A vascular interventional surgical robot based on surgeon's operating skills

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ORIGINAL ARTICLE

A vascular interventional surgical robot based on surgeon's operating skills

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Abstract

Interventional surgery is widely used in the treatment of cardiovascular and cerebrovascular diseases, and the development of surgical robots can greatly reduce the fatigue and radiation risks brought to surgeons during surgery. In this paper, we present a novel interventional surgical robot which allows surgeons to fully use their operating skills during remote control. Fuzzy control theory is used to guarantee control precision during the master-slave operation. The safety force feedback control is designed based on the catheter and guidewire spring model, and the force-position control is designed to decrease the potential damage due to the control delay. This study first evaluates the force-position control strategy using a vascular model experiment, and then an in vivo experiment is used to evaluate the precision of the surgical robot controlling the catheter and guidewire to the designated position. The in vivo experiment results and surgeon's feedback demonstrate that the proposed surgical robot is able to perform complex remote surgery in clinical application.

Keywords Vascular interventional surgery · Robot-assisted surgery · Master-slave control system · "In vivo" experiment

1 Introduction

According to the World Health Organization (WHO) report in 2015, cardiovascular and cerebrovascular diseases like coronary artery disease are among the top causes of death worldwide. As the death caused by these diseases are rising, vascular interventional surgery is widely used for cardiovascular and cerebrovascular diseases due to its small trauma and quick recovery time [1]. In traditional vascular interventional surgery, surgeons have to perform the surgery for hours, standing beside the patient and position the catheter and guidewire on the target location under the guidance of a digital reduction shadow angiography (DSA) system. The surgeon's fatigue and physiological tremors affect the success of the surgery, and long radiation exposure poses a risk to the surgeon's health. Therefore, researchers have become increasingly interested in vascular interventional robotic systems that allow surgery to be performed outside the operating room using remote control [2].

In the last 20 years, several robotic systems have been developed [3]. Stereotaxis Inc. (St. Louis, MO, USA) developed the NIOBE® remote navigation system that can navigate the catheter via a magnetic field in 2002 [4]. Its slave side controller provides three degrees of freedom including pushing, pulling, rotating, and bending of the catheter tip. The CorPath® 200 robot system, developed by Corindus Vascular Robotics (Waltham, MA, USA) in 2005, can control catheters to grip and rotate using friction wheels [5]. The Sensei Robotic System developed by Hansen Medical in 2006 has a specialized vascular intervention propulsion mechanism for the catheter and guidewire [6–8]. It is a typical wire-

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drive robotic system and has been widely applied in clinical trials. Catheter Precision (Ledgewood, NJ, USA) designed the Amigo™ robot system in 2008, which provides remote controllers with push buttons on the master side, and a multi-freedom steerable catheter controller on the slave side [9].

In addition to commercial products, universities worldwide have also provided robotic systems for vascular interventional surgery. In our lab's previous research, a novel catheter inserting robotic interventional surgery system was presented, consisting of a coaxial force sensor structure that can measure the resistance of a catheter using push force during operations [10–16]. Other university labs have also presented robotic systems such as the 3-DOF cardiac ablation catheter operating system presented by Jun Woo Park at Korea University [17].

Although such robotic systems have been widely studied, the existing vascular intervention surgery robot still has common weaknesses such as lack of force feedback and no cooperation between the catheter and guidewire.

During a traditional vascular interventional surgery, the surgeon manipulates the catheter and guidewire based on two types of feedback—visual feedback and force feedback. Visual feedback provides the location and catheter tip direction to the surgeon, and force feedback provides the information of collision and torque to the surgeon. These two types of feedback construct the operation habits of the surgeon [18, 19]. An experienced surgeon can perform surgery efficiently and safely depending on the operation habits [20]. Due to the size of the catheter and guidewire, the force sensor and feedback are limited and are commonly replaced by visual assist only in practical application, which will cause the absence of surgeon's operation habits during the remote surgery [21].

To simplify the difficulty of the structure, the existing robotic system can only send either catheter or guidewire during the operation. As in traditional vascular interventional surgeries, the operations require the coordination between catheter and guidewire. Surgeons need the guidewire to choose the target vessel in narrow places and guide the catheter through. Robot systems sending a single catheter or guidewire are of little clinical significance. Therefore, cooperation robot between the catheter and guidewire is needed in interventional medical research.

Based on these previous studies, our lab developed a novel remote-controlled vascular interventional robot [22, 23]. This robot can provide force feedback for catheter and guidewire. It is remotely controlled by the surgeon and the surgeon can operate catheter and guidewire at the same time. However, due to its bulky design, it cannot be applied to actual surgical needs. In order to apply our study to the actual surgical environment, we present a novel master-slave surgical robot and evaluate its operation performance in this paper.

The remainder of this paper is structured as follows: in Section 2, a surgery robot system is introduced that cooperates the catheter and guidewire. The control strategy based on the surgeon's surgical technique is designed for the collaborative operation, including the force-position control strategy. In Section 3, we evaluate the force-position control strategy through a human body vascular model and remote control precision through an in vivo experiment. The discussion is presented in Section 4. Finally, we outline our conclusions in Section 5.

2 Materials and methods

2.1 Robot module overview

The routine operation procedure of catheter and guidewire in an interventional surgery is shown in Fig. 1 [24]. The guidewire is responsible for finding the advancement path in the narrow blood vessels and providing guidance for the catheter. The surgeon determines the state of the catheter guidewire in the blood vessel by the frictional resistance between the catheter guidewire and finger. The tactile feedback generated by the friction assists the surgeon, along with the visual feedback of the X-rays. This operating habit ensures the safety of the interventional procedure. At the same time, all the surgeon's operations can be simplified into a combination of the following three operating habits:

(1) Pushing and retracting: to advance and retreat the catheter or guidewire in the blood vessel;
(2) Rotation: to change the direction of the catheter or guidewire in the blood vessel;
(3) Cooperation of push and rotation: to achieve the positioning of the catheter or guidewire in key areas.

However, some commercial surgical robots do not follow the surgeon's operating habits when designing the control side. For example, the Sensei robot developed by Hansen Medical uses a control pad to control the forward/backward of the catheter and the rotation of the tip. The advantage of this is that the joysticks are convenient for the surgeons to get started, but surgeons will lose the hand feeling of operating the catheter and guidewire in the operating room, and the accumulated operational skill cannot be exerted. Moreover, during cardio or cerebral vascular interventional surgery, the surgeon needs to operate the catheter and guidewire to pass through narrow blood vessel branch collaboratively. According to our communication with surgeons in cooperative hospital and observations of actual surgery, we found that at this time, the surgeon's operating skills will greatly determine how long the surgery lasts. Under these circumstances, control side of the vascular interventional robot system needs to be designed with two degrees of freedom: a linear cannula motion degree of freedom and a rotational degree of freedom.

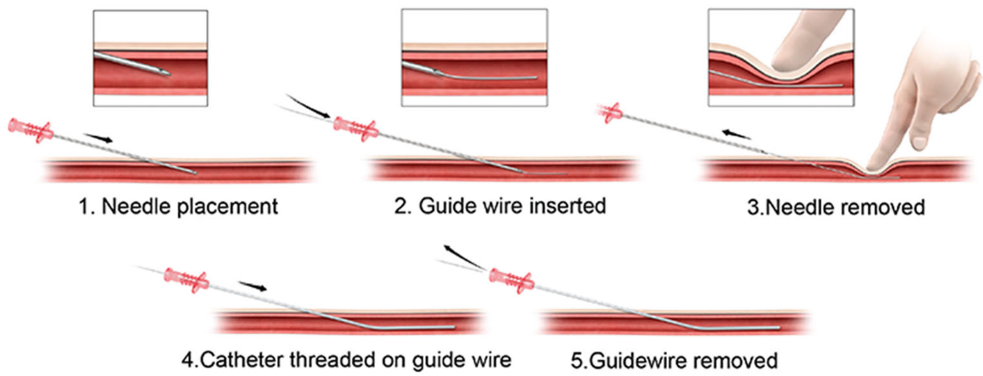

Fig. 1 Routine operation procedure of interventional surgery. From step 4 to step 5 is the main procedure of interventional surgery

The operation requires that these two degrees of freedom be performed simultaneously as a real catheter or guidewire for the surgeon to complete a vascular interventional procedure.

The entire robot system consists of two parts: the master side and the slave side. In order to improve the efficiency and success rate of interventional surgery, the interventional robotic system should imitate the actual operation of doctors and repeat their operation skills. The master side is the control part of the robot system. The design purpose of the master side is to record the surgeon's movement and transport the movement to the slave side. The master side contains the master controller and the master control system cabinet. It is constructed outside the operating room to prevent the surgeon from being exposed to radiation. Surgeons can use the main controller and control system cabinet for surgery. The slave side is the operating part of the robot system. The slave side is designed to replicate the surgeon's movement from the master side. The slave side movement is performed by the slave manipulator. The manipulator has sliding units to control the movement of the catheter and the guidewire. It is connected to the master side through a shielded twisted pair cable. The proposed robot diagram of the complete system structure is shown in Fig. 2. This section introduces the system architecture of the interventional robot from both the master and the slave side.

2.1.1 System master side design

The master side contains the master controller and the master control system cabinet. The master controller we used consisted of two identical haptic interaction devices (Geomagic® Touch, 3D Systems Corp, Rock Hill, SC, USA). The haptic device has two functions: capturing operational data from the surgeon's motion and generating force feedback to the surgeon. As in traditional minimally invasive vascular procedures, the surgeon uses both hands to manipulate the catheter and guidewire. Two haptic devices are designed as catheter controllers and guidewire controllers. Both controllers are capable of recording the linear and rotational motion of the surgeon by using a motor encoder. A torque motor in the haptic device can generate force feedback based on force sensor feedback on the slave side. The two haptic devices are tied together with a sleeve to simulate the relationship between the catheter and the guidewire in traditional minimally invasive surgery, giving the surgeon a vivid operational experience. The control system cabinet is the central processing unit of the entire robot system. The purpose of the cabinet is to capture control signals from the master controller and control the slave manipulator to replicate the same motion on the slave side, and also receive force feedback from the slave side and transfer the data to the master controller and computer screen. The complete structure of the master side is shown in Fig. 3.

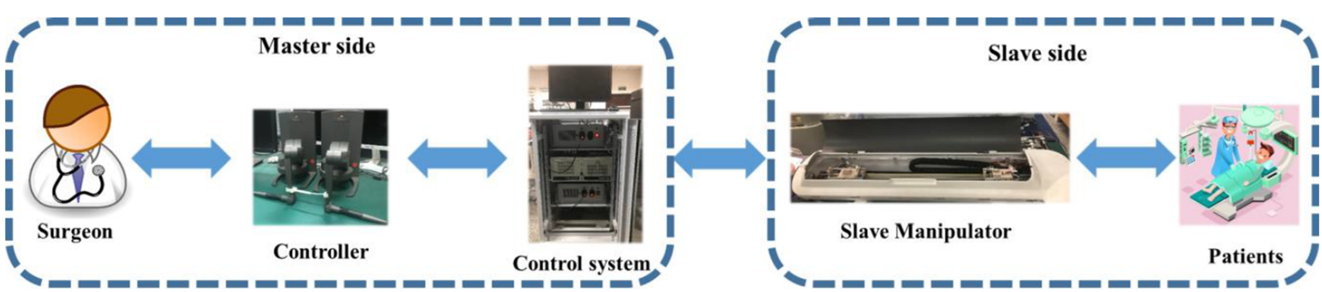

Fig. 2 Diagram of the complete system structure. The surgeon uses controllers to give instructions. The slave manipulator follows the surgeon's directions and operates the catheter and guidewire to complete the surgery. The system master side and slave side communicates through shielded wires

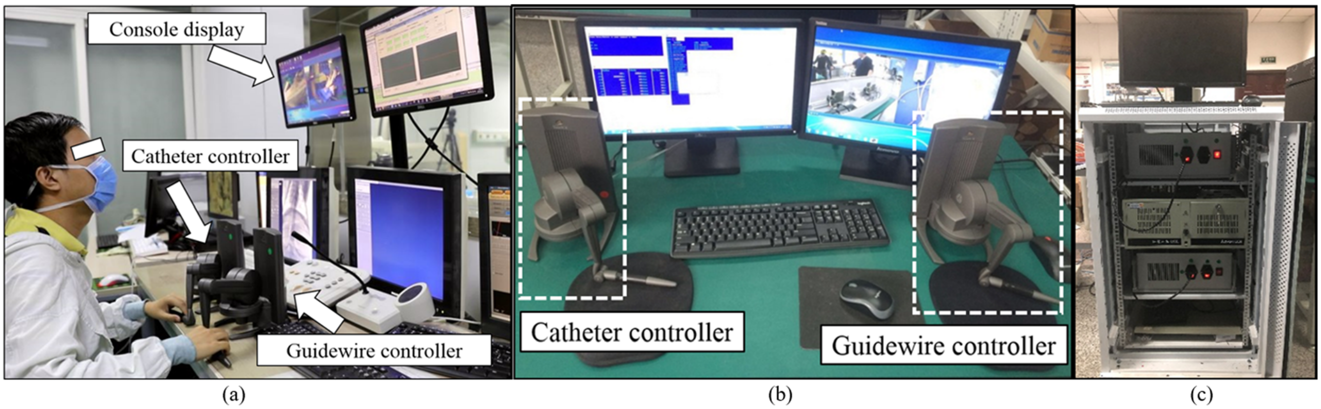

Fig. 3 The complete structure of the master side. **a** Surgeon master side operation display. **b** System master side controller and console interface **c** System master side control system cabinet

2.1.2 System slave side design

The slave side robot is the operating unit of the robot system. The prototype structure of the slave side manipulator is shown in Fig. 4a. The robot has a linear motion platform and two manipulator units. The robot units are mounted on the platform and each unit is connected to a separate brushless dc motor via a pulley. The two manipulator units are a catheter manipulator and a guidewire manipulator, respectively. When the surgeon moves the main catheter controller or guidewire controller in a linear direction, the corresponding dc motor on the linear motion platform moves a precise amount in the same direction. This allows the surgeon to push and drag the catheter and guidewire remotely outside the operating room. We fixed the grating scale on the side of the platform as a calibration feedback to measure the specified linear position of the catheter and guidewire manipulator.

The catheter manipulator and the guidewire manipulator consist of two parts: the upper disposable module and the lower control module. Our former published papers have detailed descriptions of the slave manipulator working principle [25, 26]. The prototype internal structure of the upper and lower module is shown in Fig. 4c [22].The upper module of the manipulator is shown in Fig. 4b, which contains the clamping unit and rotational unit. By the cooperation of the rotational unit and the clamping unit, the surgeon can control

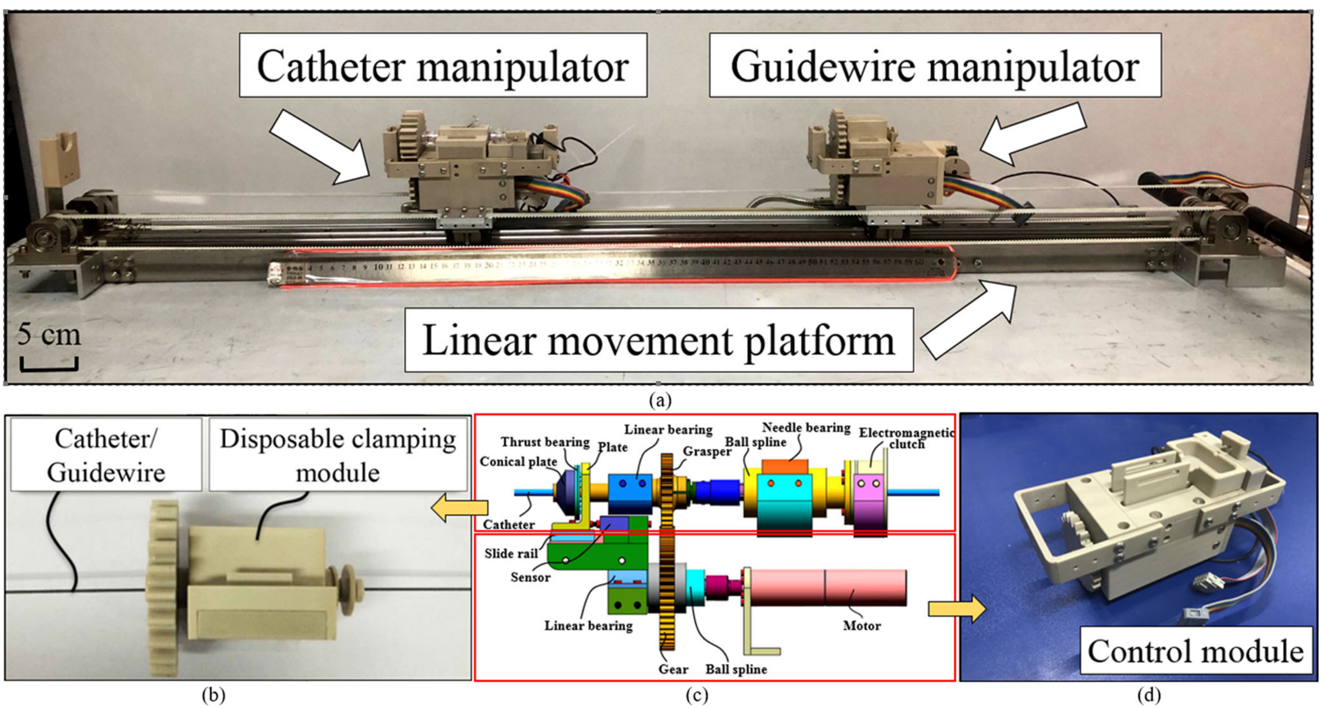

Fig. 4 The prototype structure of the slave side, including the linear movement platform and the catheter and guidewire manipulator. **a** The prototype structure of the slave side. **b** The upper disposable clamping module of the catheter and guidewire manipulator. **c** The internal structure of the slave manipulator [22]. **d** The control module of the catheter and guidewire manipulator

the rotation of the catheter and the guidewire by transmitting the angle of the master controller to the manipulator. The lower module of the manipulator is shown in Fig. 4d, which contains the rotation driving motor and force detection sensor. The force detection sensor is used to measure the proximal force of the catheter and the guidewire during surgery. As shown in Fig. 4c, if the catheter or guidewire collides with the blood vessel during operation, the feedback force will push the slide rail toward the force sensor, which will generate force signal back to the master control system cabinet. The detail precision evaluation results of the force detection structure are shown in our former published paper [22]. For the safety of in vivo experiment, the gear position of the upper and lower module of the manipulator was moved forward, which facilitates the disassembly and disinfection of the upper disposable module.

As the robot master and slave side are being built, the surgeon is able to perform the push, drag movement, and rotation motion at the master side, and replicate the movement at the slave side. Meanwhile, the proximal force signal of catheter and guidewire can be detected and fed back to the master side. This robot system design not only enables the surgeon to complete the operation outside the operating room but also provides a vivid situation for the surgeon to fully use their operating skills learned in traditional surgery.

2.2 System control strategy

2.2.1 Fuzzy control PID design

After the robot system is constructed, the control strategy is designed for the surgeon to remotely operate the robot. The block diagram of the system control strategy is shown in Fig. 5. For our robots, we used an industrial computer as the processing core of the system. After the motion signal operated by the surgeon is collected, the programmable multi-axis controller (PMAC) inside the computer sends the signal to the slave side according to the programmed command. The controller also has the function of receiving the slave side position for closed-loop motion control and limiting operations. Although the PMAC controller has multiple functions, the control accuracy cannot fulfill the standard in practical applications. For example, in the initial operation phase of low speed and high acceleration and the deceleration phase at high speed, the master-slave tracking effect was still limited by the lack of single PID (proportional–integral–derivative) parameter control [27]. Considering the high-precision requirement of the robot control system, the control system is based on fuzzy PID closed-loop control.

The basic PID control strategy is as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{1}$$

As shown in Fig. 6, $u(t)$ is the control signal and $e(t)$ is the control error. For different speeds, different error intervals are set for control. The displacement error and change of displacement error are used as the inputs to the fuzzy control. The control signal thus includes three terms: the P-term (which is proportional to the error), the I-term (which is proportional to the integral of the error), the D-term (which is proportional to the derivative of the error). The controller parameters are proportional gain K_p, integral gain K_i, derivative gain K_d. The implementation of the fuzzy control is performed using the following procedures: measure the current output of displacement in the dc motor and calculate the error $e(t)$ and error change $e_c(t)$; fuzzify the inputs using the rule base; transform the fuzzified inputs into a fuzzy inference using the min-max operation; and defuzzify the information using the center of gravity method to convert to fuzzy control. Next, the defuzzified information consisting of K_p, K_i, and K_d is transmitted to the PID controller and used as the input control signals to adjust the output signal. As shown in Table 1, seven different error intervals are set for control. They are negative-big (NB), negative-medium (NM), negative-small (NS), zero (Z), positive-small (PS), positive-medium (PM), and positive-big (PB). According to the different errors, $e_c(t)$ is set to seven different intervals. The setting of the interval for $e_c(t)$ and $e(t)$ are the same, which presents 49 different model choices in this method.

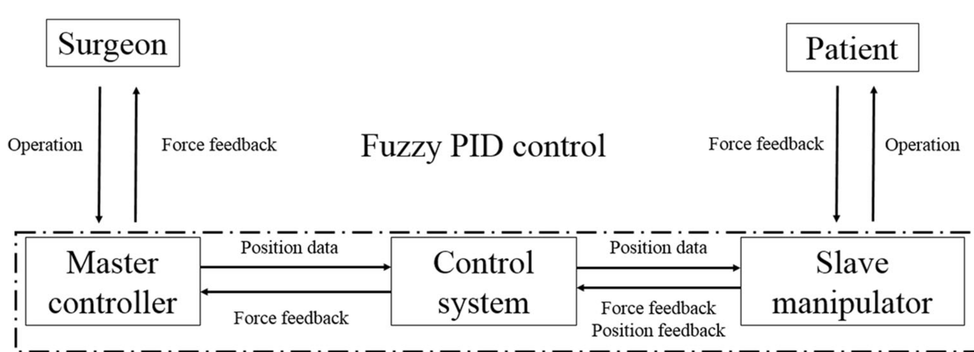

Fig. 5 Block diagram of the system control strategy. Demonstrate the system control and feedback process

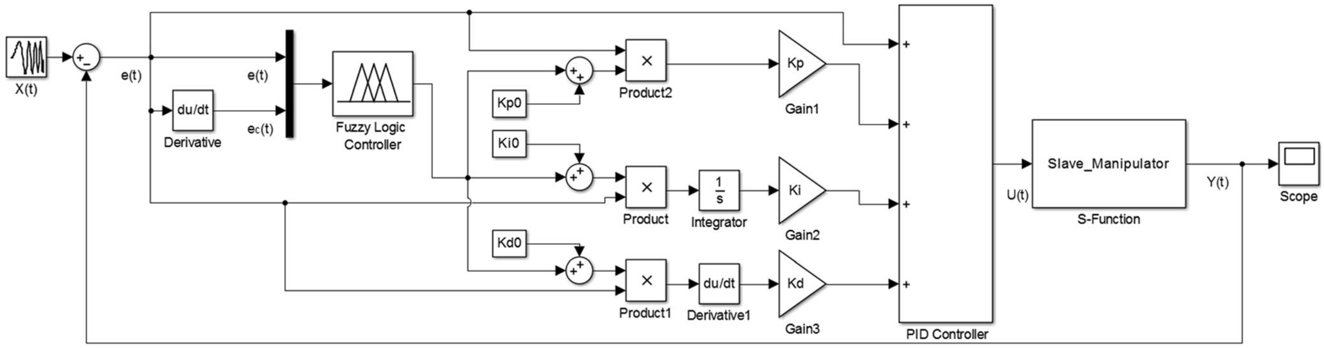

Fig. 6 Fuzzy PID controller flowchart

2.2.2 Calibration of force feedback safety threshold and force-position control

For the force feedback compensation, we designed an early warning mechanism: if the force feedback value is greater than a specified threshold, the control system decreases the followed precision of the master-slave interaction. The threshold value is determined by the guidewire and the catheter. For the robotic system described in this paper, the guidewire was a 0.75-mm diameter loach guidewire. For an average human, blood pressure should be 80 to 120 mmHg. The maximum stress that human vessels can bear is related to the systolic pressure. When the guidewire touches the vessel wall, the area of contact can be considered a small rectangle where one side length is always the diameter of the guidewire, 0.75 mm; the other side length is 0.75 to 1.5 mm. If the contact area is S, systolic pressure is $\boldsymbol{P}$, the maximum safety pressure $\boldsymbol{F}$ can be given by:

$$\mathbf{F} = \mathbf{SP} \tag{2}$$

The calculated range of $\boldsymbol{F}$ is 0.006 to 0.009 N. In order to ensure the safety of the entire surgical procedure, the minimum value 0.006 N is used as a safety threshold. The surface coating of the guidewire is Teflon, with a static friction coefficient μ of 0.014. The maximum pressure $\boldsymbol{F}_{\mathrm{M}}$ can be calculated by the following formula:

$$\mathbf{F} = \mu \mathbf{F}_{\mathrm{M}} \tag{3}$$

The result of $\boldsymbol{F}_{\mathrm{M}}$ is 0.429 to 0.643 N. It should be noticed that in this system, the result of the measured force feedback is at the end of the guidewire, and the guidewire is a flexible material that will inevitably decay during the whole process of transmission of force. Therefore, in order to ensure safety, it is necessary to reduce the influence of such attenuation on the measurement results. The guidewire can be modeled as a long spring with an elastic modulus of 193GPa. An elastic coefficient K can be obtained, given by:

$$K = \frac{ES_{\mathrm{c}}}{L} \tag{4}$$

where S_{C} is the cross-sectional area; L is the length of the guidewire in the aorta, which is in the range of 0.4 to 0.5 m; and E is the elastic modulus. Taking S_{C} as the circumferential area of the guidewire, the range of K is calculated to be 170.44 to 213.05 N/m. According to the relationship between the elastic coefficient, and the spring force and deformation, we obtain the deformation force $\boldsymbol{F}_{\mathrm{d}}$ as follows:

$$\mathbf{F}_{\mathrm{d}} = \mathrm{K} \cdot \Delta \mathbf{L} \tag{5}$$

Due to the limitations of catheters and blood vessels, the amount of deformation of the guidewire $\Delta \boldsymbol{L}$ is quite small.

Table 1 Fuzzy control rules of the robot remote control

	$e(t)$	$e_{\mathrm{c}}(t)$						
		NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
K_{p}	**NB**	PB	PB	PM	PM	PS	Z	Z
	NM	PB	PB	PM	PS	PS	Z	NS
	NS	PM	PM	PM	PS	Z	NS	NS
	Z	PM	PM	PS	Z	NS	NM	NM
	PS	PS	PS	Z	NS	NS	NM	NM
	PM	PS	Z	NS	NM	NM	NM	NB
	PB	Z	Z	NM	NM	NM	NB	NB
K_{i}	**NB**	NB	NB	NM	NM	NS	Z	Z
	NM	NB	NB	NM	NS	NS	Z	Z
	NS	NB	NM	NS	NS	Z	PS	PS
	Z	NM	NM	NS	Z	PS	PM	PM
	PS	NM	NS	Z	PS	PS	PM	PB
	PM	Z	Z	PS	PS	PM	PB	PB
	PB	Z	Z	PS	PM	PM	PB	PB
K_{d}	**NB**	PS	NS	NB	NB	NM	NM	PS
	NM	PS	NS	NB	NM	NS	NS	Z
	NS	Z	NS	NM	NM	NS	NS	Z
	Z	Z	NS	NS	NS	NS	NS	Z
	PS	Z	Z	Z	Z	Z	Z	Z
	PM	PB	PS	PM	PS	PS	PS	PB
	PB	PB	PM	PM	PM	PS	PS	PB

When the change of guidewire bending is less than 2.5°, the range of $\boldsymbol{F}_{\mathrm{d}}$ should be 0.136 to 0.212 N. According to the range of the elastic force and the safety threshold obtained above, it could be dangerous when the force detected from the tip of the guidewire is 0.217 to 0.507 N or more. Similarly, the force feedback safety threshold of the 5F catheter we use is 0.315 to 0.55 N or more.

Based on the above calculation, we take 0.35 N as the force feedback threshold of the guidewire and 0.45 N as the force feedback threshold of the catheter. The complete control strategy is given as follows:

$$\mathbf{X}_{\mathrm{M}}(t) = \mathbf{F}_{\mathrm{S}}(t)/\mathrm{K} \tag{6}$$

$$u(t) = K_{\mathrm{p}}e(t) + K_{\mathrm{i}}\int_{0}^{t} e(t)dt + K_{\mathrm{d}}\frac{de(t)}{dt} \pm |\mathbf{X}_{\mathrm{M}}(t)| \tag{7}$$

where $\boldsymbol{X}_{\mathrm{M}}$ is the decrease amount of the following precision, and $\boldsymbol{F}_{\mathrm{S}}$ is the value of proximal force feedback from the slave side force sensor. Taking the guidewire as an example, we divided the operating condition into the following four cases:

(1) When the value of guidewire proximal force feedback is between 0 and 0.05 N, the slave manipulator will follow the master side movement without a precision decrease.
(2) When the value of guidewire proximal force feedback is between 0.05 and 0.35 N (0.45 N for the catheter) and increasing ($\boldsymbol{F}_{\mathrm{S}}(t) > \boldsymbol{F}_{\mathrm{S}}(t-1)$), the slave manipulator will follow the master side movement after the precision decrease is removed.
(3) When the value of guidewire proximal force feedback is between 0.05 and 0.35 N (0.45 N for the catheter) and decreasing ($\boldsymbol{F}_{\mathrm{S}}(t) < \boldsymbol{F}_{\mathrm{S}}(t-1)$), the slave manipulator will follow the master side movement after the precision decrease is added until the following error is under 0.05 mm.
(4) When the value of guidewire proximal force feedback is above 0.35 N (0.45 N for the catheter), the slave manipulator will stop following the master side movement and will alert the surgeon to retreat the guidewire.

This force-position control strategy is designed to improve the safety of surgery during the master-slave operation. During the master-slave surgery, the inevitable delay problem will cause operational lag for the operation, which means that when the slave side guidewire or catheter collides with the vessel wall, the surgeon operating at the master side cannot quickly feel the force feedback and retreat. Under this circumstance, the control system will decrease the following precision of slave to reduce the collision damage. After the surgeon realizes the force feedback and decreases the force by retreating or rotating the catheter or guidewire, the control system will adjust the slave side to gradually catch up with the master side to guarantee the accuracy of the operation.

3 Evaluation experiments and results

After the robot system and software design was completed, we performed two experiments to verify the actual operating performance and control precision of the robot: a vascular model experiment and an in vivo experiment using the robot system.

The vascular model experiment applied a simulation vascular model as the experimental environment. The vascular model can be highly realistic in simulating the blood vessel environment in the body, including blood pressure and heart rhythm. Meanwhile, enough lubricant is added to the blood vessel model to simulate the real friction of a blood vessel wall. Therefore, it can provide a more authentic verification effect for the surgical robot. The vascular model experiment is mainly to evaluate the ability of the force-position control strategy when guidewire or catheter collides with the vessel wall.

The animals used in the animal experiments in this paper are small pigs. The animal experiment is mainly to evaluate the ability of the surgical robot to control the catheter and guidewire to the designated position of the animal blood vessel through master-slave control. For the robot design, it is evaluated by the precision of the control and the theoretical value. For clinical application, it is evaluated by whether the experiment conforms to the surgeon's operating habits. In addition, the outcome of the animal experiment determines whether it can be used in the clinical trial [28].

3.1 System performance evaluation and results of the vascular model

The process of simulated surgery is illustrated in Fig. 7. The surgeon operates the master side surgeon control platform. The master sends the detected action to the controller. With this information, the controller controls the slave side to operate the catheter and guidewire. The catheter is inserted from the femoral artery insertion entrance and pushed to the ascending aorta. The operation and force feedback data from the insertion started at the femoral artery to the ascending aorta was collected and analyzed.

The experiment consists of using the robot to make the catheter and guidewire pass through the aortic arch. In this operation, the catheter and guidewire insertion distance is approximately 450 mm and the operating time is approximately 20 s. This experiment verifies the feasibility of using a robot for vascular intervention and using experimental data to verify that the proposed force-position control strategy can adjust the master and slave side tracking accuracy according to different feedback force magnitudes and trend conditions after detecting the force feedback signal from the slave side. To ensure repeatability, five volunteers participated in the experiment and each completed ten operations.

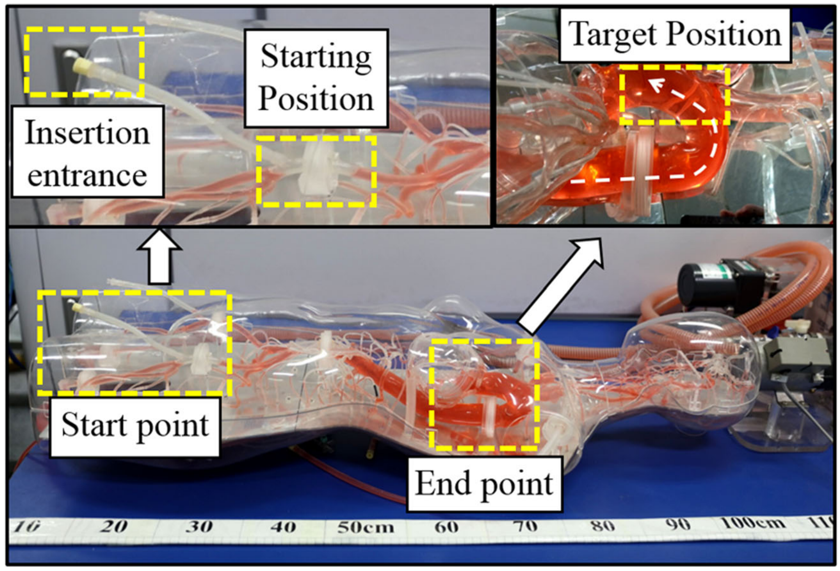

Fig. 7 Vascular model experiment environment. Including the starting position (the femoral artery) and the target position (the ascending aorta)

Figure 8 illustrates the master-slave force-position control strategy motion following the results of the vascular model experimental process. It can be seen that since the catheter has greater stiffness than the guidewire, the feedback force detected during the experiment is relatively larger. The operator performs multiple retrace adjustments based on the force feedback information during the experiment. Based on these results, it can be found that the master-slave following precision dynamically adjusts according to the force feedback result. It can be seen that due to the influence of the master-slave operation delay, the operator cannot immediately adjust the attitude of the catheter and guidewire after detecting the force feedback from the slave side. At this time, the control system automatically reduces the master-slave side following accuracy according to the obtained force feedback information to reduce the possibility of damage caused by collision with the blood vessel. When the operator detects the force feedback at the master side and adjusts the position of the catheter and guidewire to a safety range by retracting and rotating, the system gradually compensates the precision error during the following master-slave motion. The process is similar to the PID tuning process. As shown in Fig. 8, the errors of dynamic tracking performance are between −0.5 and 2.4 mm at the appropriate speed. When the feedback force does not exceed the safety threshold, the maximum error of the master-slave motion is under 0.5 mm.

3.2 Performance evaluation and results of the in vivo experiment

In order to verify whether the surgical robot can meet the high-precision standard in an actual surgical operation, we performed in vivo experiments using a pig as the patient. Although the vascular model can provide a simulated environment that simulates blood pulsation, it is different from an actual in vivo environment. In order to enable the surgeon to adapt to the robot's operation more quickly and to better evaluate the accuracy of the robot master-slave control, we

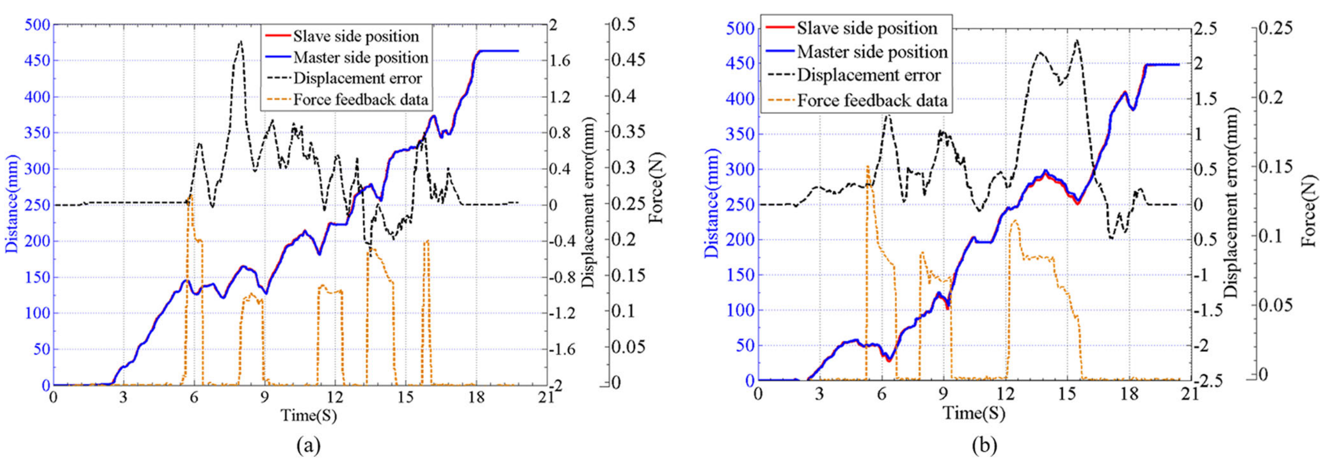

Fig. 8 Force-position control vascular model experiment result. **a** Catheter motion following result. **b** Guidewire motion following result

removed the control strategy of adjusting the master-slave following accuracy based on the force feedback data. In the in vivo experiment, the master-slave control strategy is fuzzy PID control, and the linear and rotation operations performed by the surgeon at the master side are accurately replicated to the slave side. The surgeon uses the force interaction controller at the master side to feel the force feedback, and at the same time, the force feedback line graph can be observed on the computer real-time feedback interface.

The operating room environment of the in vivo experiment is shown in Fig. 9a. The experiment was conducted at Beijing Tiantan Hospital. The slave side manipulator system was fixed to the side of the operating bed by a mechanical arm. The tilt angle of the robot and the position above the operating bed can be adjusted by the robot arm. In vivo experiments were mainly performed by a surgeon with years of experience in neurosurgery. Several neurology interns also operated the robot after the main experiment had completed. The master side of the robotic system was placed outside the operating room. As shown in Fig. 9b, the surgeon controls the master side controller to operate the experiment. The surgeon uses the master controller to operate the catheter and guidewire to move from the blood vessels of the experimental pig's thigh to the left and right common carotid artery.

The in vivo experiments reach several locations in animal's blood vessels multiple times. In this paper, the right subclavian artery angiography process is taken as an example to evaluate the control performance of the robot. During the experiment, the catheter started at the external iliac artery, passed the descending aorta and the aortic arch to reach the right subclavian artery. The duration of the operation was approximately 80 s. The X-ray film and angiographic result of the right subclavian artery of the experimental pig are shown in Fig. 10.

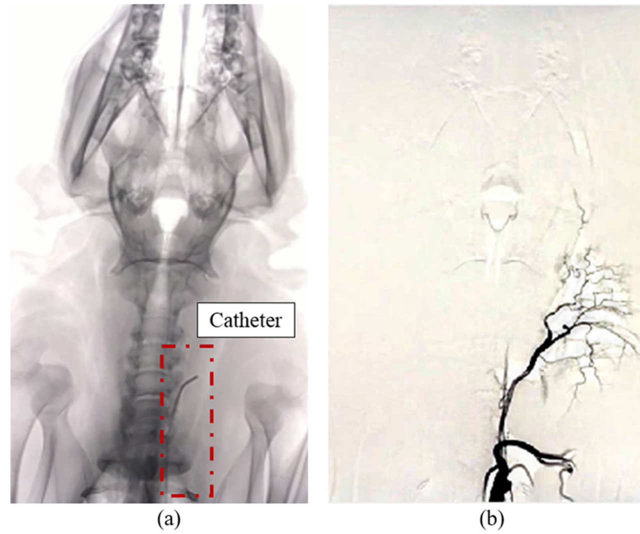

Fig. 10 Part of the angiograms results of the in vivo experiment. **a** The X-ray image of the pig's right subclavian arteries. **b** The angiogram of the pig's right subclavian arteries

The in vivo experimental results of reaching the right subclavian artery are shown in Fig. 11. Results show that the dynamic performance of the system is stable during the experiment. The following error of the catheter linear tracking performance is between 1.5 and −2.0 mm, the average error is 0.18 mm. The following error of the guidewire linear tracking performance is between 1.3 and −1.8 mm, the average error is 0.11 mm. According to the surgeon's feedback, this error is within the acceptable range during the surgery. The error of the rotation movement is between 2.4° and −1.9°, the average error

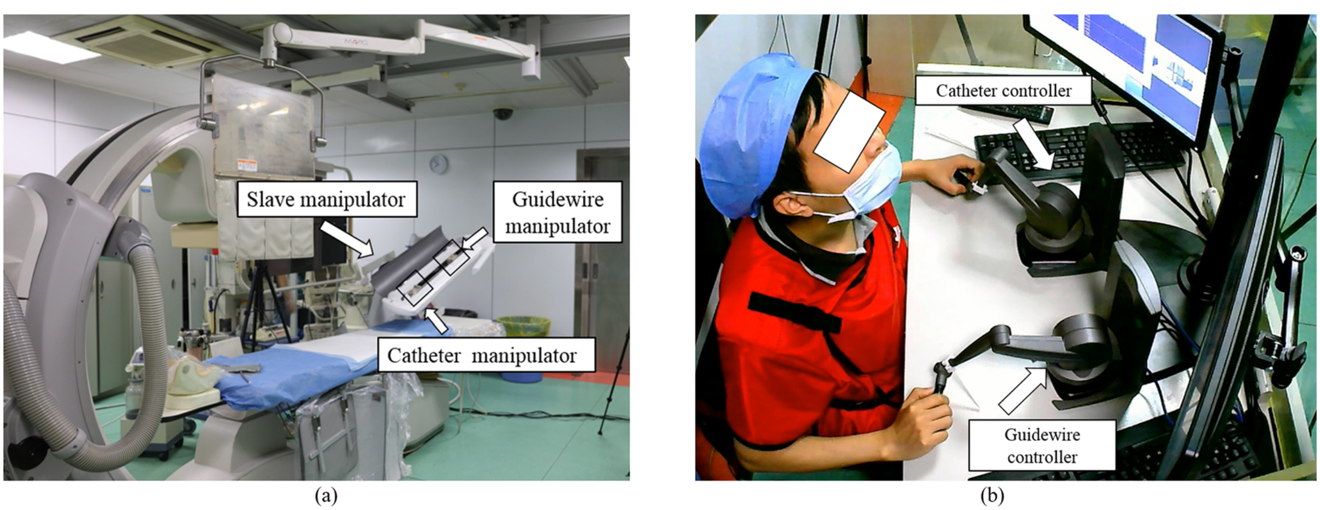

Fig. 9 The in vivo experiment environment. **a** Operating room environment of the in vivo experiment. **b** Surgeon controls the master side controller to operate the experiment

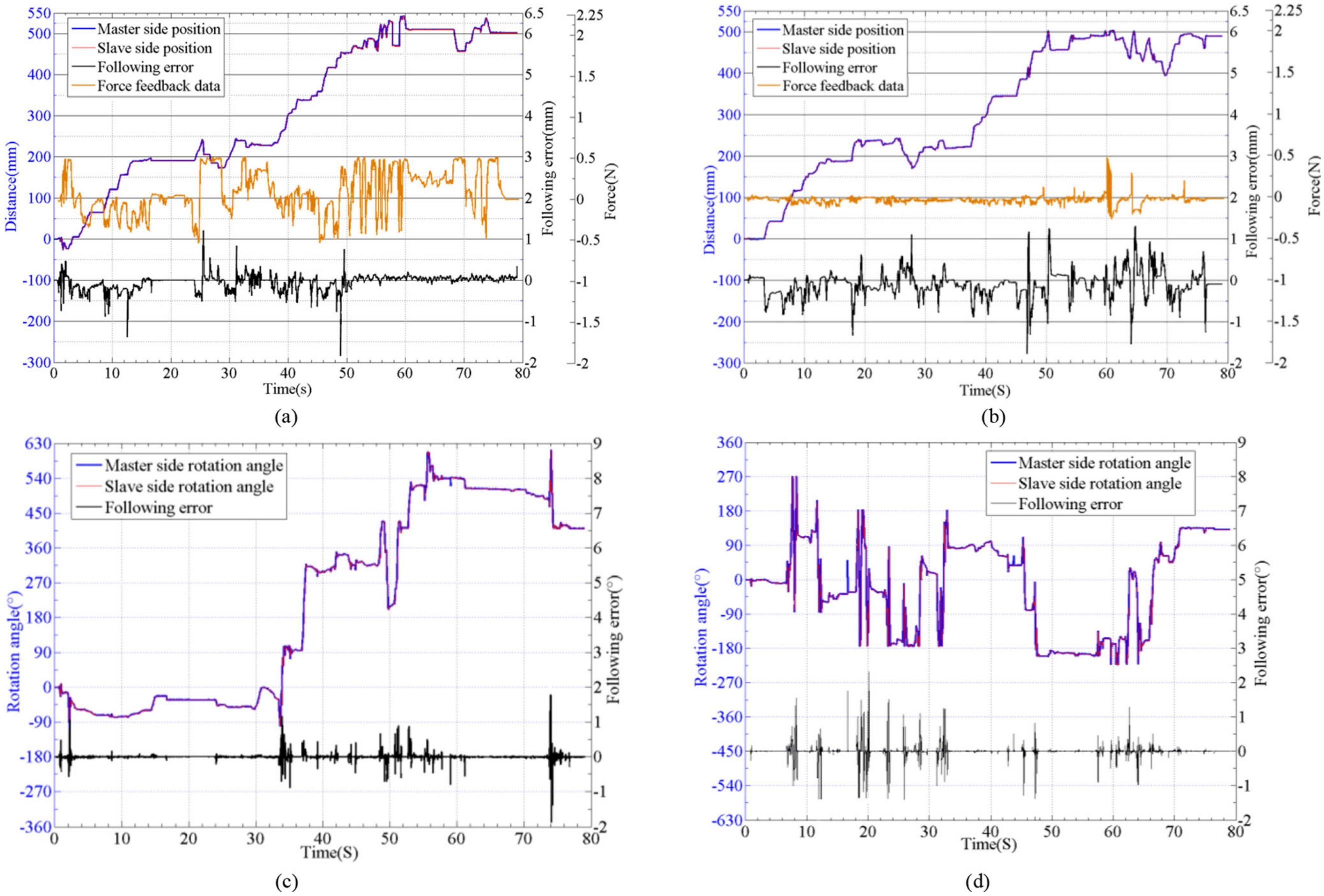

Fig. 11 Linear movement, rotational movement result, and the displacement error of catheter and guidewire from the in vivo heart experimental procedure. **a** Linear movement result and the following error of catheter. **b** Linear movement result and the following error of guidewire. **c** Rotational movement result and the following error of catheter. **d** Rotational movement result and the following error of guidewire

is 0.17°. According to the surgeon's feedback, this error is also within the acceptable range during the surgery.

4 Discussion

As shown in Figs. 8 and 11, the performance of the proposed interventional robot and the effects of the control strategy are investigated herein. This paper focused on solving two problems of interventional surgery robot research. Firstly, transplanting the surgeon's surgical skills to the master-slave surgery robot structure, so that surgeons can rely on their experience of past surgeries to operate the master side to achieve rapid adaptation, which improves the stability of the surgical operation. Secondly, the fuzzy PID is used for master-slave control, and the surgical operation is divided into multiple cases for PID control to ensure the accuracy of the robot remote control can meet the requirements during the operation. Thirdly, a force-position control strategy is proposed to enable force feedback data to be added to the closed control loop as an operational threshold when necessary, reducing possible blood vessel collision damage and improving surgical safety.

Compared with our previous study results [26], the robot system is lighter and the master-slave control error is smaller. However, the system still has some short-comings to improve: Firstly, the master and slave structures of the robot are isomerism, although the operation mode is similar but not exactly the same, and the master side can only operate at a smaller distance than the slave. The surgeon has to disconnect the master-slave connection when reaching the master side operation limit, and readjust the position of the master side before controlling the slave side to move further. Secondly, the accuracy of the proximal force detection is limited. Although the force feedback sensor we used has a high accuracy of 0.001 N, since the force measuring device is located inside the catheter and guidewire controller, mechanical vibration and unavoidable mechanical friction are encountered during the force measurement. At the same time, the catheter and guidewire have a bending condition in some experiments, so that the detection force accuracy is affected. Thirdly, the setting of the force threshold can be more precise in the force-position control.

The threshold force range was estimated by human blood pressure and the contact area between the guidewire and the blood vessel. In order to improve the threshold accuracy, a high-precision sensor can be designed for actual measurements in subsequent animal experiments.

5 Conclusion

This paper proposed a novel interventional surgical robot and evaluated its control performance through a vascular model experiment and an in vivo experiment. The results demonstrate that the proposed surgical robot is able to perform complex remote surgeries in clinical application. This paper provides several foundations for our future research in surgical robots:

(1) We proposed control strategy for a surgical robot which allowed surgeons to fully use their operating skills during remote control.
(2) The fuzzy PID was used to guarantee the control precision and the safety force feedback control was designed.
(3) A preliminary force-position control was designed to decrease the potential damage due to the control delay.

For further study, we will focus on the problems that surgeon feedback after several in vivo experiments. Firstly, a specially designed master controller is necessary for our robot. According to surgeon's feedback, although they can remotely control the catheter and guidewire in the same way as in the operating room during surgery, the redundancy degree of freedom still gives them a lot of operational incompatibility. Secondly, a surgeon needs to extract the guidewire from the patient's body after the catheter reached the affected area and prepare for angiograms. The current control strategy of extracting guidewire costs too much time. Our next step is to develop a relevant control method which can automatically control the withdrawal of the guidewire, improve the safety of the operation, and the convenience of the remote surgery. Finally, several in vivo experiments do not fully evaluate the operational performance of the robot. With the assistance of the cooperative hospital, we will seek for more opportunities for animal and clinical experiments, evaluate and improve the performance of the robot through statistics and actual feedback from surgeons.

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Compliance with ethical standards

Ethical approval All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

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