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Development of a Grasper for Vascular Interventional Surgery Robotic System

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***Abstract* – In recent years, Vascular interventional surgery robotic system has become a research hotspot of many research teams because of its characteristics of minimal trauma, less blood loss and rapid recovery. However, due to its own limitations, most of the vascular interventional surgery robotic systems are still in the laboratory stage. It is a difficult problem to develop a vascular interventional surgery robotic system that can simulate doctors' hand. So, from the perspective of doctors' clinical operation, this paper proposed a new grasper for vascular interventional surgery robotic system. The grasper can simulate the opening and closing of doctors' thumb and index finger. In addition, the part where the grasper contacts the surgical catheter are filled with rubber. The purpose of this is to increase the friction between the grasper and the surgical catheter to prevent slipping during the operation. Finally. ANSYS software was used to simulate the feasibility of the proposed grasper. Simulation results showed that the grasper can not only prevent the surgical catheter from being damage, but also operate the surgical catheter effectively.**

Index Terms - Vascular interventional surgery robotic system. Grasper. Thumb and index finger. Rubber.

I. INTRODUCTION

Nowadays, the increasingly mature vascular interventional surgery has saved more and more patients with cardiovascular and cerebrovascular diseases. Vascular interventional surgery is a very complicated operation, which requires a doctor with rich clinical experience to directly operate the surgical catheter and guidewire under the guidance of medical imaging, transmit them to the lesion location, and carry out a series of treatment Vascular interventional surgery is a new medical technology Traditional vascular intervention procedure needs a doctor to directly operate a medical surgical catheter on patients' side which has the advantages of minimal trauma, rapid recovery and less blood loss. However, because it needs the doctor to be exposed to X-ray for a long time, which will affect the doctor's health. So. In order to prevent X-ray from harming the doctor, development of a vascular interventional surgery robot system is becoming more and more important. A complete vascular interventional surgery robotic system can replace the doctor to complete the surgery, which can not only avoid x-ray damage to the doctor, but also improve the efficiency of surgery and ensure the safety of surgery.

In recent years, there are 3 research teams led by professor Guo. The research team in Kagawa University developed the Master-slave Vascular Interventional Surgery Robotic System based on Magnetorheological Fluid to achieve force feedback [1][2], a slave manipulator of the robotic system with collision protection mechanism based on electromagnetic induction was developed by Linshuai Zhang, et al [3][4]. In addition, A novel contactless catheter-sensing method was proposed by Jin Guo et al [5][6], which can measure the surgical catheter motion by detecting a passive marker with four feature-point groups. The research team in Beijing Institute of Technology, a cooperation of the catheters and guidewires remote-controlled robotic system was designed by Xianqiang Bao et al [7]. Besides, they also proposed combining compensation force with multimodal force feedback to improve the accuracy of the force feedback [8]. Besides, a method that applies transverse microvibrations at the proximal end of a guidewire to reduce viscous resistance was presented by Chaonan Zhang, et al [9]. The research team in Tianjin University of Technology. A vascular interventional surgery robotic system based on the principle of electromagnetic force generation to realize force feedback was designed by Jian Guo, et al [10][11], the method was proved to be effective through the experiments “In vitro”.

Other research groups have also made some achievements. University of Chinese Academy of Sciences, Olatunji Mumini Omisore, et al, developed a novel robotic system [12]. In order to reduce the tracking error between the master and slave side, they also designed an adaptive neuro-fuzzy inference system to predict possible backlash gap based on bounded input-output signals. Experimental results showed that the proposed system can aid smooth motion of the surgical catheter with minimized backlash. Then. University of Hong Kong, Kit-Hang Lee et al, they introduced a Magnetic Resonance Imaging (MRI)-guided catheter robotic system [13]. The robotic system will increase confidence to perform Radio Frequency (RF) ablation Besides, it can improve the safety of catheter navigation. In the master and slave manipulator, the hydraulic transmission fluid was designed to reduce the hysteresis. Finally. Department of Mechanical Engineering, Worcester Polytechnic Institute, Hao Su et al, they presented the fully-actuated robotic system for MRI-guided prostate interventions adopting piezoelectric actuation [14].

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At present, there are some mature vascular interventional surgery robotic systems have been applied in clinical surgery and assisted doctors to complete multiple operations. Magellan Medical Vascular Catheter Control System (VCCS) [15]. The VCCS was feasible to be used for intervention surgery without apparent increased risk to the patient was reported in reference [16]. VCCS has the features of operator ergonomic comfort radiation reduction to operator, navigating tortuous anatomy reduced vessel trauma and greater catheter positional control However, according to Dr. Rao spoke analysis, this system still has room for improvement. Sensei X™ Robotic Navigation System (RNS) has been developed by Hansen Medical. This system has been validated for contact force sensing expressed in grams. In order to verify the effectiveness of Sensei X™ RNS. Antonio Dello Russo et al, studied the catheter contact force with and without RNS during Pulmonary Vein Isolation procedures [17]. CorPath 200 robotic system. To evaluate the safety, clinical, technical performance of CorPath 200 robotic system, Giora Weisz et al, used CorPath 200 robotic system conducted the coronary intervention surgery [18]. patients with clinical indications for percutaneous intervention and coronary artery disease were enrolled. Results showed that the CorPath 200 robotic system without affecting procedural performance and patient safety. The first-generation CorPath 200 robotic-assisted system for Percutaneous Coronary Intervention (PCI) is effective, but it is limited by the lack of an active robotic guide-catheter control. The second-generation robotic-assisted system CorPath GRX for Percutaneous Coronary Intervention has been developed in 2018 [19]. Amigo™ has been designed by Catheter Robotics, Inc. This system is simple and relatively inexpensive [20], Ejaz M. Khan et al. has been verified that Amigo™ could be used to position catheters throughout the right side of the heart by the trial.

In this paper, A novel slave manipulator of the vascular interventional surgery robotic system is designed. To simulate the opening and closing of the doctor's thumb and index finger, we proposed a grasper for the vascular interventional surgery robotic system. The main structure of this paper as follows: Part I is introduction. Part II is vascular interventional surgery robotic system. Part III is design of a grasper for novel slave manipulator. Part IV is simulation and analysis of the grasper. Part V is conclusions and future work.

II. Vascular Interventional Surgery Robotic System

A. *Overview of the Robotic System*

A complete vascular interventional surgery robotic system mainly includes three parts: the master manipulator, the slave manipulator and the computer console. the master manipulator located on the proximal is not only used to collect the motion information of the input catheter, but also to generate feedback force. Our research team implements force feedback based on magnetorheological fluid [1][2][21][22]. A slave manipulator is located on the distal, instead of clinical doctors to complete the intervention surgery. As the same time, it can also detect the movement and force information of the surgical catheter in real time. And then feed it back to the proximal. the computer console is used to realize information exchange between the proximal site and the distal site.

B. *Master Manipulator*

Fig.1 shows the prototype of the master manipulator of the vascular interventional surgery robotic system was designed by the doctoral candidate of our research team. They adopted the photoelectric encoder to record linear and rotation movement information of the input catheter, and realized haptic feedback based on Magnetorheological Fluid (MRF). MRF is an active branch of intelligent materials. Magnetorheological fluid is a suspension composed of small soft magnetic particles with high permeability and low hysteresis and non-magnetic liquid. The purpose of developing the master manipulator is to control the slave manipulator remotely and prevent the harm of X-ray to surgeons. It has been proved to be feasible and has good force feedback performance by experiments "In vitro".

C. *Slave Manipulator*

Vascular interventional surgery needs the surgical catheter and guidewire to be delivered to the lesion site by the slave manipulator, therefore, the basic design idea of the novel slave manipulator is shown in Fig.2, which has three parts (motion driven unit, grasper unit and force detection unit). The motion driven unit is used to drive the forward, backward and rotary motion of the surgical catheter or guidewire. At the same time. The position information of the surgical catheter or guidewire will be fed back to the master side by the position sensor.

The function of the force detection unit is to detect the force information of the surgical catheter or guide wire in real time and feed it back to the master side. Finally. The grasper unit is designed to simulate the surgeon's thumb and index finger clamping or releasing the surgical catheter or guidewire. The design of the grasper is particularly important. Firstly, it cannot damage the surgical catheter or guidewire. Secondly, it must to effectively clamping the surgical catheter or guidewire. So, the part where the grasper contacts the surgical catheter or guidewire are filled with rubber. The purpose is to increase the friction between the novel grasper and the surgical catheter or guidewire, preventing it from slipping and being damaged by the grasper during surgery.

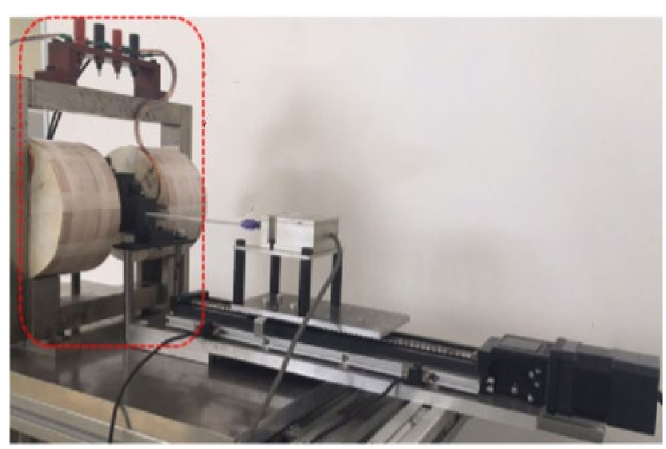

Fig. 1 The prototype of the master manipulator [21].

As shown in Fig.3, it is the whole structure of the novel slave manipulator. The linear motion and rotation motion of the surgical catheter and guidewire are transmitted through the synchronous belt. the synchronous belt has the characteristics of accurate transmission ratio, high transmission efficiency and large transmission ratio and compact structure. In addition, the surgical catheter driven unit and the guidewire driven unit are compact and easy to assemble. The axial force information of the surgical catheter or guidewire is measured by a load cell, and the radial force information of the surgical catheter or guidewire is measured by a torque sensor.

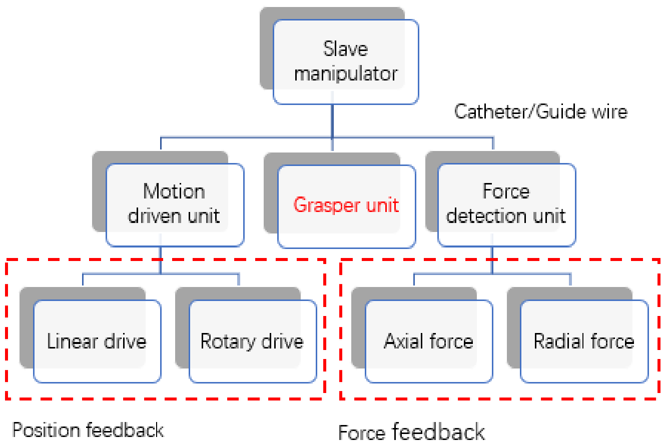

Fig. 2 The basic design idea of the novel slave manipulator.

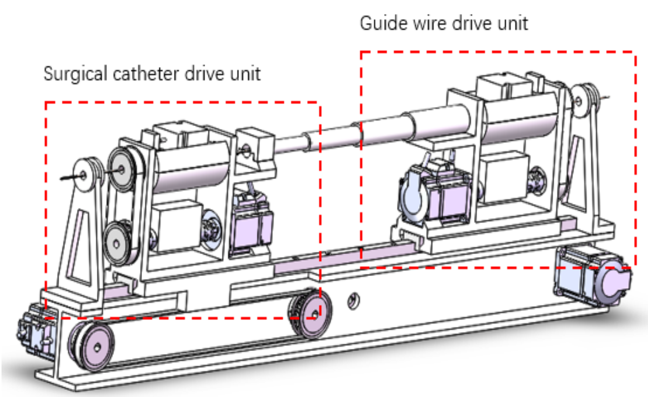

Fig. 3 The whole structure of the novel slave manipulator.

III. Design of a Grasper for Novel Slave Manipulator

A. Analysis of Traditional Vascular Interventional Surgery

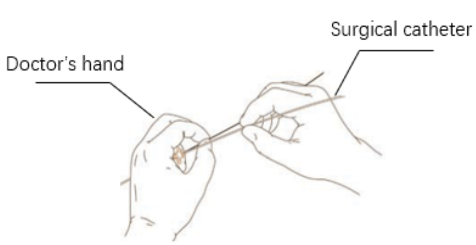

Fig. 4 The doctor operates the surgical catheter [23].

In traditional vascular interventional surgery, the surgeon delivers the surgical catheter to the lesion location by pushing, pulling and rotating the surgical catheter on the patient's side according to their own clinical experience. As shown in Fig.4 [23], The surgeon uses the thumb and index finger to grasp the surgical catheter and perform the operation. However, vascular interventional surgery is a complicated operation technique, which requires doctors to be exposed to X-ray for a long time. To protect doctors from the X-ray injuries, we developed the vascular interventional surgery robotic system for surgery. A complete vascular interventional surgery robotic system should have a master manipulator, a slave manipulator the computer console. The slave manipulator replaces the surgeon complete the operation on the patient's side, and the grasper of the slave manipulator, just like the doctor's hand, grasps the surgical catheter and realizes the push, pull and rotation of the surgical catheter. Then, how to develop a grasper to simulate doctor's thumb and index finger becomes crucial.

B. The Principle of the Grasper

As shown in Fig.5, the clamping principle of the grasper for the novel slave manipulator. The spring is used to provide the grasping force of the slider (Simulation of the thumb) and the slider (Simulation of the index finger), Among them, slider (Simulation of the thumb) simulates the surgeon's thumb and slider (Simulation of the index finger) simulates the surgeon's index finger. To increase the friction between the grasper and the surgical catheter, and prevent the grasper from damaging the surgical catheter due to excessive grasping force, the parts where the grasper contacts the surgical catheter are filled with rubber.

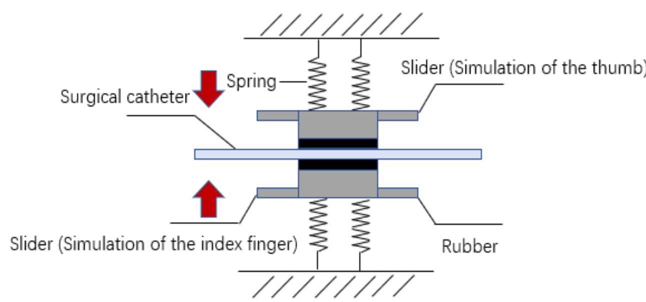

Fig. 5 The clamping principle of the grasper for the novel slave manipulator.

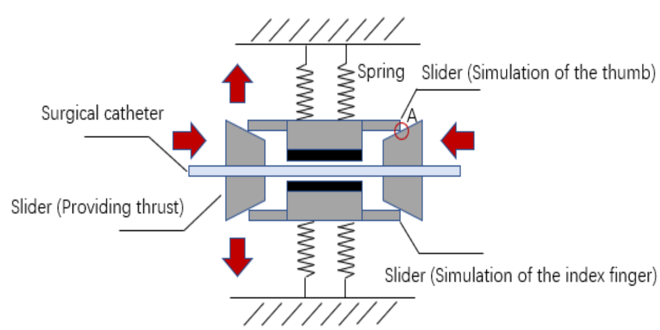

Fig. 6 The releasing principle of the grasper for the novel slave manipulator.

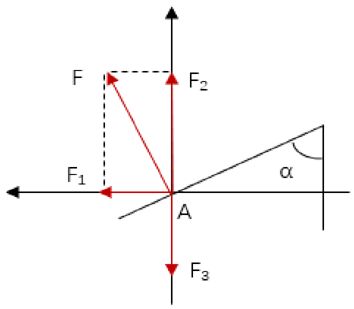

Fig. 7 The diagram of force analysis of point A in Fig.6

As shown in Fig.6, the releasing principle of the grasper for novel slave manipulator. Two hollow shaft stepping motors are used to provide thrust to the slider (Providing thrust), and then slider (Providing thrust) pushes the slider (Simulation of the thumb) and the slider (Simulation of the index finger) to complete the release of the surgical catheter, the force analysis of point A in Fig.6 is shown in Fig.7.

As shown in Fig.7, F_1 represents the thrust provided by the stepping motor, according to the angle relation between F_1 and F_2, the following formula can be obtained:

$$F_2 = \frac{F_1}{\tan(90^{\circ} - \alpha)} \tag{1}$$

F_3 represents the elastic force generated by the spring. According to Hooke's Law, F_3=KX can be obtained. K is the coefficient of the spring. X is the amount of compression of the spring. Since F_2 is greater than F_3, the slider (Simulation of the thumb) and the slider (Simulation of the index finger) will be separated to complete the release of the surgical catheter.

C. The Structure of the Grasper

The structure of the grasper is shown in Fig.8, which is mainly composed of two stepping motors, two sliders (Provide thrust), the slider (Simulation of the thumb) and the slider (Simulation of the index finger).

IV. Simulation Analysis of the Grasper

The ANSYS software is used to complete the simulation analysis of the grasper. Firstly, we need to set the material of the grasper. The surgery catheter was set as nylon, two sliders

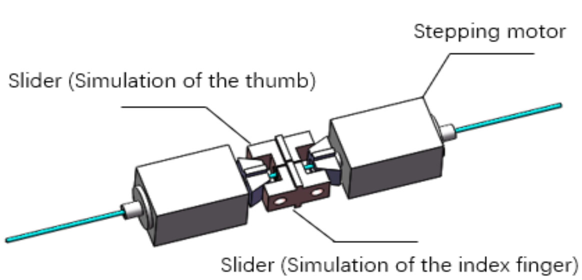

Fig. 8 The structure of the grasper.

(Provide thrust), the slider (Simulation of the thumb) and the slider (Simulation of the index finger) were set as ABS, the parts where the grasper contacts the surgical catheter was set as rubber. Secondly, we need to set simulation conditions. Relative displacements of the slider (Simulation of the thumb) and the slider (Simulation of the index finger) are 0.15mm, at the same time, two sliders (Providing thrust) also move 1.5mm in opposite directions. When the grasper is in a completely closed state, the simulation results are shown in Fig.9.

Fig. 9 shows the total deformation of the grasper and the surgical catheter, the part where the grasper in contact with the surgical catheter was slightly deformed. It's negligible.

Fig.10 shows the strain of the grasper and the surgical catheter. the greatest strain of the surgical catheter is where the grasper contacts the surgical catheter. However, the surgical catheter has a strong hardness, therefore, the grasper will not damage the surgical catheter.

Fig.11 shows the stress of the grasper and the surgical catheter. the greatest stress of the surgery catheter is where the grasper contacts the surgical catheter, which not to damage the surgery catheter. Under the action of rubbers, the friction between the grasper and the surgical catheter can be increased to prevent slipping.

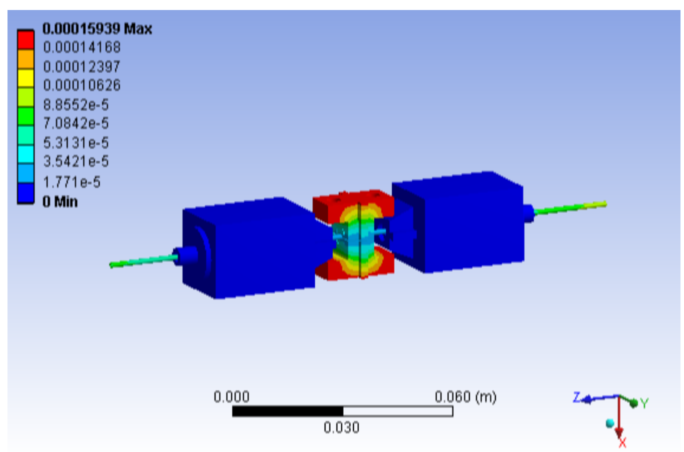

Fig.9 The total deformation between the grasper and the surgical catheter.

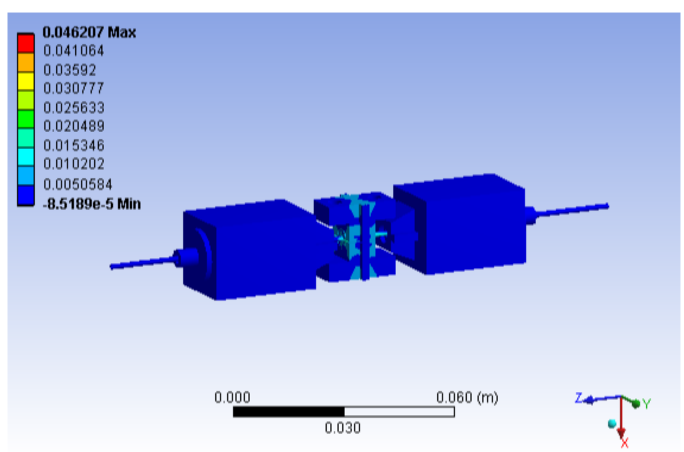

Fig.10 The strain between the grasper and the surgical catheter.

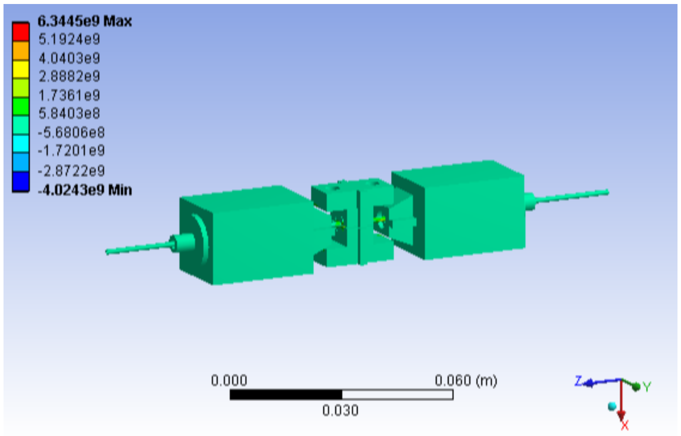

Fig.11 The stress between the grasper and the surgical catheter.

V. Conclusions and Future Work

Vascular interventional surgery is a complicated operation and the development of vascular interventional surgery robotic system has become a research hot topic due to its advantages. In this paper, a novel slave manipulator is introduced. we also developed a grasper for the slave manipulator. The grasper can simulate doctors' thumb and index finger from the perspective of doctors' clinical surgery. the part where the grasper contacts the surgical catheter are filled with rubber. The purpose of this is to increase the friction between the grasper and the surgical catheter and to prevent slipping during the vascular surgery. In addition, the working principle of the grasper is analyzed in detail. Finally. The simulation experiment of the grasper is completed by ANSYS simulation software. Simulation results showed that the proposed grasper is effective.

The future work of this article is to finish the verification experiment of the grasper of the novel slave manipulator and the evaluation experiment of the novel slave manipulator.

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