Study on Haptic Feedback Functions for an Interventional Surgical Robot System

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Abstract—In medical practice, endovascular treatment has become increasingly popular. Compared to traditional interventional surgery, robotic surgical system has higher precision and ability to remotely control. However, the existing robotic surgical system dose not provide doctors with real-time effective haptic feedback function. This paper presents a novel interventional surgical robot system. In this design, the robot system will simulate the procedure of the doctor's hand to operate the guide wire, and providing haptic feedback to the doctor. In this paper, the Study of haptic feedback function in the developed interventional surgical robot system was introduced. The advantage of this interventional operation robot system was analyze. And performance improvement of the robot operation system which brought by the haptic feedback function was confirmed. The function of haptic feedback can provide effective support for the doctor in operation.

Index Terms —Interventional surgical robot system, Haptic feedback, Remotely control

I. INTRODUCTION

In medical practice, intravascular intervention has become more popular, and was accepted by more and more patients and surgeon. Whether for diagnostic or surgical treatment it already is the current mainstream solution. As a branch of technology of minimally invasive surgery, endovascular surgery has a majority of the outstanding characteristics of minimally invasive surgery, such as a small wound, low postoperative pain and faster recovery time. However, it can't like minimally invasive surgery to reduce the risks of surgery. As an emerging technology, it requires a lot of operating skills. In addition, an object of diagnosis and treatment is vascular of patients which are fragility and narrow parts. And the operation is impossible to directly monitor, because tools are motion within the blood vessels. Thus during the catheter is inserted into a patient's blood vessel, any operational errors are likely to cause injury to the patient. Much more skills and experience are required for doctors to insert the catheter. Vascular interventional procedures are divided into cardiovascular interventional surgery and neuro intervention. Cardiovascular intervention includes cardiac ablation procedures, heart stents and valve repair surgery. Neuro intervention including cerebrovascular thrombus ablation, arterial dilation. In operation, the accuracy requirement of neuro intervention is higher than the requirement of interventional cardiovascular surgery. An experienced neurosurgery doctor can achieve a precision about 1mm in the surgery. Collision parts between the vessel wall and catheter is the main source of danger, collision force will not damage blood vessels is the important condition of safe operation. However, the contact force between the vessels and catheter cannot be detected, it cannot be directly to the doctor for warning. Hence now doctors are combined with the resistance at operated catheter proximal tip, experience and all kinds of medical imaging, is mainly for X optical imaging, to guide their operation. Therefore during the operation process, the X-ray camera is used, long time of irradiation for doctors and patients can cause physical damage. Especially for doctors, after treatment for more patients, his exposure time in X-ray will be much higher than patients. Although the doctor be dressed in protective clothing, it is difficult to effectively protect the doctor’s face and hands which radiated in X-ray. Lead protective clothing has great weight, causing a great challenge of the doctor's stamina. When the fatigue state, the doctor will be very difficult to guarantee the quality of operation. The long-term weight-bearing caused great damage on doctor body especially the spine. To overcome these challenges, we need better technology and mechanism to help and training doctors. So interventional surgical robot system emerge as the times require. But the existing surgical robot system is not adequate to replace conventional surgery. Not only because the machine is not as flexible as hands of human being but also the robot system can not provide accurate haptic feedback to give the doctor operation guide.

The robot system have high accuracy and stability. It can provide the high precision operation for the surgery. And it can be remote control and realize patient isolation. Doctors will is liberated from X ray irradiation environment [1-3]. And the hidden danger of the body caused by long term irradiation with X rays will be solved. However, the current interventional surgical robot system is also not possible to meet all of the operational requirements of intravascular intervention. When the surgery, the real-time haptic information is very important to guarantee the operation safety [4-10]. However, existing studies have not realize perfect haptic feedback function, which leads to the lack of important guidance information in the operation of the doctor [11-15]. It serious impact on the efficiency and safety of operation. Haptic feedback implementation consists of two key technologies, force
measurement and providing feedback force [16-20]. In order to solve these problems, this paper proposes a new robotic catheter navigation system. The slave side of the system, the catheter manipulator, will simulate the doctor's hand movements to the operation the catheter or guide wire [21-23]. And the use of mechanical sensor integrated in the catheter manipulator complete testing of resistance at catheter. A new type of doctor’s console is designed. The console can be skilfull operation. And it can detection accurate operation commands of doctor, and use the reverse driving to generate resistance at the same time, providing haptic feedback effect for the operation of doctors [24-26].

In this article, a complete system was described, and using experimental to study the system to provide haptic feedback to enhance the performance of operative intervention. The rest of the paper is organized as follows. The development interventional surgical robot systems was proposed in the next section, method of force measurement and providing force feedback were introduced. Then, design experiments to evaluate the function of haptic feedback effect. Finally is the conclusion part.

II. THE FRAMEWORK OF SYSTEM

The research adopts the design idea of the master-slave system, to allow remote operation, completed the doctor-patient separation of functions, will liberation the doctor from the exposure operation environment in X ray [27], operation diagram as Fig 1. The master side is surgeon’s console, the main function is to provide a simulation operation and haptic feedback for the doctor, and collecting control commands of the doctor from the guide wire in the operation. The slave side, catheter manipulator, will be responsible for the control of guide wire in the patient’s intravascular. The part B is the mechanism which direct operation the guide wire, it is the core of the guide wire manipulator. Prototype of part B as shown Fig 4.

A. The guide wire manipulator

The guide wire manipulator will imitate movements of physician's hand to operate the guide wire, the structure as shown in Fig 3. The green line in the figure represents the guide wire, the part A is platform which fixed catheter sheath, will contact with patients. The part B is guide wire manipulator, its function is to control the guide wire rotary and fixed. It will be fixed in the part C. The part C is a slide motor, its function is to drive the B part to the translation.

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The element 5 is guide wire holder used in traditional intervention, use it operating guide wire can effectively fasten the guide wire to prevent slipping, and increase the torque when the guide wire rotating. Using slider motor (part C) below the part B, guide wire manipulator can insert guide wire. And using wheel gear (element 2), the guide wire could be rotated. The yellow equipment (element 7) is force sensor, it can detect weak resistance on guide wire, its precision can reach 0.001N.
The operational process of guide wire movement as shown in Fig. 5. The red arrowhead marks the specific position and direction of guide wire. In the step 1, the clamp was loosen and manipulator go forward, the guide wire will go forward. During movement, resistance of guide wire will be passed on to the guide wire holder. Through the backstand which fixed on the guide wire holder, the resistance will passed to the force sensor. Because the backstand contact with the slide rail, the frictional force is extremely small. This mechanism can guarantee the measuring accuracy. In the step 2, the clamp was loosen and wheel gear rotate, the guide wire will rotate. In the step 3, the clamp was gripping, wheel gear rotate and manipulator fall back, the guide wire holder will be loosen and guide wire keep still. In the step 4, wheel gear rotate and the clamp was loosen, the guide wire holder will be gripping and guide wire keep still. After the complete procedure, manipulator returned the initial state and guide wire forward 50mm and rotate 90 degrees.

A motor with an angle sensor is installed at the A point, the crank AB length is R, connecting rod BC length is L, the slider placed in the position of C. The A bit is set to the coordinate origin, theory travel of slider H is 2R, is in the range of [L-R, L+R]. In the doctor’s control with simulated C slider guide wire, change through the A point in the motor angle sensor crank angle α, then using the kinematics model can obtains the accurate displacement of C point. At the same time, the implementation process of mechanical feedback is the use of motor provides a rotating angular velocity \( \omega \) crank drives the sliding block C to the opposite direction of doctor operation exercise, so as to provide resistance F which is required for haptic feedback. In the slider crank mechanism, size of feedback resistance F can be obtained by variable kinematic model for crank angle \( \alpha \) and angular velocity \( \omega \) calculation. Through mathematical analysis to model the slider position C in crank slider mechanism can be define:

\[
\begin{align*}
\begin{bmatrix}
 x^c \\
 y^c
\end{bmatrix} = & \begin{bmatrix}
 \cos \alpha & -\sin \alpha & R(\cos \alpha - \cos \beta) & R + L \\
 \sin \alpha & \cos \alpha & R(\sin \alpha - \sin \beta) & 0
\end{bmatrix} \begin{bmatrix}
 1 \\
 0 \\
 0 \\
 1
\end{bmatrix}
\end{align*}
\]

(1)

In this design, the use of crank slider mechanism, the slider C along the X axis motion, which is always \( y^c = 0 \). The displacement of slider C can be obtained by formula:

\[
S = x^c = R \cos \alpha + L \cos \beta
\]

(2)

The relationship between \( \alpha \) and \( \beta \) can be defined by:

\[
\beta = \arcsin \left( -\frac{R}{L} \sin \alpha \right)
\]

(3)

In the type 3 to type 2 can be obtained for \( S=f(\alpha) \), the slider displacement can be measured only on the angle \( \alpha \) function. Hence, displacement of the surgeon’s console and control command of surgeon was detected. The first and second derivative of displacement formula on time \( t \) was calculated and simplified respectively. The slider C were obtained respectively in speed \( V \) and acceleration \( a \) on the of rotation speed \( \omega \) and
crank angle $\alpha$ formula:

$$v = \frac{R \omega \sin(\alpha + \beta)}{\cos \beta}$$

$$a = R \omega^2 \left(\frac{\cos(\alpha + \beta)}{\cos \beta} + \frac{R \cos^2 \alpha}{L \cos^3 \beta}\right)$$

(4)

(5)

When the sliding block and the guide wire quality simulation is $m$, can get the reverse driving force feedback mechanism provides $F$ formula:

$$F = ma = mR \omega^2 \left(\frac{\cos(\alpha + \beta)}{\cos \beta} + \frac{R \cos^2 \alpha}{L \cos^3 \beta}\right),$$

$$\beta = \arcsin \left(\frac{R}{L} \sin \alpha\right)$$

(6)

Type 6 to the feedback force $F=f(\alpha, \omega)$ to a function capable of measuring angle $\alpha$ with velocity $\omega$.

In the prototype, Phantom omni, a commercial products, was used as the master side. In order to measure the real force of haptic feedback, a novel handle which equipped sensor was design and Instead of the original handle. The prototype of master side is shown in Fig.7.

Fig. 7 surgeon’s console and novel handle

Using the force measured by the sensor, closed-loop control of haptic function can be achieve. The haptic feedback function will be optimized.

III. THE EXPERIMENTAL OF HAPTIC FEEDBACK EFFECT

An insertion experiment was carried out to evaluate the effect of the haptic feedback function. In the experiment, invited 10 volunteers without operation experience. The operation was carried out in simulation environment with and without haptic feedback respectively. Medical training vessel model as treatment object, show in Fig 8, was used to detect operation process of the volunteers.

Each volunteer achieved simulant treatment for 5 different lesions, 10 times operations was carried out at each lesion with and without haptic feedback respectively. Resistance and completion time of each volunteer’s operation was recorded.

Completion time of operation are show in the Fig 9. The three sets of data representing average operation time of each volunteers at three different conditions of operation. As can be seen from the graph, completion time of manual operation consumed the least time, completion time of robotic operation without haptic feedback consumed the most time. Hence, compared to the condition of operation without haptic feedback, the condition of operation with force feedback makes the completion of operation are more efficient.

The resistance are show in the Fig 10. The resistance was measured by sensor of slave side and approximate the collision force between guide wire and blood vessel. Smaller resistance means safer operation. Fig 10(a) express the resistance of situation without haptic feedback, the average is 0.0126N and the maximum is 0.0412N. Fig 10(b) express the resistance of situation with haptic feedback, the average is 0.0072N and the maximum is 0.0233N. Two resistance was measured when the guide wire was inserting same lesions. As can be seen from the graph, haptic feedback function improved the safety of operation.
This paper introduces a new type of intervention operation robot system simulation hand motion of doctors to operate on the guide wire, the doctor can cast the clinical operation skill required for stable, health requirements.

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