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Research Article

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Force measurement method and analysis of guide wire in minimally invasive cardiovascular interventional surgery

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ABSTRACT

This paper presents a method of detecting the resistant force that acting on the guide wire when it moving into the body blood vessel for minimally invasive cardiovascular interventional surgery operated by a robot system. To learn more about the influenced factors for measured force, some simulations of body blood flow environment have been given. And then some analyses have been worked on blood flow to study whether the parameters of blood flow influence the resistant force measurement results. All of these studies will make us know more about the reliability of this force detecting method and lay the foundation for realizing force feedback in minimally invasive surgery robot system to further improve the system reliability.

Keywords: Minimally Invasive Surgery, Force Detecting, Blood Environment Simulation, Force Feedback

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INTRODUCTION

Minimally invasive cardiovascular interventional surgery: Vascular interventional surgery is the Digital Subtraction Angiography (DSA) to guide the doctor to insert the catheter, guide wire, saccule and stent into blood vessels and cure lesions so that the catheter reaches the embolism and malformed vascular to dissolve the clot of narrow blood vessels or to use other purposes [1, 2, 3].

Vascular interventional surgeries have been applied to a variety of surgical, such as cardiovascular surgery, which is considered as the one of the most application value clinical medicine specialist [4]. Minimally invasive cardiovascular interventional surgery is that the doctor inserts a catheter whose diameter less than 2mm to the specific aorta, and then steers the catheter following the aorta to desired position, injects the radiotetrane into coronary artery and observes the stenosis extent of coronary artery on computer screen. If more than 70% stenosis, that the doctor pushes a steel wire less than 0.3mm, along the catheter, cross cabined vessel, into coronary artery distal, and finds a track. In succession, the doctor pushes a sacculus along the steel guide wire track to splay the cabined vessel, and then puts a steel stent in the cabined vessel to eliminate vessel stenosis thoroughly and achieve the purpose of improving the blood supply.

In order to push a guide wire into target branch vessel, the robot system needs to be able to complete the motion of pulling, pushing and rotating the guide wire. And how the robot system accomplishes these actions is the problem that the mechanical should solve. To avoid the vessel wall being destroyed, it is very important to detect the touch force timely and exactly. Depending on the force detected, the doctor should timely operate the device to improve surgery's security, so the device must have reliable detecting function [5]. What we should do in this paper is detecting the pushing resistant force and deciding the next operation according to the detected force. And the resistant force should be detected and analyzed.

Current commercial systems that use haptic feedback include those of Hansen Medical [6] and MAKO Surgical Corporation [7]. However, no data exists demonstrating the relative effectiveness of those systems with and without haptic feedback [8]. The University of Electro-Communication developed a novel catheter operating system using micro force sensors for medical application [9]. Scuola Superiore Sant'Anna reported a miniaturized triaxial force sensorized cutting tool for minimally invasive robotic surgery whose outer diameter is less than 3mm [10]. All of the force detected devices are expensive or complex. Accordingly, the research for the force detecting of the minimally invasive surgery robot system has extremely important practical significance of application.

Work environment of guide wire: The guide wire advancing direction is opposite to the direction of blood flow and the resistant force is influenced by blood flow environment. The blood vessel of human is also bend, long and narrow, atactic, more embranchments [11], the guide wire may easily hit the walls of blood vessels or enter into wrong vessel embranchments. The guide wire moves in the blood vessel, and many factors of the blood environment will influence the guide wire's movement. In my opinion, these factors mainly include blood vessel diameter and the velocity of blood flow. Then the density and viscosity of the blood and the environment temperature also are the influence factors. The change of these factors will bring about some changes of blood environment, and then influence the guide wire's movement resistant force.

RESISTANT FORCE DETECTING OF GUIDE WIRE

The possibility of force detecting: In order to make the robot system to better assist doctor do operation, some sensing system should be added to detect and transmit the information of the end-effector's work environment and state. And now, most surgery robot system only can realize image feedback. Image feedback that is environment monitoring system has been used in many areas, such as public transportation system [12]. But only with the help of a robot system which has no function of force feedback, the operator can percept the end-effector's working condition and know the promoting position of the guide wire by feedback image. In this way, the system delay and collimation error are inevitable, and these problems will bring some unsafe factors. Based on the image feedback, the new robot system we have designed has been added the function of force feedback, that will make the doctor who is operating the system have more accuracy and real feeling of perceiving terminal environment. Even if the doctors do not directly manipulate the guide wire, they can also have force telepresence.

In this case, feedback force is actually based on the resistant force that the guide wire suffered when being promoted. When some block or branch appeared, the resistant force will be suddenly increased. The pressure sensor will detect the waved information and send the signals to the control system, and these signals will be translated into feedback force acted on the operation doctor. The function realization of force feedback first needs to be able to detect the real force. However, it is a very difficult thing to install a pressure sensor in a complex vascular environment, and harsh requirements are needed for the pressure sensor to adapt to the peculiar working environment. The specific requirements mainly include four parts. First is the size and shape of the sensor, which should be small enough to move freely in the vessel. Second is that the high sensitivity is needed. Third is the good corrosion and impact resistance. The last aspect is that the sensor should be easy to be installed and disassembled. In view of the above points, we can know that the selection of the sensor is a difficult thing. The suitable type has not been founded now, and even is able to find, we believe that the cost will be higher. According to these reasons, we have to give up the idea of installing a pressure sensor on the terminal of the guide wire to detect the resistant force. Installing a pressure sensor on the external device is our new thinking. This way can greatly reduce the requirements of the sensor shape and size, and extend the limitation of the use environment, to facilitate the selection of the sensor as well as to reduce the costs. But without direct measurement, the result will be influenced by various external factors which will lead to the results inaccurate. In order to be able to get a more accurate signal of the force, we need to further understand the impact of the bloodstream environmental on the results of the dynamometer.

Measurement principle: To make the detected force more credible and accuracy, some measures should be taken to reduce the influence from mechanism transmission and friction. The promoting finger which is designed for delivery the guide wire is equipped with a sensor, and the resistant force can be transferred to the mechanism through the guide wire. In this way, the force between the guide wire and vessel wall can be detected. The relationship between resistance of guide wire and pressure of the sensor is based on the leverage as shown in Figure 1. Since the detected force is not influenced by friction of machine and transmission structure, the force signals from the sensor are correct and credible.

Mechanism realization: The catheter intervention device is composed of a fixed finger, a promoting finger and a rotating finger as shown in Figure 2. The fixed finger is located in the front of the device. It is used to locate the first catheter that has inserted into vessel and pave a way for subsequent wires. The promoting finger is located in the middle of the device. It is used to grasp the catheter or guide wire and bring them moving along axial directions. The rotating finger is located in the end of the device. It is used to rotate the catheter and guide wire. Cooperation action of three fingers can promote the guide wire to the lesion location.

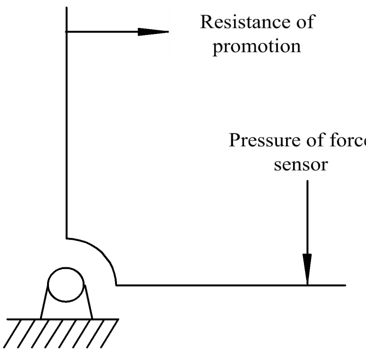

Fig.1. Force detecting principle

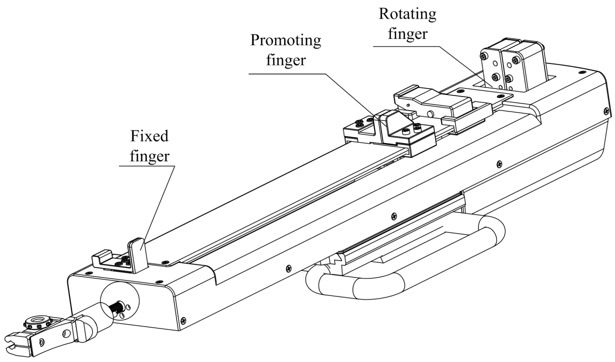

Fig.2 The catheter interventional device

In order to detect the resistant force of the guide wire moving in the blood vessel, a pressure sensor is fixed on the promoting finger. The working process of the sensor will be given as follows. The pressure sensor is fixed on the scaffold. In order to keep the oscillating deck always contacted with the pressure sensor and maintain a certain preload, a preloaded spring is installed in the other side of the scaffold relative to the pressure sensor. When delivering the guide wire, if some blockings or branches happened, the resistance acted on the guide wire will increase. The gripper will roll a little angle round about the rotation pin roll. The structure has been shown as Figure 3 and Figure 4.

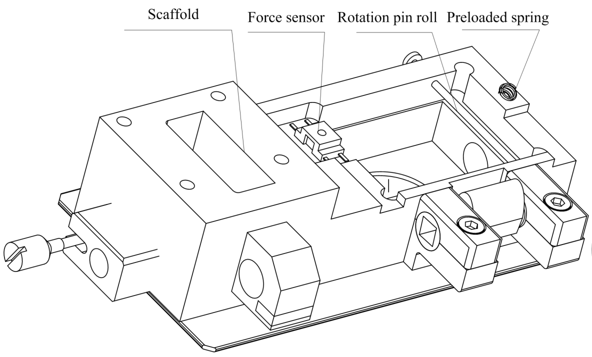

Fig.3 Drawing of force sensor fixed

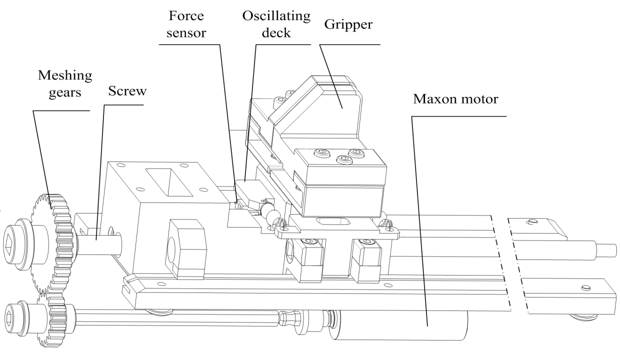

Fig.4 Drawing of promoting finger

Then act this resistance on the resilient contacts of the pressure sensor through the oscillating deck, and the force sensor signal changes. The force information can be used for force feedback control, which will make the operate doctor have force telepresent to improve the safety.

FORCE ANALYSIS

Guide wire force source: The catheter interventional device is used to clamp the surgery catheter and guide wire and move carrying them. The driving force of the movement comes from a motor. The power outputted from the motor can be transferred to a screw through a pair of meshing gears. The screw rotation drives the meshing screw nut move back and forth. The promoting part of the mechanism is fixed on the screw nut, so it will move back and forth following the screw nut (as Figure 4). The drive motor is maxon motor produced in Switzerland. The motor model we used is maxon-RE13. There is no reducer connected with the motor, but a pair of meshing gears is fixed on the output shaft. The thrust of the screw can be expressed as follows:

$$F = \eta \frac{2\pi \times T}{i \times s}$$

Where, η is the mechanical efficiency of the screw.

T is the nominal torque of the motor.

i is the reduction ratio of gears.

s is the screw lead.

We make η equals to 0.6, the nominal torque T is 0.0024NM, the ratio i is 16/30, the screw lead is 1mm and the diameter of the screw is 6mm. Then we can obtained the value of pushing force of the screw $F = 16.97N$, that is the maximum thrust of the device pushing the guide wire is 16.97N.

Due to the complexity of the vessel shape and viscosity of the blood, the guide wire will suffer multiple resistances when moving in the blood vessel. These resistances mainly include: 1) the contact force between the head of the guide wire and the vascular wall; 2) the frictional force between the guide wire and the vessel wall over the entire length; 3) the viscous resistance of the guide wire effected by blood; and so on. Detecting these forces and providing them to the operator can not only help the operator know the position and state of the guide wire, and then decide the next operation, forward, backward or rotate. The most important is that it can restrict the size of force to protect the patients from injury.

Simulation of the guide wire's movement environment: Although the force detected by the method mentioned above is not influenced by mechanical transmission and frication, the resistant force will inevitably be influenced by the blood flow. So analyzing the force on the guide wire in the bloodstream environment is needed. Then the degree of the impact on the force that the blood flow worked on the guide wire will be known. Whether the blood flow influence the judgment of the point that the resistant force fluctuate can be known.

The average velocity of the blood flow in the aorta approximately is 0.22m/s. The total sectional area of the small arteries is about 2 times of the aorta's. According to the principle of continuity, the average velocity of blood in small arteries is about 0.11m/s. Due to the caliber of small arteries is small, the small artery blood flow velocity gradient will significantly increase. Also due to the internal friction with viscous liquid flow is proportional to the velocity gradient, the resistance of blood flow is significantly increased in the small arteries.

Some simulations on heart artery blood flow environment have been given, with the comparing the resistant force of the guide wire from blood flow with the resistant force of bumping the blood vessel wall. Then do some analyses on whether the guide wire resistant force from blood flow will influence the judgment of whether the guide wire pumping the blood vessel wall or not.

Firstly, some preferences should be set in order to filter quantities that pertain to this case only. Turn on FLOTRAN CFD filtering, and then create areas for the inlet, outlet and transition regions as Figure 5.

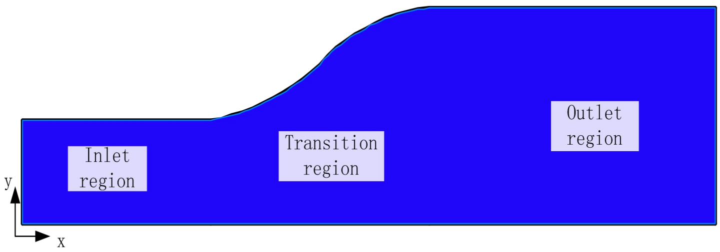

Fig.5 Blood flow region model

Then establish mesh patterns. Apply 10 elements in the transverse direction (Y) and bias them slightly towards the top and bottom boundaries. This will help capture boundary layer effects. For high Reynolds number problems, finer meshes should be used. Along the inlet flow direction (X) in the inlet, use the number of divisions tabulated below as Table 1.

Table 1 Mesh division strategy

Mesh Division Strategy	
Transverse (Y) direction	**10 divisions** - bias towards walls
Inlet region, flow direction (X)	**15 divisions** - bias towards inlet and transition
Transition region	**12 divisions** - uniform spacing
Outlet region (initial)	**15 divisions** - larger elements near outlet

After setting these parameters, the finite element mesh should be created. And the next step is establishing fluid properties. The density of the blood is 1.056g/cm^3, and blood viscosity is about 0.04dyn.s/cm^2. The body's normal temperature is about 37ºC.

Analysis of simulation result

According to the parameters of human blood environmental, the simulation environment has been built. After parameters having been set, FLOTRAN solution will be executed. The Figure 6 is the vector plot result. The Figure 7 is the total pressure contours plot result.

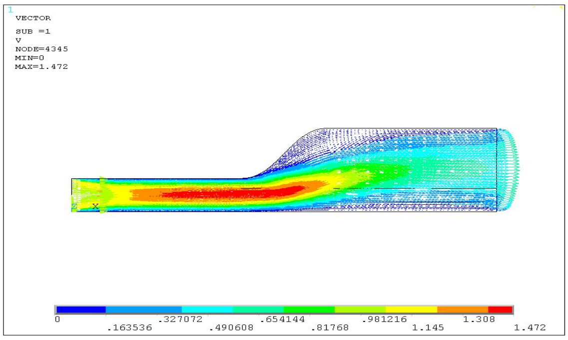

Fig.6 Vector plot result

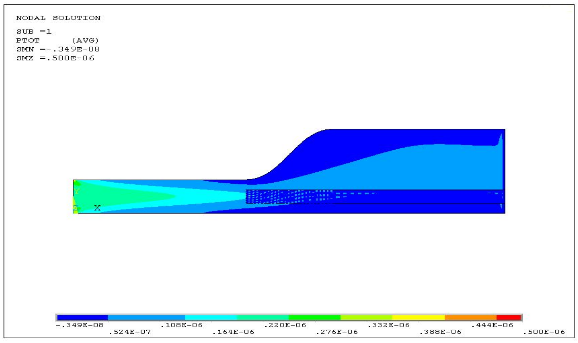

Fig.7 The total pressure contours plot result

From the results, we can know that the blood pressure will change greatly when flowing from branch arteriole into aorta. So the resistance force detected by the pressure sensor is influenced by the blood flow.

CONCLUSION

This paper designs a method of detecting the resistant force that acting on the guide wire when moving in the body blood vessel. In order to learn more about the influenced factors for measured force, some simulations of body blood flow environment have been given. According to the analysis, it is revealed that the resistant force detected is greatly influenced by the blood flow. So the measured force is not very dependable.

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