intravascular infusion is the interventional instrument being operated. But what they have in common is both of them using a guidewire to guide the catheter to the desired location.

Angioplasty aims to inflate and deploy the balloon after the balloon catheter is sent to the designated location. PCI is a typical application of angioplasty. The goal of intravascular infusion is to deliver the microcatheter to the designated location and then place the drug to the designated location through the microcatheter. TACE is a typical application of intravascular infusion. The main difference between surgical robots designed for angioplasty and intravascular infusion is the manipulation of interventional instruments. Surgical robots designed for angioplasty need to manipulate the balloon catheter and guidewire; surgical robots designed for intravascular infusion need to manipulate the microcatheter and guidewire.

Guo Shuxiang, with his groups at Beijing Institute of Technology and Kagawa University, has designed multiple interventional surgery robot systems. His first-generation system uses a friction wheel mechanism to deliver the interventional device. This generation of robots can only support the two-degree-of-freedom motion of single device [10]. The second-generation system uses a linear slide to deliver the device. It has a wealth of force sensing functions while improving accuracy [11]. The third-generation system uses two sets of linear slides at the same time. While having abundant force-sensing functions, it can also achieve the codelivery of the interventional guidewire and catheter. This generation of the system outperforms human surgeons [12, 13]. Xiao Nan et al. of Beijing Institute of Technology developed the LUBAN interventional surgery robot system based on Guo's third-generation system and completed China's first robot-assisted whole-brain angiography in 2020 [14].

Fig. 2. Three generations designed by Guo et al. With their surgical robot design iterations from generation to generation, the robots integrate richer sensing functions, can control more surgical devices at the same time, and the mechanical design becomes more compact and reliable.

The models and specifications of guidewires and catheters for interventional surgery are very diverse. It is important to be compatible with as many types of interventional devices as possible. Kundong Wang et al. of Shanghai Jiaotong University designed a novel universal endovascular surgical robot. This robotic system was composed of four manipulators with 12 degrees of freedom, which can be compatible with various interventional instruments on the market to complete a variety of different surgical procedures. However, such a mechanism design imposes a stroke limit on the delivery of the catheter or the guidewire. Moreover, the rotation angle of the catheter guidewire is limited, and it is impossible to achieve a full 360° rotation.

Fig. 2. A universal endovascular robot designed by Kundong Wang et al. Four independent grippers can achieve various action combinations, and the soft clamp can hold interventional instruments of any shape.

Doctors often manipulate the delivery and rotation of the interventional guidewire with one pair of fingers. However, interventional surgical robots often divide delivery and rotation into different modules to complete. Through the design of the friction wheel arrangement, only one pair of friction wheels can simultaneously achieve the rotation and delivery of the guidewire, shown as Fig. 4. This design is very close to the actual doctor's manual operating technique and greatly reduces the volume of the surgical robot. Such a design appeared in a bionic interventional surgery robot designed by Zhenqiu Feng et al. (the Institute of Automation of the Chinese Academy of Sciences) and Hansen's Magellan system.

Fig. 4. Guidewire manipulator designed by Zhenqiu Feng et al. (a) and Hansen Medical (b). This design only uses a pair of friction wheels to achieve two kinds of movement of the guidewire, not only there is no stroke restriction on delivery, but the volume is also very small.

Rafael Beyar et al. of Israel's Haifa Center have developed a surgical robot system for PCI based on friction wheel mechanism. This system can operate both the interventional guidewire and the balloon catheter at the same time. The system is very versatile, which has successfully deployed heart stents

in 18 patients. This surgical robot system is also the predecessor of Corindus' Corpath series surgical robot system [15]. The principle of the current Corpath GRX to drive interventional instruments is still the same as the original. But one very important change is that for hygienic considerations, a large part of the structure is disposable and replaceable. The same goes for Robocath R-One, another commercial interventional surgical robot product [16].

Fig. 5. Commercial robot systems Corpath GRX. It can deliver and rotate the guidewire, deliver the balloon catheter, control the switch of the Y-Connector, and is compatible with PCI and PVI surgery. For hygienic considerations, a large part of the structure is disposable and replaceable.

B. Electrophysiology Therapies

Interventional electrophysiological therapy has a wide range of applications, and can be used to treat atrial fibrillation, lung tumors, liver tumors and other diseases. Electrophysiological (EP) catheter is the main instrument for electrophysiological surgery. The head tip of the electrophysiological catheter can be flexibly bent. The operation process does not require a guidewire, but under the guidance of steerable electrophysiological catheter itself. The ablation instrument installed on the catheter head tip releases radio frequency current to treat the target tissue [6, 7].

Fig. 6. Electrophysiological (EP) catheters. The handle of the EP catheter has a function that can manipulate its tip to bend.

Interventional surgery robots designed for electrophysiological therapy are mainly to manipulate EP catheters. To be compatible with general electrophysiological catheters, the interventional electrophysiological treatment surgical robot system under development generally adopts a three-degree-of-freedom control design, and the structural design is similar. A common structure provides delivery freedom using a linear moving platform, clamps and rotates the electrophysiological catheter to achieve rotational freedom and designs a special operating mechanism to control the bending freedom of the electrophysiological catheter.

Cercenelli et al. of the University of Bologna designed a highly compact and versatile remote catheter navigation system

named CathROB [17-19], which uses two sets of liner slider structures to achieve full control of general electrophysiological catheter. Jun Woo Park et al. of Korea University [20] and Ganji et al. of the University of Waterloo [21] used similar structures to manipulate EP catheters. Their structures include liner slider platform, rotation driver, and steering driver to achieve the translation, rotation, and tip bending motions of EP catheters.

Fig. 7. The mechanical structure of CathROB from Cercenelli et al. The operating handle of an ordinary EP catheter is installed on the robot. Different actuators operate the delivery, rotation, and tip steering of the EP catheter. Many robotic systems have adopted similar schemes to manipulate EP catheters.

In radiofrequency ablation, it is very important for the EP catheter to point to the target tissue accurately and stably. Conventional EP catheter distal bend is driven by ropes. EP catheters driven by magnetic fields can achieve higher flexibility and stability [22]. The Genesis RMN from Stereotaxis uses a specially designed magnetic drive catheter to control the movement of the catheter's front end by changing the external magnetic field [23]. Magnetic navigation has the advantages of high flexibility and strong maneuverability.

Fig. 8. Stereotaxis' Genesis RMN. Its catheter navigation system named VDrive coordinating with Its Magnetic navigation system named Niobe to complete the operations. By changing the external magnetic field by the magnetic field generator, the catheter tip can be accurately and stably pointed to the target location.

III. KEY FEATURES OF VASCULAR INTERVENTIONAL ROBOTS

A. Force Sensing

The forces that can be collected by interventional surgical instruments are generally divided into two types: the force collected by the tip of the surgical tool, which is in the human body, is called the "distal force", and the force collected by the operating end of the surgical tool outside the human body is called "Proximal force". The distal force is generally composed of the contact force between the surgical tool and the vessel wall, while the proximal force is a complex composite force, including contact force, friction force, and viscous resistance of

blood.

The measurement of distal force often requires sensors to be placed at the tip of the interventional instrument. This arrangement can directly measure the force between the interventional device and the blood vessel. Sensitive rubbers, strain gauges, and fiber optic pressure sensors are often used to measure distal force. Guo Shuxiang et al. of Kagawa University have proposed various remote sensor arrangement forms in different papers [24-27]. They arrayed pressure-sensitive rubbers into tactile sensors and set them at the distal end of the catheter. Similar schemes are also very common in other research groups, such as Omisore et al. (Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences) [28], Payne et al. (Imperial College of the United Kingdom) [29], and Liu Da et al. (Beijing University of Aeronautics and Astronautics) [30].

Fig. 9. Distal sensors Sensor arrangement from Guo et al. Array pressure-sensitive rubbers into sensing units, arrange them at the distal end of the catheter and encapsulate the lead. Generally, force sensing units are installed at multiple locations on the catheter to monitor the force conditions at different nodes.

In clinical applications, the current distal sensors of interventional instruments are relatively common in electrophysiological (EP) treatments. They are mostly arranged in electrophysiological catheters. Due to the size of the sensor and its lead packaging volume, it is difficult to apply in general vascular interventional operations, especially interventional surgery in small blood vessels. In the field of commercial surgical robots, Hansen Medical's Sensei surgical robot integrates a force sensor on the head of its Artisan active catheter [31].

The force that doctors feel during the operation is mostly the proximal force, and the collection of the proximal force is relatively easy. In the interventional surgical robot, the collection of the proximal force is easier than the distal force. Therefore, the measurement of proximal force appears most frequently in interventional surgery systems. Setting force sensors between the transmission components of the robot is the most widely used approach.

Besides arranging force sensors between the transmission components, Zhou et al. of Xiamen University also tried to arrange a sensing pipe at the front of the robot and indirectly judged the magnitude of the resistance through the squeezing between the interventional device and the sensing pipe [32]. Hyo-Jeong et al. of Hanyang University in South Korea [33] and Sankaran et al. of the University of Illinois [34, 35] measured the resistance forces by the input current of the motors. These methods arrange sensors on the outside of the robot, or even no sensors, and achieve the measurement of resistance force.

Fig. 10. Proximal sensors arrangement by Arai et al. of Nagoya University [45]. Force sensors are set between the transmission components of the robot. When the guidewire moves, the resistance will be transmitted to the force sensors.

Since the proximal force is a relatively complex resultant force, the robot's structure of the robot, the shape of the interventional device, and the different arrangement angles of the robot will all affect the resultant force. The reliability of the proximal force is poor, and it needs to be further processed by the algorithm to achieve the related function of force feedback.

B. Master Controllers and Haptic Feedback

The master controller is the most important part of the human-computer interaction. From the design perspective, it can be divided into master-slave isomorphic and master-slave heterogeneous. The former refers to the use of a completely different operation method from the interventional technique. Interventional doctors need more study and experimentation to adapt to its operation method, while the latter refers to using roughly the same operation method as the interventional technique. The interventional doctor can quickly become familiar with the operation of the robot and even reproduce the surgical habits or experience acquired in the manual interventional operation into the operation of the robot.

Many research groups have adopted commercial force feedback manipulators, such as Novint Falcon [36, 37], Phantom Omni [10, 27] and Geomagic Touch X [12, 13]. Commercial force feedback controllers have rich and stable force feedback functions, and it is simple and efficient to develop a haptic feedback system based on these controllers. But the disadvantage of using them for master controllers is also obvious; that is, they are general-purpose controllers, not specifically designed for interventional surgery. The experience accumulated by doctors in manual interventional surgery is difficult to apply to such controllers.

To get haptic feedback master controllers of the master-slave isomorphism, many research groups have developed their own master controllers. Tanimoto et al. of Nagoya University designed a rod-shaped controller in 2000, generating resistance to the doctor's hand through the connected motor [38, 39]. Since then, similar structures have been adopted by many research groups, such as Feng Zhenqiu et al. [40, 41] (Institute of Automation of the Chinese Academy of Sciences), Kundong Wang et al. [42, 43] (Shanghai Jiao Tong University), and Guo et al. [11, 24, 44] (Kagawa University).

Fig. 11. Rod-shaped master controller designed by Tanimoto et al. The operator controls the rotation or delivery of the interventional instrument by rotating or pushing the handle. Both the rotation and linear movements of the handle will be recorded by encoders. At the same time, the internal motor can generate resistance to its handle.

Master-slave catheter controllers are another form of master controller design that puts a catheter in its master controller. The robot system will copy the actions from the master catheter to the slave catheter. This form of design makes the operation method of the robot completely consistent with the actual interventional surgery, which can greatly reduce the doctor's learning threshold and reproduce the interventional doctor's operation techniques and skills. Early master-slave catheter controllers only achieved master-catheter's motion detection, such as Tavallaei et al. [45] (The University of Western Ontario, London). Later, some groups have found ways to put resistance on the master-catheter. Guo et al. (Kagawa University) developed a haptic feedback system based on magnetorheological fluid [25, 46-48]. Payne et al. (Imperial College) added resistance to a master-catheter using a voice coil motor [29].

Fig. 12. This master-slave catheter controller with haptic feedback was designed by Payne et al. Its built-in sensors and encoders can detect the movement of master-catheter and output resistance to the operator through voice coil actuator and linear motor.

C. Safety Strategies

In the interventional surgery robot system, the safest strategy is very important. During surgery, common dangerous situations include excessive contact force on the blood vessel wall, excessive deformation of surgical instruments, and doctor's incorrect operation. These dangerous situations will cause the patient to be injured, and the interventional surgical robot systems need to avoid such situations as much as possible.

Monitoring and controlling the force of interventional devices is a common force safety strategy. The simplest and most direct method is to measure the force through a force sensor and set a threshold for the feedback signal. Many research groups have adopted this approach, such as Guo Shuxiang et al. of Kagawa University [27], Cercenelli et al. of

the University of Bologna [17] and Zhou et al. of Xiamen University [32]. The Corpath GRX system also has such a warning function. When excessive force is detected on the interventional device, a warning message will output on the user interface. At the same time, the system will prohibit the advancement of the device.

However, setting a threshold for the detected force is a crude approach. The force state of the interventional device is the result of a combination of multiple conditions. It is necessary to distinguish dangerous situations more accurately. Guo Shuxiang et al. of Beijing Institute of Technology proposed a neural network-based force safety method. The neural network will intelligently warn and take measures based on the resistance force and torque detected by the sensor to ensure the safety of surgery [49].

The abnormal deformation of surgical instruments is also very dangerous. Dagnino et al. of Imperial College London have introduced image recognition in their surgical robot system by identifying interventional images to track the position information of the guidewire and the blood vessel wall and make safety judgments, applying dynamic constraints [50].

Fig. 13. In addition to the magnitude of the force, the current security situation is also related to the deep fuzzy information in the force signal. Using neural networks to learn these fuzzy information helps to judge the current security situation more accurately. By observing the position and posture of the guidewire and the state of the vascular environment through the image, the safety state can also be judged.

The doctor's incorrect operation can have a fatal impact on the patient. Hao Shen et al. of Shanghai Jiaotong University designed an "eccentric spring" algorithm to reduce the error signal input to the controller caused by trembling hands [51]. Yujia Xiang et al. used a Kalman filter in their algorithm to eliminate the tremor signal of the doctor's hand [52]. Guo Shuxiang et al. of Beijing Institute of Technology used a support vector machine (SVM) to identify the input operation signal to detect signals caused by trembling hands [53]. At the same time, they designed an algorithm applied to the master controller by magnetorheological fluid to resist hand tremors [47]. To prevent the misoperation from causing serious injury to the patient, they designed a braking device that can stop the movement of the surgical instrument in time when the safety system detects a misoperation [54].

D. Control Methods

To separate the operator from the radiation environment, the hardware structure of the interventional surgery robot system is often composed of an upper computer and a lower computer. The upper computer is placed in No radiation area and connected to the master controllers while the lower computer is placed in the radiation area and connected to the robot. In such an upper and lower system, the robot system adopts a master-slave method for control.

Open-loop speed control is a common control method. In this method, the input signal of the master controller is mapped to the speed space of the surgical robot and converted into the corresponding motor control signal. The mapping space is often divided into multiple sections to reduce excessive speed changes and jitter caused by trembling hands or misoperations. Fig. 14 shows the control mapping curve of Hao Shen et al. (Shanghai Jiaotong University) and Zhou et al. (Xiamen University). Such open-loop speed control is relatively simple.

Fig. 14. (a) Control mapping curve of Hao Shen et al. They mapped the input position of an Omega 3 controller handle to the speed of surgery robot [51, 55]. (b) The mapping curve of Zhou et al. They mapped the input voltage from a commercial joystick to the speed of catheter and guidewire [32].

If the surgical robot system is equipped with position or angle sensors, more precise and stable closed-loop control can be achieved. Closed-loop control is more used in position or angle control; that is, the input signal of the master controller is mapped to the position space of the surgical robot and converted into the corresponding motor control signal. At the same time, the control system compares the feedback position of the sensor to achieve accuracy. Commonly used position sensors include angle encoders, position sensors of linear platforms, and electromagnetic tracking sensors, such as NDI Aurora.

Suppose the motion of the control object of the surgical robot is complicated, such as an electrophysiological catheter that can be bent at the front end. In that case, the relationship between the input of the robot system actuator and the output position of the interventional instrument can be solved by building a kinematic model [21, 55, 56]. In addition to control methods based on classical control theory, the use of control methods in modern control theory can sometimes improve the control system's performance. For example, Xiaomei Wang et al. of the University of Hong Kong have used a control method based on optimal control in their interventional surgery robot system. Their experiments show that the method's performance based on the optimal control theory is better than the control method based on the kinematic model [57].

PID control is the most used feedback control method. It performs proportional, integral, and derivative of the difference

between the target value and the measured actual position value and combines these control variables to achieve stable tracking of the controlled object. Many research groups use PID controllers for surgical robot control [29, 45]. Based on PID control, setting fuzzy rules to dynamically adjust the PID controller parameters can realize more sensitive and stable fuzzy adaptive PID control. Wang et al. of Yanshan University applied a fuzzy PID controller in their surgical robot system and the fuzzy PID controller of them shown better performance than the traditional PID controller [58, 59].

IV. FRONTIERS OF VASCULAR INTERVENTIONAL ROBOTS

A. Automation surgeries

Traditional master-slave interventional surgery robots perform actions that generally depend on the operator input actions, so surgery result depends on the operator's performance. There are often mistakes in manual operation. The mistakes potentially reduce the efficiency. Human reaction abilities, accuracy, and flexibility are far weaker than those of robot systems. In the future, autonomous surgery might even replace doctors to save the hospital's human resources. The goal of autonomous control technology is to enable robot systems to complete part of the surgery operation process or even completely take over the operation.

To achieve autonomous delivery, a common method is to specify a delivery rule to deliver based on the state of the interventional device. Jayender et al. (Weston University) proposed an autonomous method by machine vision [56, 60]. Through image recognition of the path of the in vitro model, the robot can autonomously deliver the catheter to the target location. Corindus has introduced an FDA-approved guidewire autonomous feature known as "Rotate-on-Retract". This function is to rotate the guidewire whenever it is retracted by the operator, changing the guidewire tip's orientation in preparation for the next advancement [61].

Fig. 15. The environment of intravascular surgery is quite complex, and model-based methods may be difficult to make complex and ambiguous decisions. AI-based methods can learn fuzzy environmental regulations through supervised learning or reinforcement learning and make more complex decisions.

However, the environment of interventional surgery is very complicated, rules set by people can handle very limited situations. Moreover, many operate experience of interventional surgery is very vague and difficult to describe with specific rules. Using artificial intelligence to learn how to

operate interventional devices from the experience of experts or self-exploration is an emerging method. Guo et al. (Beijing Institute of Technology) proposed an intelligent autonomous interventional surgery agent by using neural networks to learn from the operate records of multiple human experts.

In addition to learning from human demonstrations, agent can also learn from self-exploration, which called reinforcement learning. Through reinforcement learning, it is even possible to obtain an agent whose ability far exceeds that of human beings. Chi, Wenqiang et al. (Imperial College) applied reinforcement learning methods to their artificial intelligence agent. They used the most advanced algorithm in the field of reinforcement learning named proximal policy optimization, and their agent performs better than human expert in vitro models [62]. The application of reinforcement learning in various fields has shown outstanding performance, autonomous interventional surgery agents based on reinforcement learning are very promising.

B. Long Geographic Distances Robotic Telestenting

The Long Geographic Distances Robotic Telestenting of interventional surgical robots has received more and more attention in recent years. Using remote communication to allow doctors to perform long geographic distances remote operations on patients in another place can alleviate the uneven geographical distribution of interventional doctors, optimize human resources, and popularize interventional operations in various regions. Today's Internet technology is very mature, especially the emerging 5G network technology, which can fully meet the needs of low latency and large data throughput required by Internet surgery.

Guo Shuxiang et al. built a cloud server platform for their surgical robot platform, verifying that the cloud server can fully meet the needs of remote surgery [63]. Based on the Corpath GRX surgical robot system, Madder et al. performed the first remote model intervention experiment and animal in vivo intervention experiment in 2018, which confirmed the safety and feasibility of remote intervention surgery [64]. In 2020, they used wired networks and 5G wireless networks to perform remote transcontinental intervention experiments and succeeded [65].

Fig. 16. Madder et al.'s experiments in 2018. By trying wired connection and 5G connection, they successfully completed the remote surgery experiment in two places separated by more than 3000 miles.

C. MRI Compatible

The fusion of interventional surgical robots and magnetic resonance imaging (MRI) navigation is also a research direction of several institutions. Since MRI does not have fluorescent

radiation on the human body, children, pregnant women, and other people who are sensitive to radiation are more suitable for interventional surgery under MRI. Although the MRI environment will not pose any threat to the health of interventional surgeons, the application of surgical robots can still reduce the labor burden of doctors and improve the performance of surgery.

However, ferromagnetic and conductive materials cannot be compatible with the MRI environment, so designing such robot is challenging. A feasible solution is to place the power source outside the MRI operating room and transmitting the power to the operating room through MRI-compatible mediums. For example, Ka-Wai Kwok et al. (University of Hong Kong) designed a hydraulic Interventional electrophysiological robot [57, 66, 67], and Abdelaziz et al. (Imperial College, London) designed a pneumatic interventional robot [68]. The bodies and internal transmission parts of these robots are made of plastic or other materials compatible with the MRI environment.

Fig. 17. MRI-compatible interventional robot by Kwok et al. used for electrophysiological treatment (a) and Abdelaziz et al. used for general vasculature interventional treatment (b). This type of design is quite challenging in separating the actuator (with ferromagnetic and conductive materials) from the surgical robot and transferring the power through MRI-compatible mediums.

V. PROSPECTS AND CONCLUSIONS

At present, the vascular interventional surgical robot system has mostly fulfilled the demand for remote manipulation of surgical instruments and is moving in the direction of stronger compatibility with interventional instruments and with more surgical functions. In scientific research, the research on the mechanical structure and control methods of robots has gradually matured. Still, more in-depth development is needed in terms of haptic feedback, safety strategies, and autonomous delivery strategies. With the continuous research and development of the vascular interventional surgical robot system, the future surgical robot system is expected to be more perfect in the following aspects:

1. A more compatible robot system for vascular interventional surgery. There are many surgical options for vascular intervention, and the surgical instruments used are also different. The future vascular interventional surgical robot system will be compatible with more surgical instruments, with richer functions and corresponding modules, enabling more surgical procedures, and further reducing the manual operations required by doctors.

2. Richer sensor information. It is very important to add more relevant sensors through the design to monitor the surgical

status in greater detail. The contact force between the surgical instrument and the blood vessel wall, the specific position and shape of the catheter and the guidewire, the shape and pressure of the blood vessel lumen, and other complex information have important guiding significance for the surgical robot system.

3. More powerful master controllers. The hand perception of interventional doctors plays an important role in guiding their operations, and the rich surgical experience of interventional doctors is also extremely important. Therefore, the more precise and reliable haptic feedback and the design of the master manipulator that is more in line with the operating habits of interventional doctors can make it easier for interventional doctors to use the robot system and improve operating efficiency.

4. Long geographic distances robotic telesteering. With the development of communication technology and the popularization of 5G Internet technology, remote surgery technology may be an important feature of surgical robot systems in the future. Remote surgery can alleviate the problem of uneven distribution of human resources for interventional doctors. Experienced interventional doctors can remotely perform interventional operations on patients from far away.

5. A training and teaching system for vascular interventional surgery robots combined with virtual reality technology. Through virtual reality technology, blood vessel models, interventional instruments, and robot mechanisms can be established in a virtual environment. Students can experience the simulated interventional surgery process and practice the operating methods of surgical robots through only one manipulator.

6. Extensive application of artificial intelligence. With the accelerating development in artificial intelligence in recent years, more and more artificial intelligence methods will be applied to interventional surgical robot systems, such as medical image recognition, robot sensor information analysis and safety warning, and autonomous intelligent surgery.

Vascular interventional surgery robotics has huge potential. In the future, it will inevitably replace many interventional doctors in the operating room, reduce the workload of interventional doctors, and complete the surgical goals more efficiently and safely. Table I lists researches of vascular interventional surgical robots.

TABLE I
RESEARCHES OF INTERVENTIONAL SURGICAL ROBOTS

Research institute	Field	Haptics feedback	Force sensing	Autonomous delivery
University of Bologna [17-19]	EP		Distal	✓
University of Hong Kong [57, 66, 67]	EP			
Korea University [69]	EP			
Harbin Institute of Technology [36, 70]	EP	✓	Proximal	
Weston University [45, 56, 60, 71-76]	EP, GV			✓
University of Waterloo [21]	EP			✓
Beijing University of Aeronautics and Astronautics [30, 77-81]	GV	✓	Distal	

Yanshan University [58, 59, 82-85]	GV	✓	Proximal	
Tianjin University [86]	GV		Distal	
Shanghai Jiao Tong University [42, 43, 51, 52, 55, 87-89]	GV	✓	Proximal	
Shanghai University [90]	GV	✓	Proximal	
Xiamen University [32]	GV		Proximal	
Saitama Institute of Technology [91]	GV	✓	Proximal	
University of Illinois Urbana Champaign [34, 35, 92]	GV	✓	Proximal	
Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences [28, 93, 94]	GV	✓	Proximal, Distal	✓
Institute of Automation, Chinese Academy of Sciences [40, 41, 95, 96]	GV	✓		✓
Hanyang University [97-101]	GV	✓	Proximal	
Imperial College London [29, 50, 62, 68, 102-108]	GV	✓	Distal	✓
Beijing Institute of Technology [12, 13, 25, 44, 49, 53, 54, 63, 109-111]	GV	✓	Proximal, Distal	
Nagoya University [38, 39, 112-114]	GV	✓	Proximal, Distal	
State University of New York [115]	GV	✓	Proximal	
Katholieke Universiteit Leuven [116]	TAVI			
Kagawa University [10, 11, 26, 27, 46-48]	GV	✓	Proximal, Distal	
Harbin Engineering University [117]	GV			

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