Abstract - In minimally invasive neurosurgical field, specialized education and surgical training for physicians are urgent demanded, at the same time, development and improvement of the field medical equipment are very essential. Vascular Interventional Surgery (VIS) is expected to become increasingly popular in medical practice, both for diagnosis and for surgery. However, there are some problems. For example, doctor's hands and faces are exposed to X-rays during an operation. To solve these problems, researches of robotic systems for minimally invasive surgery assistant have been carried out widely. The purpose of this paper is to develop force measurement device for a teleoperative catheter operating system. Some experiments based on the designed device have been done. The results illustrate that the designed device is good for training the surgeon.

Index Terms - Vascular Interventional Surgery, Mater-slave system, Force measurement device, Frictional force and resistance.

I. INTRODUCTION

The worlds has become an aging society. Therefore, social demands are very high to develop advanced medical support, rehabilitation and life support systems. In minimally invasive neurosurgical field, highly specialized education and training for physicians are urgent demanded, at the same time, development and improvement of the art medical equipment are very becoming essential. In recent years, there are more and more people who choose minimally invasive surgery because of the high rate of procedural success and other various advantages. The advantages are the short duration of hospitalization and asmall operative scar when compared with the conventional method. Use of X-rays is mentioned as one of the problems of the existing low invasion medical treatment. X-rays are used to acquire the position information on the catheter inside apatient's body. During operations, in order to reduce the exposure X-rays, doctors wear protecting suits, but it is very difficult to protect doctors' hands and face from the radiation of the X-ray.[1]-[5]. A patient's body, doctor's hands and face are exposed to X-rays during an operation. A patient’s exposure can be managed minimized, but since doctors must perform many operations, doctors are anxious about cumulative exposure. In addition, there are dangers of mingling or breaking the blood vessels. In order to solve the problem, the communication technique using the Internet is used and the remote catheter system which can under go an operation distantly is proposed. Robotic system have many advantages, like higher precision and can be controlled remotely, etc. However, compared with the hands of human beings, none of the current robotic system can satisfy all of the requirements of a minimally invasive surgery[6][7]. Not only because the machine is not as flexible as human hands, but also lacks the sense of touch.

Therefore the resistance force felt by the surgeon is very important during the catheter minimally invasive neurosurgical operation. Indeed, when the physician use remotely catheter surgical system, in order to ensure the safety of the surgery, the force applied to the catheter is very important data for operation of the whole. Therefore, in order to retain the flexibility of a conventional device, it is urgent to design a device which can improve the accuracy force measurement during the catheter intervention neurosurgery. Prior work of catheter robotic research has been done in our Lab. for several years[8][9]. The robotic catheter master-slave system had been designed and evaluated. However, the force measurement accuracy is need to improve. So, in this paper, a new device for force measurement has been proposed, the measure force can be used to establish a data base providing to the surgeon training system and as the first data to the education of surgical student.

The robotic catheter operating system in the slave side was designed by our prior research group as shown in Fig.1. In this device, the measurement principle is very good for this kind of minimally insertion force measurement. But, as for design, there still have two little problems should be improved. First, measurement noise affected the accuracy of the measurement results is caused by the method of load cell connected with clamping structure[10][11]. Secondly, the gravity of the clamping structure will influence the force measurement during the catheter insertion and rotation actuated by the stepping motor. Therefore, The objective of this paper is improve the force measurement device design based on the original structure. The measurement force in the slave manipulator was feedback to the master robotic system[12]. On one side, from the robotic master-slave system consideration, the measured force was transmitted to master can realize a safety operating for surgeon operated in the master side. On the other side, the force measurement in the slave manipulator can be used to establish data bases for catheter operation simulation. Since surgical simulation is a major technology in today surgical training[13]. However, the surgical simulation established on the force measurement in surgical practice and measurement. So, the new force measurement device with...
high accuracy is urgent to robotic catheter intervention minimally neurosurgical surgery[14].

The remainder of this paper is organized as follows: the new force measurement device structure design is introduced in section II. Experimental measurement principle and experimental method illustrated in section III. In section IV, experimental results and discussion will be described. Finally, the conclusions and future work in section V.

II. FORCE MEASUREMENT STRUCTURE DESIGN

In generally, a teleoperation surgical system as shown in Fig.1 consists of master system (console) and slave manipulator system (executing), in which the slave manipulator tracks the motion of the master device that is commanded by the surgeon and in which the measured force fed back to the master device form the slave manipulator [15] [16] [17].

The prior force measurement device attached on the slave catheter robotic manipulator is shown in Fig. 2. This designed idea of this structure is imitated the surgeon’s action which operate in the catheter minimally invasive surgery practice. The surgeon operated the catheter insertion into the blood vessel system. One freedom of operation is insertion motion, when catheter tip entered into the branch of the blood system, another mechanical freedom in need for catheter practice is rotation catheter to advance in the small blood vessel. So the robotic catheter slave operation system was established to instead surgeon operating the catheter besides the patient and protect the surgeon from X-ray radiation, which has two degrees of freedom. During catheter operating practice, the force felt by the operator is significant important to ensure the safety of the minimally invasive neurosurgery. Since the force is very small to usually measurement, which comprised by the friction force between the catheter surface with the blood and the catheter tip contact force with blood vessel wall. Therefore, the force measurement is a challenging objective in catheter operation practice. The fabricated force measurement device is shown in Fig.3.

The robotic catheter operating system is comprised of several parts illustrated in Fig.1. Stepping motor catheter insertion structure, catheter rotation structure, catheter guide, catheter clamping structure and force measurement sensor-load cell. The fabricated robotic catheter operating system is shown in Fig.2. Since of the catheter clamping structure connected with the load cell was placed on the lean station. The gravity will influence the force measurement accuracy. The force measurement principle analysis of the robotic catheter operating system is shown in Fig.3. According to the Newton’s second law, the measured force by the load cell can be expressed by the Equation 1. as follows:

\[ f_r - f_{cg} \sin \theta - f_m = ma \]  

where \( f_r \) represents the resistance force of catheter insertion practice, \( f_{cg} \) represents the gravity of the catheter clamping structure, \( f_m \) is the force measured by the load cell, \( m \) and \( a \) are the mass of the catheter operating structure with the catheter and acceleration of the whole system, respectively. In this force measurement system the acceleration can be neglected. So the Equation can be changed as follows:

\[ f_m = f_r - f_{cg} \sin \theta \]  

Based on above analysis, the gravity of the catheter clamping structure will influence of the force measurement.

![Fig.1 The master-slave system [14]](image1)

**A. The existing problem in the prior research**

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![Fig.2 The designed slave robotic catheter operation system[1]](image2)

![Fig.3 The fabricated force measurement device in the slave robotic catheter operating system [1]](image3)
B. The designed new device

This paper provides a new design for the force measurement in the catheter operating practice. The new device mainly consists of pressure sensor and stepping motor. The pressure sensor was attached on the under bracket. Catheter was placed between the pressure sensor and the motor stroke. Catheter guider was used to maintain the relative position of the catheter and guide catheter in a line direction insertion. The motor stroke can go down when the motor moves in clock direction and rise up in anticollock direction. The stroke distance can be controlled by the stepping motor control. The different force can be measured by control the motor stroke in Z direction motion.

III. FORCE MEASUREMENT PRINCIPLE AND METHOD

The designed new catheter force measurement device is not only used for catheter insertion force measurement, but also can be used to clamp the catheter. When the catheter insertion into blood vessel system. The resistance force is caused when catheter tip contact the blood vessel wall. The force will be changed during the catheter insertion process. The catheter will slide along x direction on condition that the same motor stroke in z direction, when the insertion resistance is become bigger during catheter insertion or rotation operation. In order to good clamping of the catheter, the motor stroke goes down with the increasing resistance force acted on the catheter. That is to say, fine catheter clamping is dependent on the prise control of motor stroke. The maximum static friction theory was used in this force measurement device. The principle of force measurement is shown in Fig.6.

During this force measurement device, the coefficient of the friction between the pressure sensor as shown in Fig.7, which is described by \( \mu \), maintains the same during the catheter insertion operation. In order to avoid the catheter slide, the force N acted on the catheter should be changed with the \( f_{\text{resistance}} \). According to Newton’s laws, the relationship of the force can be expressed as follows:

\[
f_{\text{max}} = \mu \cdot N
\]  

where \( f_{\text{max}} \) can be calibrated with the Equation (3). The pressure force N can be measured the force sensor placed between the catheter and fixed bracket. And the pressure
force F is also be controlled by control the stroke of the stepping motor.

The force measurement method is described as follows:

The most important of this catheter operation force measurement device is made the catheter maintain in static state of either insertion or rotation motion. The force acted on the catheter comprised by the friction force can tip contacted force, is the calibration through Equation (3), which is the maximum friction between the catheter and the pressure sensor.

### III. EXPERIMENTS AND RESULTS

Experimental setup is illustrated in Fig. 8. The catheter was inserted into the EVE vessel system model. The motor stroke distance is controlled through controlling the stepping motor. The motor moves in clock direction, the stroke forward to increase the force. Therefore, the maximum friction was increasing with the increasing changed catheter insertion force.

To verify the relationship between the force and the voltage obtained through Equation (4), the actual force during the catheter insertion experiment was measured. Here, we want to use curve fitting to evaluate the approximation relation between the voltage and force.

The comparison between the estimated force and the measured force is shown in Fig. 10. The blue line describes the force measured by the load cell, since the minimum sensitivity of the pressure sensor is 0.36 N. Therefore, the force below 0.36 N cannot be measured and estimated through the Equation (4). Except this situation. The force can be estimated through Equation (4).

The relationship between the force and pressure sensor volatage

When the pressure force changed, the output of the voltage of pressured sensor will be changed. So the first experiment was done, the relationship between the force and the voltage is shown in Fig. 9.

Based on the abstracted part from the Fig. 9, the relationship between the force and voltage can be expressed through the following equation:

\[ F = p_0 + p_1V + p_2V^2 + p_3V^3 \]  \( (4) \)

where the parameters of \( p_0, p_1, p_2, p_3 \) are 1.91, -5.789, 7.798, -0.986 respectively, according to the fitting curve about 99.68%.
Experiments 2: Static friction coefficient of the designed device measurement experiments

According to Fig.5, the catheter will contact the with the catheter guider, the tip of motor stroke and the pressure sensor surface. However, the friction between the catheter surface and catheter guider can be neglected, since it is too small. Therefore the main friction force caused by the motor stroke and the pressure sensor. So the friction can be expressed by the Equation (3). In order to calibrate the resistance force $f_{max}$, the friction coefficient is need to be measured. The friction coefficient experimental results is shown in Fig.11. Ten times experiments have been down to measure the static friction coefficient. The average friction coefficient of contact part is equal 0.935. This value can be used in Equation (3) as $\mu$.

![Fig. 11 The static friction coefficient experimental results](image)

Experiments 3: Cather insertion force measurements

Catheter insertion into the blood vessels, the resistance force can be felt by the operator. This force is very important to ensure the safety of the surgical operation. The following experiments is used to evaluate the designed device. The experimental process is described in Fig.12 and Fig.13. The method used to measure unknown force based on the known force.

![Fig.12 The catheter insertion force measured based on the prior device.](image)

![Fig.13 The catheter insertion force measurements based on the new designed device.](image)

![Fig.14 The catheter insertion force error between the actual force and the estimated force.](image)

![Fig.15 Measurement error of the prior force measurement device[12]](image)
The catheter insertion force measured error is shown in Fig.14. Comparing with Fig.14 and Fig.15, the new designed force maximum measurement error is below 0.40N. And the maximum error of the prior force measurement device is below 1.40N. Therefore, the new designed force measurement device is more suitable to measure catheter insertion force.

IV. CONCLUSIONS

In order to improve the safety of the teleoperative catheter operating system, we proposed a new force measurement method to measure the resistance force acted on the catheter in the slave robotic catheter operation system. A new force measurement device was designed and fabricated. Some experiments have been done to verify the designed force measurement device. The experimental results show that the measurement errors were reduced by the new force measurement device.

Due to the new force measurement device just can provide a series of sensor data, it is not enough for further research. In the future, many times of catheter insertion experiments will be done, and the database will be established. In another, it is significant important that the measured force was feedback to the master system for improving the safety of surgery.

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V. REFERENCES


