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A Novel Clamping Mechanism Design for Vascular Interventional Surgery Robot

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***Abstract* - The application of vascular interventional surgery robots (VISR) can protect doctor from radiation effectively. However, the use of vascular interventional surgery robots (VISR) is still subject to some limitations. One of the limitations is that the inconsistency of the master-slave structure leads to the complexity of the entire robot structure. Another limitation is that the operation method of the master manipulator is different from the vascular interventional surgery, which makes it difficult for doctors to use their surgical experience. In this paper, a novel clamping mechanism was proposed. It can be used on both the master side and the slave side with the same structure and the operation methods on the master side is the same as that of traditional surgery. It means that the robot will have the consistency of master-slave structure by using the proposed clamping mechanism, which is advantageous for simplification of robot structure. In addition, a better surgical presence can also be provided to doctors during operation.**

Index Terms - Vascular intervention surgery robot, Clamping mechanism, Master manipulator, Slave manipulator.

I. INTRODUCTION

With the rapid economic development, the incidence of cardiovascular and cerebrovascular diseases is also increasing year by year. A report showed that the cardiovascular and cerebrovascular diseases was the leading cause of death in China and other countries [1,2]. In the past, surgeons solved these diseases through "open surgery", which had a lot of disadvantages such as low recovery rate, more complications and so on. With the development of medical technology, endovascular interventional procedure has become the most effective method for vascular diseases, since it has the characteristics of rapid recovery rate, smaller incisions, fewer complications compared with “open surgery”. However, because of the technology limited, surgeons have to operate in an X-radiation environment, which had a bad impact on surgeon’s health [3]. Besides, surgeons have to wear heavy lead coats for radiation protection, which are inconvenient for surgeons to operate.

Providing that the traditional endovascular interventional procedure has a few limits, some commercial companies and research teams have turned towards robot technologies to assist surgeons. Among the vascular interventional surgery robots developed by commercial companies, the Sensei X robotic catheter system (Hansen Medical, Inc., Mountain-View, CA, USA) used a remote navigation system (RNS) to help guide the catheter, which made the whole operation more effective and safer [4,5]. Another commercial remote catheter system is the Amigo TM remote catheter operating system (Catheter Robotics, Inc., NJ, USA). It can remove the catheter from the robotic arm and re-attach it to the robot during the whole operation without breaking sterility. Moreover, besides, the clinical trials show that the performance of this system is safe and effective [6].

Research teams around the world have also developed several devices to improve the development of vascular interventional surgery robots. In Kagawa University, a research team led by Professor Guo proposed a novel tactile sensing robot-assisted system which could not only deliver the guidewire and catheter to the target position accurately but also measure the collision between the catheter tip and vascular wall [7,8]. Besides, a method which could assist the deflection of the tip of the catheter was also proposed by their research team [9] In order to achieve system haptic force feedback as well as produce resistance for tremor reduction, several novel master manipulators which based on the characteristic of Magnetorheological fluids was designed, and the results showed that these robotic systems performed well [10]-[14]. In Beijing Institute of Technology, in order to realize non-contact measurement of displacement and improve the tracking accuracy, a novel master manipulator was proposed. Results showed that by using this device, the tracking error could be decreased effectively [15,16]. Besides, a study on remote surgery using cloud communication was conducted, which demonstrated the feasibility of remote intubation by using vascular interventional surgery robots[17].

When it comes to the clamping mechanism design, there are mainly two types. The first type of clamping mechanism is designed by simulating the twisting of human fingers to deliver/twist the catheter and guidewire. This kind of deign has been widely used. For example, references [18]-[20] designed their clamping mechanism by simulating the twisting of human fingers. This kind of clamping mechanism can rotate the catheter/guidewire easily but its transmission efficiency is low. Besides, the length of rail will limit the distance the catheter/guidewire can deliver and the rail will also increase the size of the whole device. Another type of clamping mechanism is designed by using rollers to control the catheter’s axial motion and the rotation of catheter/guidewire is achieved by the rotation of the whole device. This kind of clamping mechanism is used widely since it has the advantage of higher transmission efficiency, simple delivery form, not limited by the size of rails and so on. For example, references [21]-[23] all used the friction wheels to drive the catheter/guidewire inserting the blood vessel. However, compared with the first clamping mechanism, this kind of device is hard to achieve the rotation of catheter/guidewire.

According to the brief introduction of the clamping mechanism mentioned above, there are several problems in the clamping mechanism proposed by other papers.

First, the clamping mechanism mentioned above can be used on the slave side but few of them can be used on the master side which makes the whole system complicated.

Besides, the operation mode of most operating device used on the master side is different from the traditional vascular interventional surgery, which makes it impossible for surgeons to take advantage of their surgical experience during operation.

Therefore, it is necessary to design a new clamping mechanism which can not only be used on the slave side as well as on the master side but also can take full advantage of doctors' surgical experience. Besides, it also needs to have transmission efficiency. In this paper, a novel clamping mechanism is proposed. It uses rollers to control the catheter's axial motion and can be used on both the master side and the slave side. Besides, it can also take advantage of doctors' surgical experience during operation.

The structure of the paper is as follows. The workflow of the vascular interventional surgery robot and the clamping mechanism will be introduced in Sec. II. The calibration will be introduced in Sec. III. The experiment will be introduced in Sec. IV. The discussion will be given in Sec. V and the conclusions will be showed in Sec. VI.

II. Robotic System

A. *Introduction of The Workflow of the Robotic System*

The robotic system has mainly three parts: the master side, the slave side and the communication system. The workflow of the robotic system is shown in Fig. 1. The surgeon operates the catheter/guidewire at the master side and the catheter/guidewire is clamped in the clamping mechanism. The clamping mechanism will record the surgeon's movement information and send it to the communication system through the master controller. Then it will send the information to the slave controller. With the help of the slave controller, the clamping mechanism at the slave side will replicate the movement of the doctor, operating the catheter/guidewire to the target position in the patient's body. Besides, the slave controller can transfer the force of the catheter/guidewire at the slave side to the master side. The master controller will generate the haptic force to the surgeon during operation. Moreover, an IP camera is used to monitor the situation during operation and provide feedback to the surgeon in the form of images. With the help of force feedback and visual feedback, the safety of the operation will be ensured.

B. *The Structure of the Clamping Mechanism*

According to the classification of the clamping mechanism mentioned in Sec.I, the structure of the clamping mechanism we proposed is shown in Fig. 2. Fig. 2(a) shows the simulation structure diagram of the clamping mechanism while Fig. 2(b) shows the physical image of the clamping mechanism. As is shown in Fig. 2, two stepper motors (S43D114A-Mc010GN, Phase Hybrid Step Motor, SHINANO MOTOR, Japan) are used as drive units to deliver catheter/guidewire. In our proposed clamping mechanism, all the meshing gears have the same number of teeth, which means their gear ratio is 1. So their speed transmission ratio is 1 as well.

Fig. 3(a) shows the structure that drives the axial movement of the catheter/guidewire in the clamping mechanism. Stepper motor 1 is fixed on the spacer connected to the big cylinder. bevel gear 1 is fixed on stepper motor 1 output shaft so when the stepper motor rotates bevel gear 1 will rotate with stepper motor 1. Two rotating cylinders with the same structure are fixed in the big cylinder. With the help of bearings, they can rotate freely. A pair of spur gears are installed on the top of rotating cylinders. They connect with each other by meshing. A pair of rollers are installed in the middle of the rotating cylinders and the surface of the roller is attached with some soft glue. The soft glue which attached to the surface of the roller can not only increase the friction between roller and catheter/guidewire but also protect the catheter/guidewire from damage. Bevel gear 2 is installed on the front rotating cylinder. It is connected to the bevel gear 1 mentioned above by meshing. Fig. 3(b) shows the structure that drives the circumferential movement of the catheter in the clamping mechanism. Stepper motor 2 is fixed on the outer wall of the clamping mechanism while bevel gear 4 is fixed on stepper motor 2 output shaft just like bevel gear 1 fixes on stepper motor 1. Bevel gear 3 is installed on the big cylinder and is connected to the bevel gear 4 by meshing.

C. *The Principle of the Clamping Mechanism in The Slave Manipulator*

When it comes to the principle of the axial movement of the catheter, the frictional force generated by the mutual rotation of the rollers will be exploited to drive the linear displacement of the catheter/guidewire. As is shown in Fig. 4,

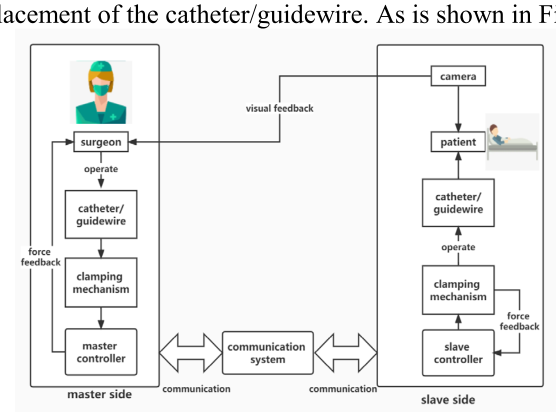
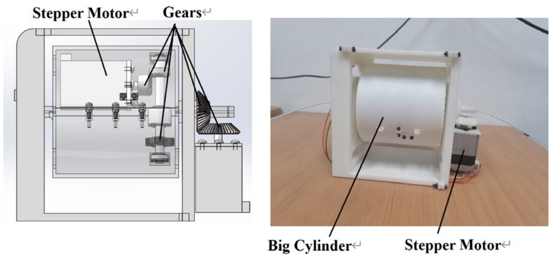
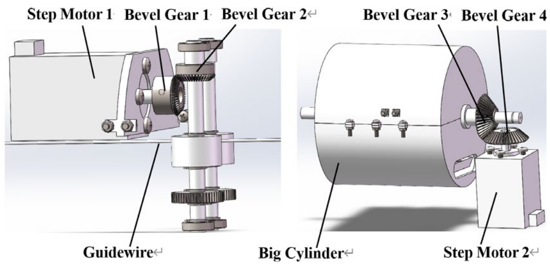


Fig. 1 The Workflow of the Robotic System



(a)Simulation Structure Diagram (b)Physical Image

Fig. 2 Clamping Mechanism



(a)The Axial Movement Structure (b) The Circumferential Movement Structure

Fig. 3 The Structure of the Clamping Mechanism

when stepper motor 1 rotates, bevel gear 1 will rotate with the stepper motor. Since bevel gear 2 meshes with bevel gear 1, so it will rotate together and drive the front rotating cylinder rotate too. With the assistance of spur gear 1 and spur gear 2 which is installed on the top of rotating cylinders respectively, both of the rotating cylinders will rotate. Because bevel gear 1 and bevel gear 2 have the same parameters, so both of the rotating cylinders will rotate at the same speed. The rotation of the rotating cylinders will drive the rotation of the rollers therefore it can realize the axial movement of the catheter.

As for the circumferential movement, the rotation of the cylindrical portion of the clamping mechanism will be exploited to drive the rotation of the catheter/guidewire. In Fig. 5, when stepper motor 2 rotates, bevel gear 4 will rotate with the stepper motor. As mentioned above, bevel gear 3 meshes with bevel gear 4. When bevel gear 4 rotates, it will drive bevel gear 3 rotate. Since bevel gear is fixed on the big cylinder, the big cylinder will rotate as well. The catheter is clamped to the central axis of the big cylinder. When the big cylinder rotates, the catheter will rotate with it. Therefore, it can realize the circumferential movement of the catheter.

D. The Principle of the Clamping Mechanism in The Master Manipulator

The clamping mechanism proposed in this paper can be used in the both slave manipulator and master manipulator which can not only simplify the whole vascular interventional surgery robot system but also makes the full use of doctor's experience.

When the clamping mechanism is used on the master side, the most important thing is to record the doctor's movement information and transmit these messages to the communication system so that the slave manipulator can replicate doctor's movement. Therefore, stepper motors which are used in the clamping mechanism will be replaced with encoders (E6C2-

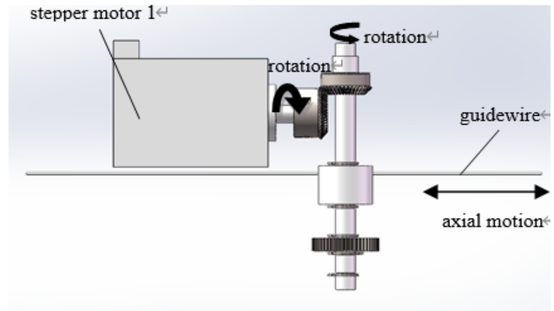


Fig. 4 The Principle of the Axial Movement

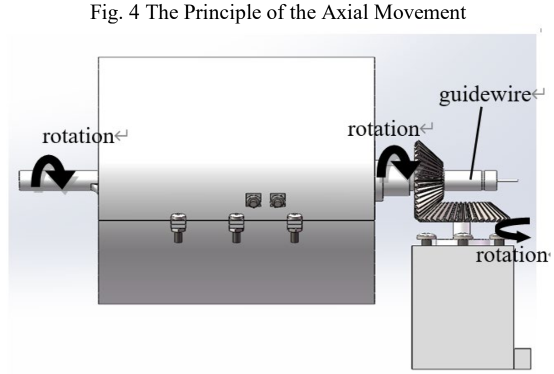


Fig. 5 The Principle of the Circumferential Movement

CWZ6C 1000P/R, OMRON, Japan) while other structures remain the same. When doctor performs surgery, the encoder replacing the stepper motor 1 will record the delivery information of the doctor's hand and the encoder replacing the stepper motor 2 will record the rotation information of the doctor's hand. Then the movement information will be transmitted to the communication system so that the slave manipulator can replicate the doctor's hand movement. By replacing stepper motors with encoders, the clamping mechanism proposed in this paper can be used in both the master manipulator and the slave manipulator, which can greatly simplify the structure of the vascular interventional surgery robotic system. It will also be easier to assemble the entire robotic system.

Besides, since the clamping mechanism is used in the master manipulator, doctors can directly manipulate the catheter and the guidewire in the master manipulator, which is the same as traditional vascular interventional surgery. So doctors can use their experience to manipulate the robotic system, which will not only make it easier for doctors to manipulate this robotic system but also make the operation safer.

III. Calibration of The Clamping Mechanism

In this section, a calibration experiment of the clamping mechanism will be conducted to verify whether the proposed clamping mechanism has good tracking performance, which is of vital importance for the safety of operation.

A. The Experimental Process of the Calibration Experiment

In the experiment, a guidewire is clamped in the clamping mechanism. A draw-wire displacement sensor is (OID-L, draw-wire displacement sensor, OID, China) employed to detect the displacement of the guidewire. The accuracy of the draw-wire displacement sensor is 0.05mm. Since the diameter of rollers in the proposed clamping mechanism is 25mm and it takes 6400 phases for stepper motors to make one revolution, so it is easy to draw the conclusion that when 6400 phases are input to stepper motors, the theoretical displacement value of the guidewire is 78.53mm. The measurement range of this experiment is from 0mm to 500mm. In order to eliminate the interference caused by accidental factors, we repeated the experiment for 5 times. Besides, in order to ensure rotation accuracy, an encoder (E6B2-CWZ6C, Increamental Optical-electrical Encoder, OMRON, Japan) is employed to detect the rotation angle of the catheter. The accuracy of the encoder is 0.18 degree/pulse. In the experiment the stepper motor rotated 360 degrees each time and the range of this experiment is from 0 degrees to 360 degrees. the experiment was also repeated for 5 times.

B. The Experimental Result of the Calibration Experiment

Experimental results are shown in Fig. 6, TAB I, Fig. 7 and TAB II. Fig. 6 is the error of the linear motion after the experiment was repeated 5 times while TAB I is the statistical result of errors after the experiment was repeated 5 times. As it was shown in Fig. 6 as well as TAB I, the maximum error of the linear motion is 2.090mm while the average error of the linear motion is 1.409mm. It is worth noting that most doctors will have linear errors greater than 2mm in the process of operating the catheter/guidewire. Since our linear motion's average error is smaller than 2mm, so the conclusion can be drawn that the accuracy of the linear motion can meet the precision requirements of operation.

Fig. 7 is the error of the rotation motion after the experiment was repeated 5 times while TAB II is the statistical result of errors after the experiment was repeated for 5 times. As shown in Fig. 7 and TAB II, the maximum error of the rotation motion is 0.450 degrees while the average error of the rotation motion is 0.270 degrees. Providing that the rotation motion is to adjust the direction of the catheter tip so that the catheter can be inserted into the correct branch of the blood vessel, so the error of the rotation motion only has a small influence on the whole operation. In that case, the conclusion can be drawn that the accuracy of the rotation motion can meet the precision requirements of operation.

Therefore, the experimental data presented above show that the proposed clamping mechanism has good tracking performance. It can meet the requirements of the surgery and deliver and rotate the catheter/guidewire precisely.

IV. Experiments and Assessments

In this section, an experiment is conducted to verify whether the proposed clamping mechanism can be manipulated remotely. Besides, a force sensor is also used to measure the force during catheter delivery and guidewire delivery to verify whether the proposed clamping mechanism can be used safely. The detail of the experiment is shown in Fig. 8.

A. The Experimental Process of the Experiment

As shown in Fig. 8, a catheter is fixed in the proposed clamping mechanism. A host computer is used to manipulate the proposed clamping mechanism for catheter delivery. A camera is used to provide visual feedback to the operator and an ATI force sensor is used to measure force between the catheter and the vessel wall to verify whether the proposed clamping mechanism can delivery catheter to the target position safely. Besides, during the experiment, the output pulse of the stepping motor in the clamping mechanism will also be transmitted to the host computer. Just as mentioned in section III, when 6400 phases are input to stepper motors, the linear displacement of the catheter is 78.53mm and the angular displacement of the catheter is 360 degrees. In that case, the catheter movement information during the experiment can be obtained. The trajectory of the catheter is shown in Fig. 9(a). Besides, the same experiment is also performed with the guidewire to verify whether guidewire can be delivered remotely by the proposed clamping mechanism. The trajectory of the guidewire is shown in Fig. 9(b).

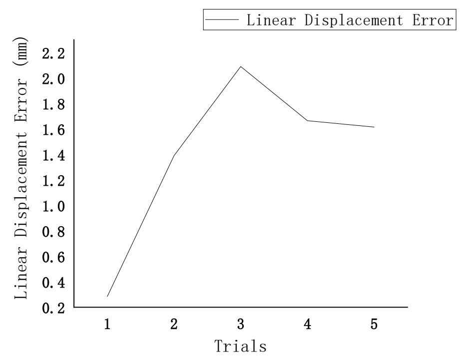


Fig. 6 The Error of Linear Motion

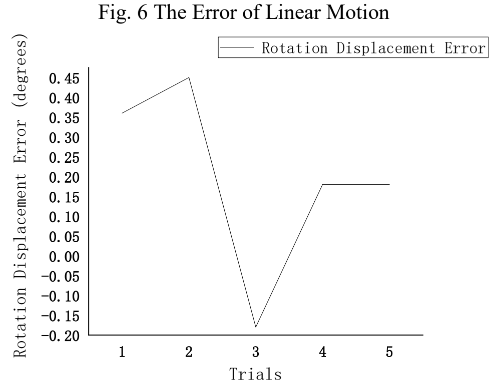


Fig. 7 The Error of Rotation Motion

TABLE I
THE STATISTICAL RESULTS OF ERRORS IN THE LINEAR MOTION

Average(mm)	1.409
Maximum(mm)	2.090
Minimum(mm)	0.285
Variance(mm)	0.459

TABLE II
THE STATISTICAL RESULTS OF ERRORS IN THE ROTATION MOTION

Average(degrees)	0.270
Maximum(degrees)	0.450
Minimum(degrees)	0.180
Variance(degrees)	0.058

B. *The Experimental Result of the Experiment*

Experimental results are shown in Fig. 10, Fig. 11 and Fig. 12(a), Fig 12(b). Fig. 10 is a double Y figure of the displacement of the catheter, where the red line represents the linear displacement of the catheter and the black line represents the rotation displacement of the catheter. The part of the red/black line with a slope of 0 in Fig. 10 represents that the catheter didn't move linearly or rotate at that time. While the part with a slope not equal to 0 means that the catheter moved linearly or rotated at a constant speed at that time.

Similar to the result in Fig. 10, Fig. 11 is a double Y figure of the displacement of the guidewire, where the red line represents the linear displacement of the guidewire and the black line represents the rotation displacement of the guidewire. The part of the red/black line with a slope of 0 in Fig. 11 represents that the guidewire didn't move linearly or rotate at that time. While the part with a slope not equal to 0 means that the guidewire moved linearly or rotated at a constant speed at that time.

Fig. 12(a) is a scatter plot of the force between the catheter and the vascular wall. Fig. 12(b) is a scatter plot of the force between the guidewire and the vascular wall. As it is shown in Fig. 12(a), discard discrete points that deviate too much due to accidental factors, the force of the catheter is less than 0.2N during the experiment. Considering the hydrophobicity of the PCI board material and the effect of the lack of bodily fluid within the PCI board on catheter delivery, the actual force between the catheter and the vessel wall during surgery is less than the current experimental value. Therefore, the conclusion can be drawn that the proposed clamping mechanism can deliver the catheter to the target position remotely and safely. As shown in Fig. 12(b), during 0-100 seconds, the force between the guidewire and the vessel wall is less than 0.1N while after 100 seconds, the force between the guidewire and the vessel wall begins to increase gradually. The reason why the force increases was that the guidewire inserted the branch of the blood vessel at that time. Therefore, the force increased. But the force still less than 0.2N during the experiment. The conclusion can be drawn that the proposed clamping mechanism can delivery guidewire/catheter to the target position remotely and safely.

V. Discussion

As shown above, the proposed clamping mechanism has the following advantages compared to other clamping mechanism.

First, compared with those clamping mechanism which simulate the twisting of human fingers, the clamping mechanism which proposed in this paper uses rollers to control the catheter's axial motion. Therefore, it has the advantage of higher transmission efficiency.

Second, most clamping mechanism can only be used on the slave side while the proposed clamping mechanism can be used on both the master side and the slave side, which can significantly simplify the structure of the vascular interventional surgery robot and simplify the assembly of the robot.

Besides, it can also take advantage of doctors' experience during operation. Since the clamping mechanism proposed in this paper operates in the same way as the endovascular interventional procedure.

VI. Conclusion

In this paper, a novel clamping mechanism for vascular interventional surgery was developed. Compared with other clamping mechanism, this clamping mechanism can not only be used on the master side but also on the slave side, which significantly simplify the structure of the vascular interventional surgery robot and simplify the assembly of the robot. Besides, it also conforms to the operating habits of doctors so doctors can take advantage of their experience during operation. Calibration experiment shows that the clamping mechanism has good tracking performance. It can deliver catheter and guidewire precisely. While section IV's experiment shows that the novel clamping mechanism can delivery guidewire/catheter to the target position remotely and safely.

It is worth noting that the clamping mechanism proposed in this paper is just a preliminary prototype machine. In the future, PID control algorithm and other control algorithms will be introduced in this novel proposed clamping device. Besides, several deep learning methods will also be incorporated into the clamping mechanism's control algorithm. In that case, the error of the rotation motion and the linear motion which proposed in Sec. IV will be definitely improved a lot and it can better meet the clinical precision needs.

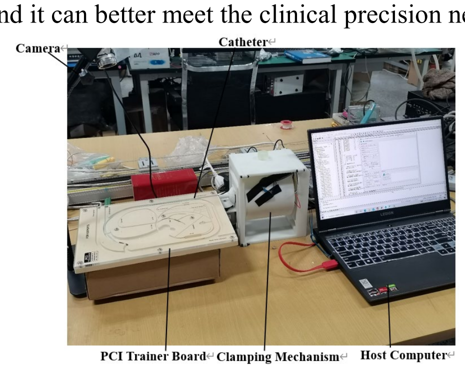
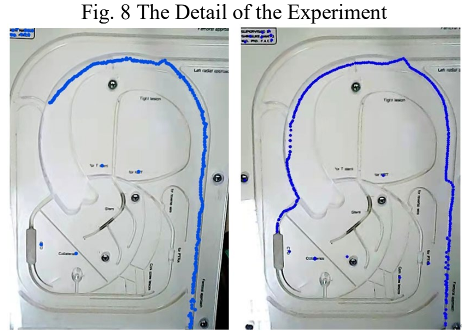


Fig. 8 The Detail of the Experiment



(a)The Trajectory of The Catheter (b) The Trajectory of The Guidewire

Fig. 9 The Trajectory of the Catheter/Guidewire

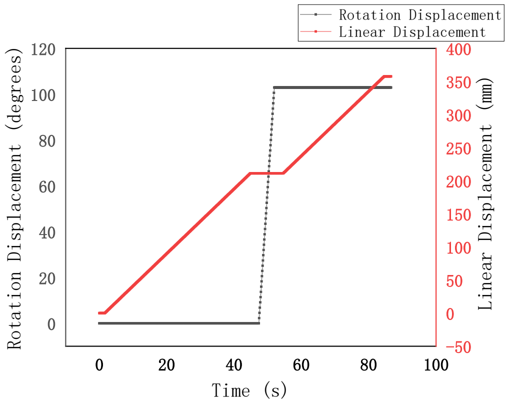


Fig. 10 Displacement of The Catheter

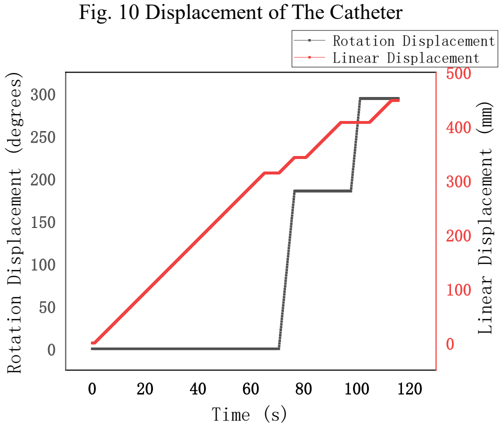
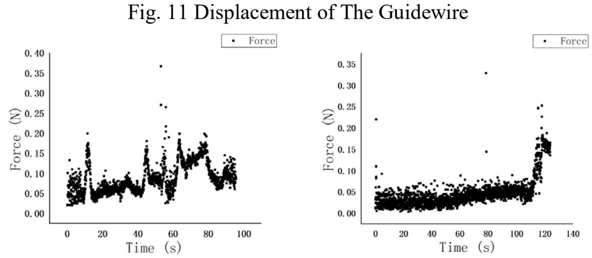


Fig. 11 Displacement of The Guidewire



(a) Force image of The Catheter (b) Force Image of The Guidewire

Fig. 12 Force Image of the Catheter/Guidewire

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