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A Portable Surgeon's Habits-based Master Manipulator for Vascular Interventional Surgery Robots

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***Abstract* – The emergence of vascular interventional surgery robot (VISR) has brought good news to patients. However, the current research on the master manipulator is still in its infancy. Nowadays, the shortcomings of the developed master manipulator include poor portability, lack of tactile feedback devices, not in line with surgeon's operating habits and so on. In order to solve the above problems, a novel master manipulator is proposed in this paper. In order to realize the linear displacement measurement of the operating handle, a linear displacement measurement (LDM) unit based on rollers was proposed. By using the brushed DC motor and the bevel gears, the angular displacement measurement (ADM) unit and the circumferential force feedback (CFF) unit were designed. The decoupling of the operating rod and the rotating rod facilitated the portability of the proposed manipulator. Evaluation experimental results showed that the maximum linear error of the master manipulator was 0.296mm and the maximum angular displacement error was 7.66 degrees, which is acceptable. Moreover, the mathematical relationship between the circumferential force generated by the CFF and the input current was also obtained. To sum up, compared with other master manipulators, the proposed master manipulator is shown to be better and more promising.**

Index Terms – Vascular Interventional Surgery Robot; Master Manipulator; Circumferential Force Feedback.

I. INTRODUCTION

In recent years, cardiovascular and cerebrovascular diseases have gradually become one of the major diseases threating people's health due to people's diet with high oil and high sault and their bad living habits. According to the survey data of the "2020 China Cardiovascular Health and Disease Report", in the past few years, the incidence of cardiovascular and cerebrovascular diseases in Chinese residents has been increasing rapidly, and its mortality rate is also much higher than that of other non-communicable diseases such as tumors. By 2020, the number of cardiovascular and cerebrovascular patients in China has already reached 330 million. Cardiovascular and cerebrovascular diseases have seriously threatened the health of Chinese residents. Therefore, how to treat cardiovascular and cerebrovascular diseases has become the focus of government health departments. Nowadays, thoracotomy/craniotomy and vascular interventional surgery (VIS) are the two most important clinical treatments for cardiovascular and cerebrovascular diseases. VIS has been widely accepted by surgeons due to its advantages of less trauma, less blood loss during operation, faster postoperative healing and lower probability of postoperative complications[1]. However, during vascular interventional procedures, surgeons need to be exposed to X-radiation for a long time. Despite the protection of the lead coat, the doctor's face and hands are still directly exposed to X-rays. In addition, the 20kg lead coat will also increase the fatigue of the doctor. Studies have shown that doctors who perform VIS for a long time have a higher risk of suffering from tumors, spondylitis and other diseases[2-4]. Fortunately, the emergence of vascular interventional surgery robots (VISR) has brought hope to overcome the above difficulties.

Nowadays, many commercial companies have carried out research on robots for vascular interventional surgery. For example, in 2018, Corindus Vascular Robotics company independently developed the CorPath® GRX and completed more than 600 cases of clinical surgery experiments[5]. Although the robot can effectively reduce the radiation dose received by doctors, it lacks tactile feedback device, and the operation method is not ergonomic. In 2012, Hansen Medical designed a VISR called Magellan™, which uses a special active catheter that can bend the tip of the catheter 180 degrees[6, 7]. However, this active catheter is not suitable for cardiovascular and cerebrovascular. It can only be used in interventional treatment of peripheral blood vessels. In the same year, a VISR called Amigo™ came out[8-12]. The master side of this robot is a manipulator like the handle of an endoscope, which is very portable. However, it still lacks a tactile feedback device. The design of the manipulator is too simple to meet the doctor's operating habits, which prolongs the doctor's learning curve.

In addition to the research of commercial companies, researchers have also carried out research on VISR. Yang et al. proposed a VISR with the characteristics of master-slave isomorphism., which also has the function of tactile feedback[13]. However, the size of the master manipulator is too large for portability. Zhou et al. proposed an ergonomic master manipulator of VISR, and realized non-contact displacement measurement, and improved the response speed of the system by using the ADRC method[4, 14]. Based on the previous research, Shi et al. designed a novel type of master manipulator[15, 16]. However, the manipulator lacks a circumferential force feedback unit, and the use of a lead screw increases the overall size. Li et al. combined MR fluid and hydrogel to make a new type of solid-state material to provide force feedback of the master manipulator. They also used the sensor in the mouse to achieve non-contact measurement of displacement information [17]. Besides, A tremor suppression system based on bimodal detection was proposed by them, which improved the safety of the surgical system [18]. Bao et al. introduced the multi-level concept of surgical force into VIS, and proposed a novel multi-level surgical strategy to ensure surgical safety [19]. Jin et al. also utilized MR fluid as the force feedback material of the master manipulator. Besides, they also conducted a series of research on surgical safety strategies[20-22]. However, the magnetic field generating device significantly increases the volume of the master manipulator. Wang et al. designed a novel master manipulator based on the principle of SEA[23, 24]. However, although the circumferential force feedback unit was designed in this paper, they didn't carry out the experimental verification of the unit. Besides, the use of the lead screw also increases the overall volume. Yan et al. proposed a novel clamping device, which can control the grasping force, thus realizing the precise clamping of catheter and guidewire [25].

According to literature research, most of the current master manipulators lack tactile feedback devices. Those manipulators with tactile feedback units require bulky external devices, thus reducing the portability of the manipulator. In addition, the operation methods of many master manipulators don't conform to the operation habits of doctors, which prolongs the learning curve for them.

In this paper, a novel portable master manipulator with circumferential force feedback function is proposed. Inspired by previous studies, two PTZ motors and rollers are connected as linear displacement recording units. A brush DC motor with an encoder is used as the recording unit of the angular displacement and the circumferential force feedback unit. The operation of the manipulator is the same as traditional interventional surgery, which can provide doctors with a better sense of immersion. The performance of the master manipulator will be verified by experiments.

The remaining structure of this paper is as follows: the structure and the working principle of the master manipulator will be introduced in Section II. Three calibration experiments will be presented in Section III. Section IV will give the conclusion of this paper.

II. System Design

Fig.1 shows the workflow of the doctor using VISR to complete the VIS. The VISR can be divided into three parts: the master manipulator, the communication unit and the slave manipulator. The slave manipulator is placed at the patient's bedside, receives the doctor's instructions to complete the corresponding interventional operation and simultaneously measures the collision force between the catheter and the vessel wall. The communication unit is the information exchange center between the master side and the slave side, which will not be introduced in detail in this paper. The master manipulator is placed in a radiation-free environment and directly operated by doctors. The two main function of the master manipulator are to record the displacement information of the doctor and realize tactile feedback. The recording function of displacement information is the core of the master manipulator, since it is related to the accuracy of the whole system. The tactile feedback function is also of vital importance. It can provide doctors with sufficient immersion and avoid damage to blood vessels by the catheter tip, thus improving the safety of surgery.

In this section, the mechanical structure and workflow of a novel master manipulator will be introduced. The master manipulator proposed in this paper not only has the recording function of rotational displacement and linear displacement information, but also can realize the feedback function of circumferential force, providing the operator with partial tactile perception. It is also worth noting that the operation mode of the master manipulator fits the doctor's operating habits and conforms to the ergonomic design. In addition, the master manipulator is small, which is convenient for loading, unloading and carrying.

A. Mechanical Structure of the Master Manipulator

Fig.2 shows a side view of the proposed master manipulator. As shown in Fig.2, the size of the master manipulator is 104*50*70mm, which is much smaller than the master manipulator proposed in other papers. The smaller size and cuboid-like shape design enhance the portability of the master manipulator, thus making it possible for doctors to carry it with them. There is also a transparent viewing window on the back side of the master manipulator, allowing the operator to observe during operation. As mentioned above, the master manipulator mainly has two functions: the recording function of displace information and the tactile feedback function. Therefore, the structure of the proposed master manipulator can be divided into three components according to these two functions: linear displacement measurement unit (LDM), angular displacement measurement unit (ADM) and circumferential force feedback unit (CFF).

Fig.3 shows a schematic diagram of the structure of the LDM, which consists of two PTZ motors (Si Tai PTZ motor, PM3505, China), a pair of spur gears and a pair of rollers. A rigid rod is clamped between two rollers and is directly manipulated by the operator. In order to ensure that the operation mode conforms to the ergonomic design, the rigid rod used in this paper has the same size as the conventional catheter, with a diameter of 3 mm. When the operator delivers the rigid rod, the roller will rotate under the action of friction, thus driving the rotation of the PTZ motor. An AS5600 magnetic encoder is fixed on the PTZ motor, thus the linear displacement measurement can be realized. Since the AS5600 encoder records a value change of 6.28 when the motor rotates 1 turn, the mathematical relationship between the actual displacement of the rigid rod x and the values x_1 and x_2 of the encoder output can be obtained:

$$\theta = \frac{|x_2 - x_1|}{6.28} * 360^{\circ} \tag{1}$$

$$x = \frac{2\pi R\theta}{360^{\circ}} \tag{2}$$

where θ is the actual rotation angle of the roller and R is the radius of the roller.

The structure diagram of the ADM is shown in Fig.4. This unit contains a brush DC motor (ASLONG motor, JGA25-370B, China), a rotating rod and a pair of bevel gears. When the rotating rod is rotated by the operator, it will drive the rotation of the brush motor, thus the encoder on the brush motor will record the operator's angular displacement information. As shown in Fig.4, it is worth noting that the rigid rod and the rotating rod are two independent structures, thus the motion between them will not interfere with each other. In other words, the LDM and the ADM of the proposed master manipulator are decoupled. Besides, the operation mode of the ADM is the same as that of the traditional interventional operation. Since the encoder on the brush motor is an incremental encoder, the mathematical relationship between the actual angular displacement θ_a and the number of output pulses of the encoder n_1 and n_2 is:

$$\theta_a = \frac{n_2 - n_1}{\lambda} \tag{3}$$

where λ is the resolution of the encoder.

The structure of the CFF is shown in Fig.4, which is the same as the structure of the ADM. Its working principle will be described below.

B. *Working Principle of the Master Manipulator*

The working principle of the CFF is shown in Fig.5. The brush motor has a certain torque. When the input voltage of the motor changes, the torque of the output shaft of the motor will also change. Therefore, the output torque of the brush motor can be controlled by changing the input voltage of the motor, thus realizing the feedback of the circumferential force. It is worth noting that usually in the vascular interventional operation, the circumferential force will not exceed 5N, while the rated torque of the brush DC motor used in this paper is 0.55kg*cm, the reduction ration is 4.4 and the diameter of the output shaft is 4mm, which meets the needs of clinical surgery.

From the above introduction, it can be concluded that the master manipulator is in line with ergonomic design and fits the traditional interventional operation mode, thus allowing doctors to make full use of their clinical experience in the process of use.

III. Experiments and Results

According to the section II, the proposed master manipulator is printed and its structure diagram is shown in Fig.5, which is an important part of the experimental platform in this section. The accuracy of the master manipulator displacement measurement is the key to characterize the accuracy of interventional surgery, since it determines the displacement of the catheter in the slave manipulator. In order to verify the feasibility of the proposed master manipulator, 2 calibration experiments are designed to evaluate the accuracy of the LDM and the ADM, respectively. Besides, as mentioned above, there must be a mathematical relationship between the input voltage and output torque of the Stepper motor in the CFF. In order to represent the circumferential force, an experiment is carried out to explore this mathematical relationship.

A. *Accuracy Calibration Experiment of LDM*

The key to verify the accuracy of the LDM is to verify the measurement accuracy of the AS5600 encoder on the PTZ motor. Therefore, in order to achieve the above purpose, an experimental platform was designed and is shown in Fig.6.

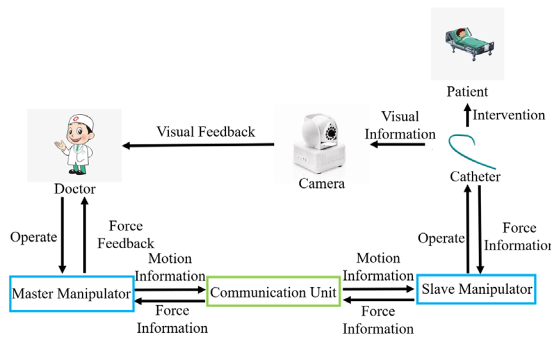

Fig. 1 the workflow of the VISR.

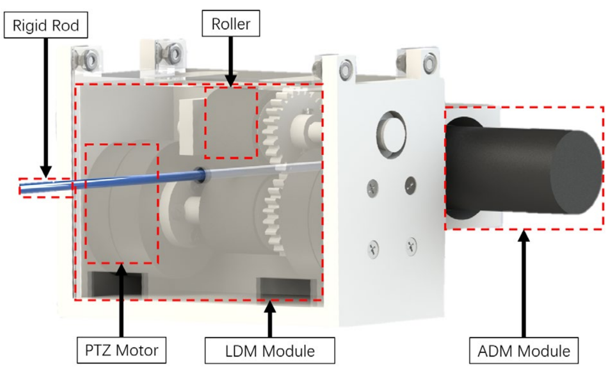

Fig. 2 Structure of the master manipulator.

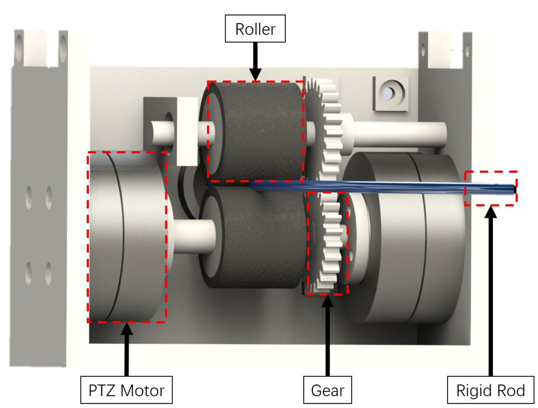

Fig. 3 Structure of the LDM.

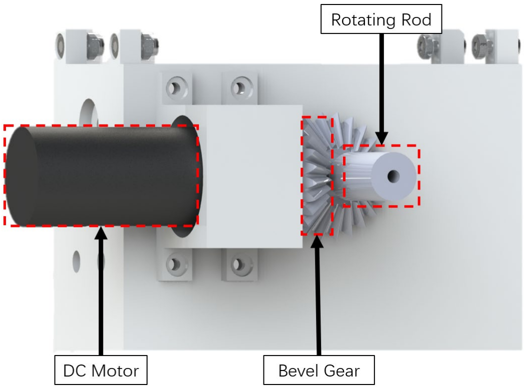

Fig. 4 Structure of the ADM.

As shown in Fig.6, the rope sensor was coaxially connected to the rigid rod through a coupling to record the real displacement of the rigid rod. The ideal displacement was recorded by AS5600. An ESP32 Board was used to read the encoder value of the AS5600. Both the ideal displacement and the actual displacement would be printed to the host computer through serial communication.

In this experiment, the operator would first withdraw the rigid rod for a distance. The operator then would pause for a few seconds before delivering the rigid rod for a certain distance, just like in a real interventional operation, and recorded the ideal displacement and actual displacement data. After the completion of the experiment, the plot would be drawn according to the real-time recorded data, and the errors would be compared.

The experimental results are shown in Fig.7 and TABLE I. Fig.7 shows the curve of displacement over time during delivery process, where the blue curve represents the real displacement, the green curve represents the ideal displacement, and the red curve is the absolute value of the difference between the two curves. According to TABLE I, the maximum error in the delivery process is 0.296mm, the mean error is 0.063mm and the variance is 0.004mm^2.

To sum up, the ideal displacement curve and the actual displacement curve fit well in the delivery process, the dynamic error curve fluctuates up and down at value 0. The maximum error in the delivery process is 0.296mm. Providing that even the most professional experts have a delivery error of more than 0.2mm during the VIS. While the maximum dynamic error of the proposed master manipulator is 0.296mm, which is only slightly higher than the expert standard. Therefore, the conclusion can be drawn that the accuracy of the LDM meets the requirements of VIS.

B. *Accuracy Calibration Experiment of ADM*

The key to verify the accuracy of the ADM is to verify the measurement accuracy of the encoder on the brush motor. Therefore, to achieve the above purpose, an experimental platform was designed and is shown in Fig.8. As shown in Fig.8, an encoder was coaxially connected to the rotating rod through a coupling. When the rotating rod was rotated by operator, the encoder on the brush motor would record the ideal angular displacement while the encoder connected to the coupling would record the actual angular displacement. Both the ideal displacement and the actual displacement would be printed to the host computer through serial communication.

In this experiment, the rotating rod were rotated at a certain angle by operator. The ideal angular displacement and the actual angular displacement were recorded respectively. After the experiment, a drawing was carried out to compare the difference between the two curves.

The experimental results are shown in Fig.9 and TABLE II. As shown in Fig.9, the blue curve represents the real displacement, the green curve represents the ideal displacement, and the red curve is the absolute value of the difference between the two curves. According to TABLE II, the maximum error in the rotation process is 7.66 degrees.

To sum up, the ideal displacement curve and the actual displacement curve fit well in the rotation processes. Although the maximum error can reach 7.66 degrees, this is mainly due to the poor quality of the coupling, which causes a certain amount of slippage between it and the rotating rod. Providing that the accuracy of angular displacement only has a certain impact on the selection of vascular branches and hardly cause dangerous behaviors such as vascular puncture[21], conclusions can be drawn that the accuracy of the ADM meets the requirements of VIS.

C. *Calibration Experiment of CFF*

To obtain the mathematical relationship between the generating circumferential force and the input current, an ATI force sensor was used to measure the circumferential force output of the brush motor. The experimental platform of this experiment was almost the same as that in Fig.10, only the encoder in Fig.10 needs to be replaced by the ATI force sensor. The speed and the steering of the motor was controlled by STM32 microcontroller. The value of the input current was changed by adjusting the duty ratio of the Pulse Width Modulation (PWM) wave and was captured by the ADC module on the STM32 microcontroller.

The duty ratio of the PWM wave of the motor was adjusted to 10%, 20%, 30%, 40%, 50%, 60% respectively. The current of the motor measured by the ADC module was collected. Meanwhile, the circumferential force of the motor was measured and collected by the ATI sensor. Finally, the curve was fitted according to the collected data.

By fitting the curve to the cubic equation, the curve relationship between the circumferential force and the input voltage was obtained as shown in Fig.10. Besides, the fitting formula was shown below:

$$\begin{gathered} F = -6.631e-08*x^3 + 2.631e-05*x^2 \\ +0.00738*x - 0.02381 \end{gathered} \tag{4}$$

where F is the output force of the motor and x is the current flowing into the motor. It is worth noting that the R-square score is 0.9776, which proves that the model is well-fitted.

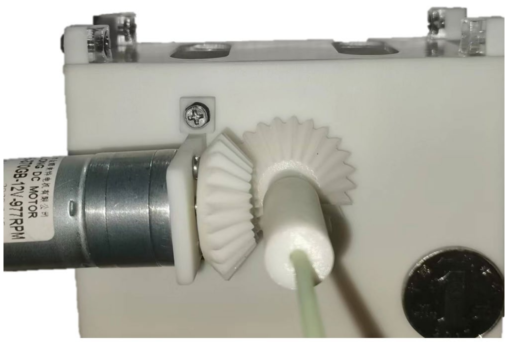

Fig. 5 Structure of the proposed master manipulator.

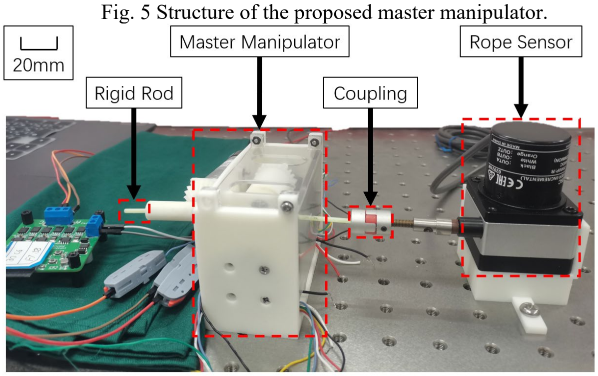

Fig. 6 Experimental platform of the LDM.

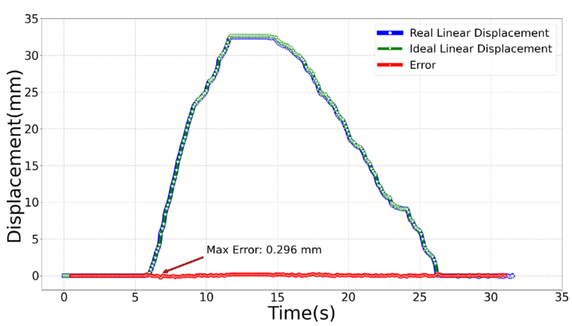

Fig. 7 Linear displacement accuracy evaluation experiment.

TABLE I

THE STATISTICAL RESULT OF ERRORS OF LDM

Mean Error (mm)	Variance Error (mm^2)	Max Error (mm)	Min Error (mm)
0.063	0.004	0.296	0

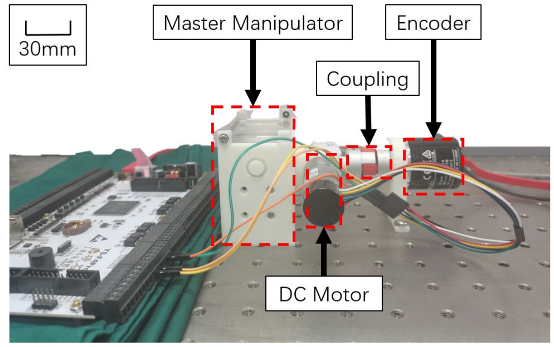

Fig. 8 Experimental platform of the ADM.

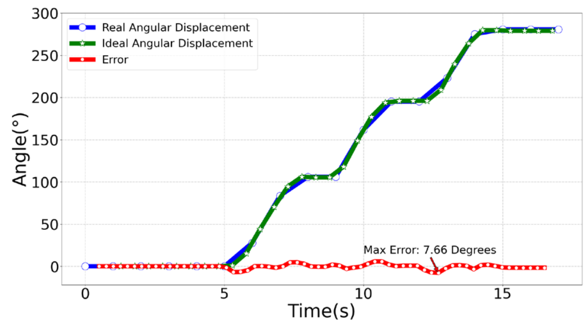

Fig. 9 Angular displacement accuracy evaluation experiment.

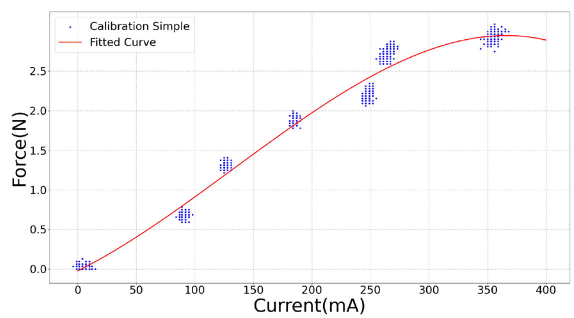

Fig. 10 Circumferential force calibration experiment.

TABLE II

THE STATISTICAL RESULT OF ERRORS OF ADM

Mean Error (°)	Variance Error (°)	Max Error (°)	Min Error (°)
1.64	4.19	7.66	0

IV. Conclusion and Discussion

In the past research of VISR, researchers usually focus on the slave manipulator and ignore the development of the master manipulator[14]. Many research teams use commercial manipulators as the master side, which increases the maintenance cost of the robot. While those self-designed master manipulators do have some problems, such as poor portability, no tactile feedback function and the mode of operation is not in line with ergonomics.

In order to solve the above problems, a novel master manipulator is designed in this paper. Compared with other manipulators, the size of this device is small, and the structure design of the cube makes it extremely portable. The design of the CFF provides tactile force feedback information for the operator, thus enhancing the sense of immersion in the operation. The operation mode of the master manipulator is consistent with the tradition VIS. Therefore, it can make better use of the doctor's surgical experience.

In order to verify the master manipulator designed in this paper, two accuracy calibration experiments were carried out. The linear displacement accuracy experiment showed that the proposed master manipulator had a good linear displacement recording function. Its maximum dynamic displacement error is 0.296mm, which meets the accuracy requirements of VIS. The angular displacement accuracy experiment showed that the proposed master manipulator had the function of recording angular displacement. Although the maximum dynamic displacement error of this unit is 7.66 degrees, the rotation operation only involves the selection of vascular branches during VIS, which doesn't pose a threat to the safety to the whole operation. Therefore, such errors are acceptable. In this paper, we adjust the output torque of a brushed DC motor by adjusting its input current, thus proving a circumferential force for operator. Therefore, a calibration experiment was carried out and the mathematical relationship between input current and output force was obtained. Circumferential force is an important part of tactile feedback, which can provide doctors with tactile perception to ensure the safety of the surgery.

However, it is worth noting that the master manipulator is only a prototype and still has some shortcomings. For example, although the proposed master manipulator can realize the function of circumferential force feedback, it still lacks axial force feedback unit. However, the axial force is an important component of tactile feedback and is decisive of for intraoperative avoidance of vascular puncture. Besides, the proposed master manipulator was not subjected to EVE model experiments, thus its performance in the vascular environment was not evaluated.

In the future, an axial force feedback unit will be added to the proposed master manipulator to improve the force feedback information. Moreover, starting with the idea of master-slave isomorphism, the slave manipulator will be designed according to the structure of the master manipulator. The feasibility and stability of the surgical robot will also be verified by later experiments.

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