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Total Force Analysis and Safety Enhancing for Operating Both Guidewire and Catheter in Endovascular Surgery

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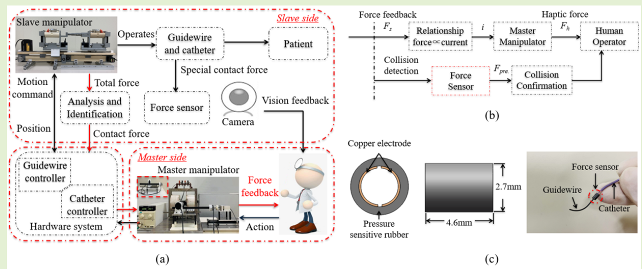
***Abstract*—In vascular interventional surgery (VIS), the doctors often need to be exposed to X-ray radiation for a long time, operate surgical instruments (Ex. Guidewires and catheters) to perform the operation, which is difficult to ensure the health of surgeons and the safety of operation. In addition, the force between the blood vessel wall and the surgical instrument is complex and variable, the existence of the external disturbance forces easily affects the judgment of the doctors. In this paper, to ensure the health and reduce the fatigue of the doctors, a novel tactile sensing robot-assisted system for VIS was developed to assist the surgeons to complete the operation. Then, the forces between the blood vessel and the surgical instrument during the surgery were analyzed. Besides, a self-developed force sensor was used to confirm the collision force between the tip of the catheter and the blood vessel wall. Finally, combining the haptic force feedback of the system and the developed force sensor, a series of experiments in "Vitro" were completed, and it was indicated by the experiment results that the accuracy of the force feedback can be improved by using the analysis method proposed in this paper, the collision force between the catheter tip and the blood vessel environment can be confirmed by the self-developed force sensor. Based on the results, the developed robot-assisted system for VIS has high safety.**

***Index Terms*—Total force analysis, safety enhancing, vascular interventional surgery, guidewire and catheter, haptic force feedback.**



The developed robot-assisted system for vascular interventional surgery. (a) The concept of the robot-assisted system. (b) The schematic diagram of safety improvement strategy. (c) The self-developed force sensor based on pressure sensitive rubbers.

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I. Introduction

CARDIOVASCULAR disease is the number one cause of death in the world. It causes heart attacks and strokes by affecting the heart and the blood vessel. Generally, there are two ways to treat cardiovascular disease, including the manual operation and the emerging robot-assisted minimally invasive surgery [1]. As shown in Fig.1, it is the process of manual operation, the doctor needs to operate guidewires and catheters in the operating room for long time to complete the treatment. The long operation time is easy to fatigue the doctor and increase the risk of surgery. In addition, the health of doctors can hardly be guaranteed because of the X-ray radiation. In contrast, the robot-assisted minimally invasive surgery is particularly advantageous, and it can improve the comfort, precision, and stability, eliminate the physiological tremor, and reduce the doctor's exposure to X-ray radiation.

A. Current Research Status

With the advances of science and technology, more and more studies on the robot-assisted systems for vascular interventional surgery have been conducted and verified, and some difficulties have been overcome one after another. For instance, to protect doctors from X-ray radiation, the structure of the robot-assisted system mostly adopts the "Master-Slave"

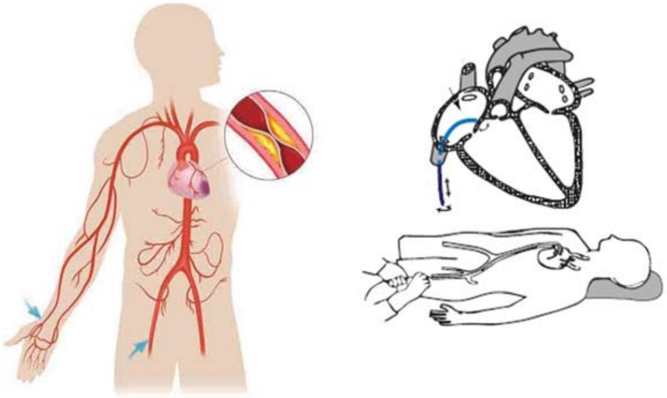

Fig. 1. The cardiovascular disease and manual operation [2], [3].

structure [4]–[13], the doctor performs the surgery by operating the master manipulator at the master (proximal) side to control the slave manipulator at the slave (distal) side. Since the surgical tools were delivered by the robot-assisted system, there needs to be a good information interaction between the system and the doctor. The novel master manipulator with haptic force feedback was designed to provide surgeons with tactile presence and improve the transparency of operation [14]–[17]. The realization method of force feedback is very new, such as inspired by the damping characteristics of the magnetorheological (MR) fluids, and the torque characteristics of a voice coil motor. The function of force feedback effectively enhances the safety of the operation. The extraction of the force between the surgical tools and the blood vessel usually includes modeling estimation based on noninvasive techniques [18], and direct detection based on optical fiber pressure sensor techniques [19]–[21]. Certainly, the visual interaction is also essential, the image guidance was verified to reduce costs and offer robustness and reliability [22]. In addition, the control of the robot-assisted system is another important metric for evaluating its transparency. Therefore, the control algorithms were proposed to improve the precision and the performance of the system [23], [24], including reducing the error of master-slave tracking motion, generating the ideal motion trajectory for catheter, and shortening the time- varying of the response. Nowadays, robot-assisted systems are gradually developing towards the direction of intelligence. For instance, a framework was used to analyze the natural behavior of the doctor and recognize the motion patterns of the guidewire [25]. And a supervised semi-autonomous control was proposed to reduce the cognitive load of the doctor, shorten the operation time and lessen the fatigue for repetitive tasks [26], [27]. Besides, the application of magnetic fields in robot-assisted systems has also achieved some good results [28]. An advanced robotics for magnetic manipulation (ARMM) was developed to achieve the automation of flexible catheters, which has the features of large workspace and high precise. The development of robot-assisted systems for vascular interventional surgery is very fast, some of developed robot-assisted systems have completed the operation evaluation experiments in human [29] and in animal [30].

B. Challenges & Contributions

Currently, the design of most robot-assisted systems needs to be improved. For instance, the master manipulator should retain the operation skills of the surgeon, the slave manipulator should perform more motion patterns to achieve different tasks, and the robot-assisted system should realize the function of haptic force feedback to improve the safety of the operation. In addition, the total force on the guidewire and the catheter needs to be analyzed, and determined, because the disturbance force is easy to reduce the precision of the haptic force feedback of the system, increase the difficult of the operation and affect the judgment of doctors.

Based on the above challenges, the contribution of this study is to develop a robot-assisted system that satisfies the design req uirements, analyze the forces of the guidewire and the catheter by modeling, and develop a force sensor to confirm the collision between the tip of the catheter and the blood vessel. To verity the proposed analysis method and the self-developed force sensor, a series of experiments in "Vitro" were carried out by combining the haptic force feedback of the system and the self-developed force sensor. It was indicated by the results that the accuracy of the force feedback can be enhanced by using the analysis method proposed in this study, the collision force can be detected by the developed force sensor, and the safety can be improved.

The remained of this paper is organized as follows, Section II introduces the proposed robot-assisted system. Section III is the principles and methods. Section IV carries out the experiments and obtains the results. Section V is the discussion, and Section VI draws the conclusion, respectively.

II. System Description

A developed robot-assisted system for VIS should satisfy the operating requirements of surgeons. Through analysis, there are some important points. 1) The master manipulator of the system should respect the doctor's operating habits, so that the doctor can make full use of their rich experience and dexterous skills. 2) The slave manipulator of the system should realize the collaborative operation between the catheter and the guidewire, which has the advantage of fast navigation to the target position. 3) The novel developed robot-assisted system should have the ability of force feedback, which has the advantage of enhancing the safety of the operation. And the details will be introduced from the following 3 aspects, the system overview of the robot-assisted system, the master manipulator, and the slave manipulator.

A. System Overview

The concept of the developed robot-assisted system is shown in Fig.2, the doctor operates the master manipulator, the actions are acquired by the master manipulator, and then transmitted to the slave side through the hardware control system. The position commands are sent to the stepping motor actuators of the slave manipulator via the motion control board (Arduino, Mega 2560, China). The slave manipulator follows the actions of the doctor to complete the operation. At the same time, the total force, and the position of the

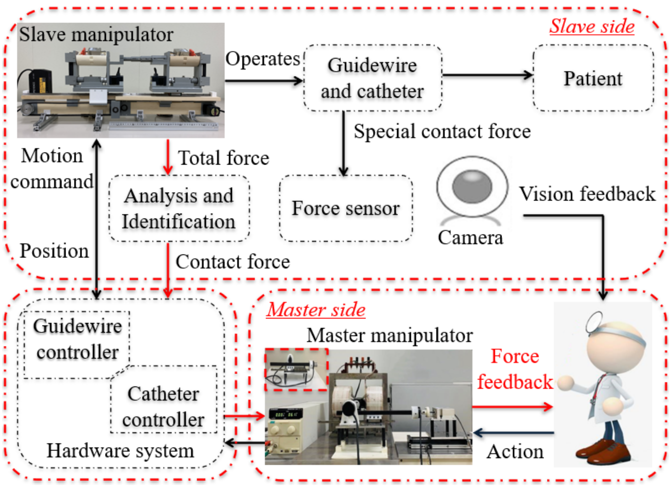

Fig. 2. The concept of the developed robot-assisted system.

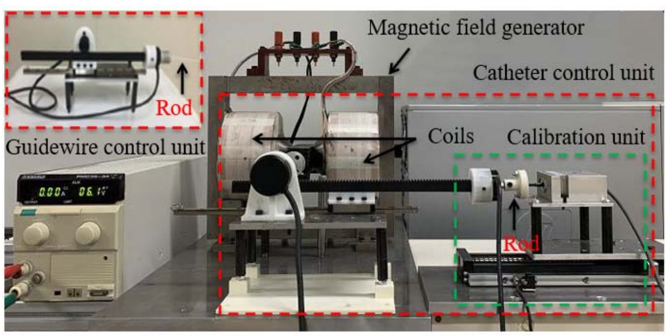

Fig. 3. The master manipulator of the system [6], [14]–[16].

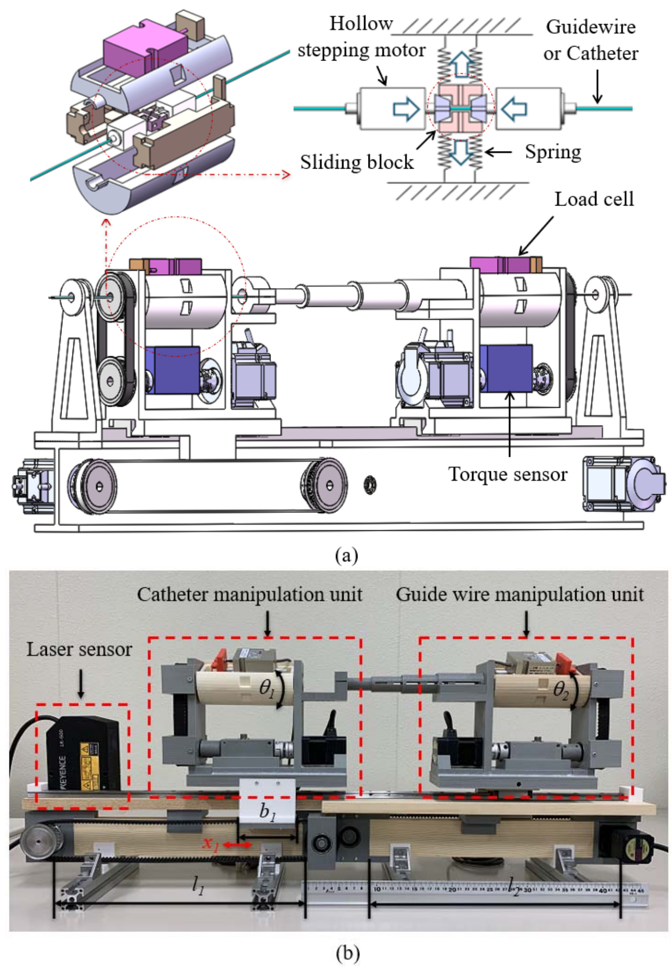

Fig. 4. The slave manipulator. (a) Schematic structure. (b) The developed device.

guidewire (catheter) are fed back to the master side, forming a closed loop. After analysis and identification by the method proposed in this study, the disturbance force during the operation is eliminated, only the contact force is fed back to the master side. Then the master manipulator generates the haptic force according to the contact force of the slave side and applies on the surgeons' hand to realize the haptic force feedback of the system. Besides, a self-developed force sensor is used to detect the collision force (that is, the special contact force) between the tip of the catheter and the blood vessel wall. To realize the visual feedback of the system, a high-resolution camera is placed on the slave side to monitor the surgical scenes of the slave side in real time. With the combination of the force-visual feedback of the robotic system and the collision detection of the self-developed force sensor, the safety of the system can be improved.

B. Master Manipulator

The master manipulator was developed and evaluated by our group [6], [14]–[16] as shown in Fig.3. It is composed of a guide wire control unit, a magnetic field generator, a calibration unit, a catheter control unit. Among them, the magnetic field generator is used to generate magnetic field that applies on the MR fluids to achieve the tactile force feedback of system. It was developed according to the principle of electromagnetics, by changing the input current to change the magnetic fields, and then change the state of the MR fluids. Therefore, the calibration unit is used to calibrate the force feedback of the system, that is the relationship between the haptic force applied on doctor's hand and the input current. Moreover, in the catheter control unit and the guidewire control unit, there are four rotary encoders (MTL, MES020-200 0P, Japan) are employed to obtain the motion information of the operating rods. The doctor can complete 3 types of operations by operating rods, including the independent operation of the guide wire, the independent operation of the catheter, and the collabor ative operation between the guidewire and the catheter.

The master manipulator developed by our group can respect the doctor's operating habits by operating a cylindrical rod (just like a real guidewire and a real catheter), so that the doctor can make full use of their rich experience and dexterous skills [31].

C. Slave Manipulator

The slave manipulator of the system is shown in Fig.4, which was developed to replace the surgeons in completing operations on the patient's side. There are a catheter manipulation unit and a guidewire manipulation unit. The two manipulation units are similar in structural design and can move without affecting each other. Therefore, the developed robot-assisted system can easily realize the collaborative operation of the guidewire and catheter. The slave manipulator has four DOFs (degrees of freedom), the insertion (retraction) of the guidewire, the rotation of the guide wire, the insertion (retraction) of the catheter and the rotation of the catheter. The manipulation units of the slave manipulator are driven by stepping motors with a resolution of 0.36 degrees (AS M46AA, ORIENTAL MOTOR, Japan). Another feature of the slave manipulator is that the force information of the guidewire and the catheter in the direction of linear motion can be detected by two load cells (TU-UJ5N, TEAC, Japan) in real time, and the load cell with the detection range from -5 N to 5 N. Besides, the force of the guidewire and the catheter in the direction of rotation motion can be measured in real time through two torque sensors.

At present, there are some developed slave manipulators that can only manipulate a catheter. The lack of guidewire to support and guide the catheter during the operation, the catheter is easy to buckle, and difficult to pass through the narrow blood vessel space. The slave manipulator developed in this paper can solve the above challenges, which can achieve three types of motion patterns, including the independent motion of the guidewire, the independent motion of the catheter, the collaborative operating motion of the guidewire and catheter. During the operation, the doctors can adjust the different motion patterns according to the operation needs to complete the operation safely and quickly.

III. Principles and Methods

In the previous section, from the perspective of the structure of the robot-assisted system, the design requirements have been basically satisfied. The principles and methods will be analyzed in this section, and the details of this section will be introduced from the following aspects, the control architecture, the contact model, the friction model, and the safety improvement strategy.

A. Control Architecture

The force feedback of the developed robot-assisted system is inspired by MR fluids. According to previous work, MR fluids is a special kind of suspension, which has the characteristics of a "Newtonian fluid" with low viscosity under the action of zero magnetic field and a "Bingham fluid" with low fluidity and high viscosity under the action of strong magnetic field.

The schematic diagram of force feedback control is shown in Fig.5. According to the force between the catheter and the blood vessel detected by a load cell, the controller controls the current driver to generate the input current, which changes the magnetic field of the master manipulator. Finally, the master manipulator generates the tactile force, and applies on doctors' hand to achieve the force feedback of the system. The purpose of force feedback is to improve the safety of the operation.

In Fig.5. Suppose the system input is x_{m}, the system output is x_{s}, the force detected by the slave manipulator at the slave side is F_{s}, and the tactile force generated by the master manipulator at the master side is F_{h}. According to the input and output variables of the robot-assisted system, the components can be represented by a hybrid matrix H [32], as shown in formula (1).

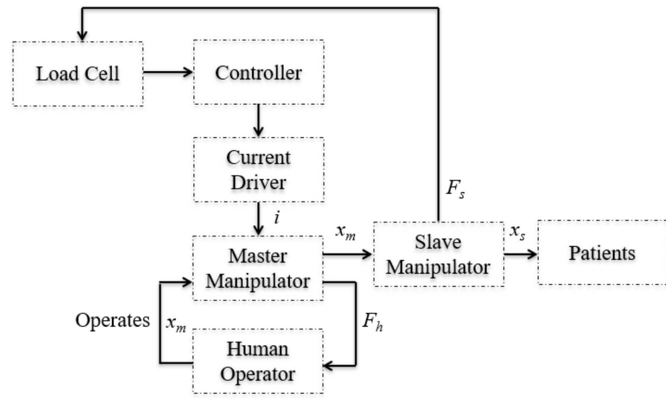

Fig. 5. The schematic diagram of force feedback control.

$$\begin{bmatrix} F_{\mathrm{h}} \\ -\dot{x}_s \end{bmatrix} = H \begin{bmatrix} \dot{x}_m \\ F_s \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} \dot{x}_m \\ F_s \end{bmatrix} \tag{1}$$

In the robot-assisted system, the impedance transmitted to the doctors can be derived by hybrid matrix parameters, the form is as shown in formula (2) [33].

$$Z_t = \frac{h_{11} + (h_{11}h_{22} - h_{12}h_{21}) \cdot Z_s}{1 + h_{22}Z_s} \tag{2}$$

where, Z_{t} is the impedance transmitted to the doctors, and Z_{s} is the environment impedance.

The transparency can be considered quantitatively as a match between the impedance transmitted to the doctors and the environment impedance. For a system to have good transparency, its conditions need to be satisfied $Z_{\mathrm{t}} = Z_{\mathrm{s}}$, that is, the hybrid matrix H should be expressed as formula (3), that is an ideal condition.

$$H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \tag{3}$$

However, some studies have shown that perfect transparency is difficult to be achieved in practice [34]. To better evaluate the transparency of the system, Colgate and Brown [35] studied the notion of Z-width to describe the dynamic range of the impedance transmitted to surgeons while maintaining the stability of the robot system. Z_{t} is examined for extreme values of Z_{s}, (Z_{s} =0 and $Z_{\mathrm{s}} \to \infty$), and the dynamic range of the impedance transmitted to the doctors can be expressed as formula (4).

$$\begin{aligned} Z_{t\,\min} &= Z_t \big|_{Z_s=0} = h_{11} \\ Z_{twidth} &= Z_t \big|_{Z_s\to\infty} - Z_{t\,\min} = \frac{-h_{12}h_{21}}{h_{22}} \end{aligned} \tag{4}$$

Based on the notion of Z-width, the good transparency of the system can be evaluated by $|Z_{\mathrm{tmin}}|$ =0 and $|Z_{\mathrm{twidth}}| = \infty$.

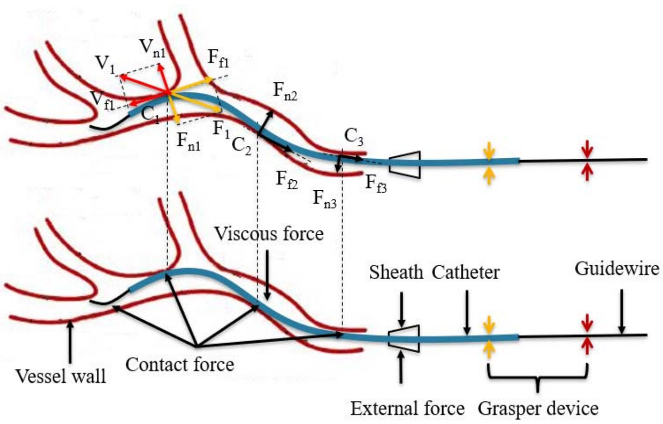

Fig. 6. The force analysis of the guidewire and the catheter in the blood vessel.

B. Contact Model

The force detected by a load cell on the catheter manipulation unit is the total force of the catheter. As shown in Fig.6, the total force is mainly composed of the contact force, the viscous force and the external force. In addition, the contact force also can be decomposed into a normal force and a tangential force (friction force). We assumed that there are 3 contact points (C_1, C_2, and C_3), and the contact force corresponding to each contact point is defined as F_1, F_2 and F_3. In fact, the status of the catheter in the blood vessel is very complex, and the number of contact points between them is also uncertain. Therefore, the total force of the catheter can be expressed as formula (5).

$$F_{cat.} = \sum_{i=1}^{k} F_i + F_v + F_e + F_{fs} \tag{5}$$

where, $F_{\text{cat.}}$ is the total force. F_{i} is the contact force between the catheter and the blood vessel wall. F_{v} is the viscous force, from viscosity of the blood. Fe is the external force, from the catheter sheath. And F_{fs} is the friction force between the outer wall of the guidewire and the inner wall of the catheter.

Hu *et al.* [36] studied that the blood vessel can be divided into the outer wall and the inner wall, the contact model between the catheter and the blood vessel wall is shown in Fig.7. Fig.7 (a) is defined as "the transitional contact" and Fig.7 (b) is defined as "the full contact". In addition, R_1 is the distance from the center line to the inner wall of the blood vessel and R_2 is the distance from the center line to the center line of vessel wall.

In the transitional contact phase, the condition that needs to be satisfied is that D is greater than R_1 and less than R_2, and its mathematical expression is shown in formula (6).

$$F_{n1} = \frac{k_p(D-R_1)^2}{2(R_2-R_1)} + \frac{(3R_2-R_1-2D)(D-R_1)^2}{(R_2-R_1)^3} c_p V_{n1} \tag{6}$$

Also, in the full contact phase, the condition that needs to be satisfied is that D is greater than R_2, its mathematical expression is shown in formula (7).

$$F_{n1} = \frac{1}{2} k_p (2D - R_2 - R_1) + c_p V_{n1} \tag{7}$$

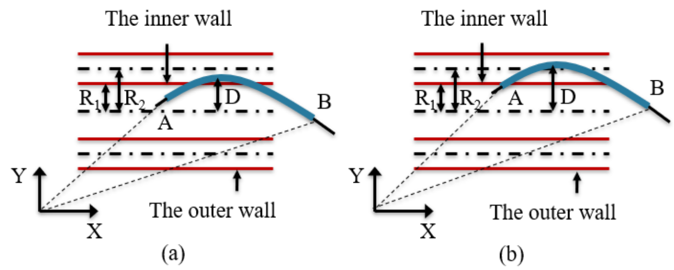

Fig. 7. The contact force model between the catheter and the blood vessel during the surgery (a) The transitional contact ($R_1 < D < R_2$). (b) The full contact ($D > R_2$).

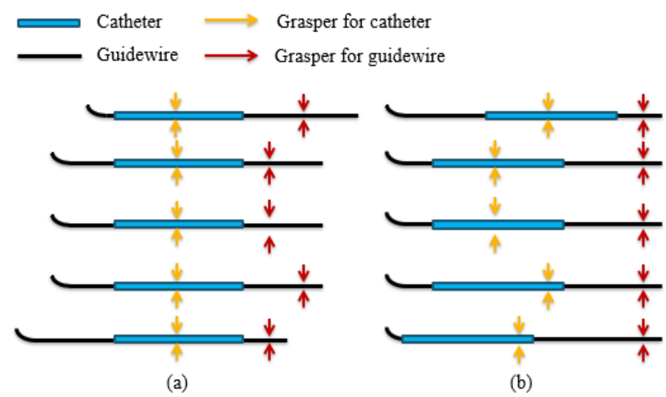

Fig. 8. The collaborative working between the guidewire and catheter. (a) The operation process of guidewire. (b) The operation process of catheter.

where, D is the cutting depth of the blood vessel wall along the normal direction, k_p and c_p are the stiffness coefficient and the damping coefficient of the blood vessel wall, respectively, and V_{n1} is the velocity of the catheter along the normal direction.

In addition, the collaborative operating between the guidewire and catheter is very important during the operation. The details of the collaborative operating working principle are as shown in Fig.8, the guidewire plays the role of guiding and supporting the catheter, and the catheter follows the guidewire to navigate the target point smoothly. Like the force analysis on the catheter, the force of the guidewire can be analyzed in the same way, the force of the guidewire mainly includes the contact force depending on the number of contact points, the viscous force, and the friction force. Compared with the total force analysis of the catheter, the difference is that there is no external force applied on the guide wire. Therefore, the total force of the guidewire can be expressed as formula (8).

$$F_{gui.} = \sum_{i=1}^{k} F_i + F_v + F_{fs} \tag{8}$$

where, $F_{\text{gui.}}$ is the total force. F_{i} is the contact force between the guidewire and the blood vessel. F_{v} is the viscous force, from the viscosity of the blood. And F_{fs} is the friction force between the inner wall of the catheter and the outer wall of the guidewire.

C. Friction Model

Canudas de Wit *et al.* [37] studied that the two surfaces that touch each other are, on a microscopic level, very rough. They

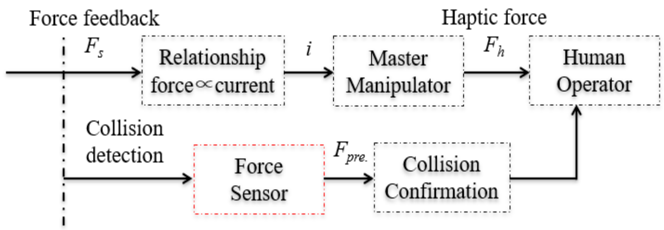

Fig. 9. The schematic diagram of safety improvement strategy.

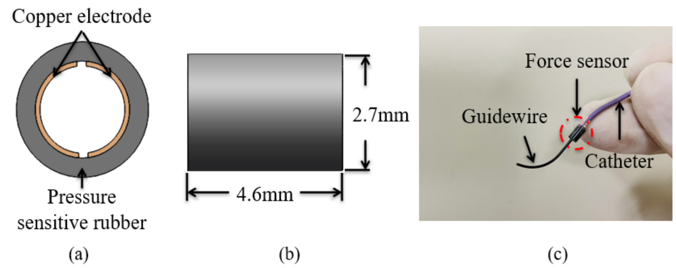

Fig. 10. The self-developed force sensor based on pressure sensitive rubbers. (a) Front view. (b) Left view. (c) The physical picture (Location: **Catheter tip**).

regarded it as two rigid bodies touching each other through the elastic bristles. When there is an external force, the elastic bristles will be deformed, and then the friction force will be generated. Besides, with the development of fluid mechanics, it was found that liquids are viscosity. Considering the viscosity of the liquid, a comprehensive typical mathematical description was also given to describe the friction behavior between the two surfaces that touch each other. The form of the friction behavior is shown in the formulas (9), (10), and (11),

$$F_{f1} = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 V_{f1} \tag{9}$$

$$\dot{z} = V_{f1} - \frac{|V_{f1}|}{g(V_{f1})} z \tag{10}$$

$$\sigma_0 g(V_{f1}) = F_c + (F_s - F_c) e^{-(V_{f1}/V_s)^2} \tag{11}$$

where, σ_0 is the stiffness coefficient, z is the average deflection of elastic bristles, σ_1 is the damping coefficient, σ_2 is the viscous coefficient, F_c is Coulomb friction, F_s is Stiction friction, V_{f1} is the velocity of the catheter along the normal direction, V_s is Stri beck velocity, and $\sigma_0 g(V_{f1})$ is Stribeck effect.

D. Safety Improvement Strategy

However, among the many contact points, one is special, that is, the contact between the tip of the catheter and the blood vessel wall. When the tip of the catheter collides with the blood vessel wall in the normal direction, it is easy to puncture the vessel wall due to excessive collision force and bring danger to the operation. In addition, in this study, the contact force between the catheter and the blood vessel was used as a reference to achieve the force feedback. Although the force feedback can provide doctors with a sense of tactile presence, the collision force between the tip of the catheter and the blood vessel cannot be well reflected.

A safety improvement strategy was proposed to enhance the safety of the robot-assisted system and its schematic diagram is shown in Fig.9, combined with the force feedback of the system, a force sensor was developed to detect the collision between the tip of the catheter and the blood vessel.

A self-developed force sensor was used to detect the collision force between the tip of the catheter and the vessel wall, and its structure is shown in Fig.10. Fig.10 (a) is the design method, and Fig.10 (b) is the dimensions, with an outer diameter of 2.7 mm and a length of 4.6 mm. Compared with the previous design [38], the dimension is significantly smaller. Fig.10 (c) is the physical picture. The working principle of the self-developed force sensor relies on the piezoresistive effect of pressure sensitive rubber to measure the contact force between the tip of the catheter and the blood vessel wall. In addition, the self-developed force sensor is simple in design and cost-saving.

A single-arm bridge is used to measure the output voltage of the self-developed force sensor, the resistance of the other three bridge arms is 1 KΩ, and the input voltage of the measurement circuit is 5 V. The self-developed force sensor is calibrated with a load cell (TU-UJ5N, TEAC, Japan), and the calibration results is fitted by MATLAB, as shown in the formula (12).

$$F_{pre.} = 0.1849U_0^3 + 0.2279U_0^2 + 0.51U_0 + 0.01437 \tag{12}$$

where, $F_{\text{pre.}}$ is the collision force of the tip of the catheter, U_0 is the output voltage of the measurement circuit.

IV. Experiments and Results

To verify the proposed method in Section V, the experiments in "Vitro" were completed in this Section. And the experiments include the determination of the force between the catheter and the sheath, the determination of the force between the outer wall of the guidewire and the inner wall of the catheter and the safety evaluation of the system in two surgical tasks.

A. The Determination of the Force Between the Catheter and the Catheter Sheath

1) Experimental Setup: The force between the catheter and the catheter sheath mainly comes from the friction between the inner wall of the sheath and the outer wall of the catheter. To obtain the friction force between the catheter and the catheter sheath, a reciprocating motion was repeated three times by slave manipulator at a velocity of 10.90 mm/s, the catheter was held straight, and the distance was 43.60 mm. The behavior includes catheter insertion and retraction. A catheter used in this experiment was a 4Fr catheter.

2) Experimental Results: Fig.11 (a) is the statistical result of the friction force between the catheter and the catheter sheath. For the behavior of catheter insertion, the average value the friction force was −0.513 N after the experiment was repeated three times. And for the behavior of catheter retraction, the average value of the friction force was 0.586 N after the experiment was repeated three times.

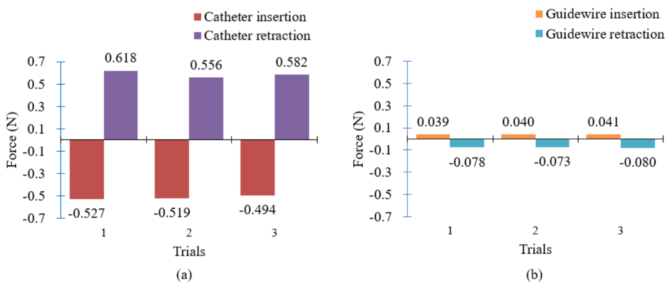

Fig. 11. The friction forces. (a) between the catheter and the catheter sheath. (b) between the inner wall of the catheter and the outer wall of the guidewire.

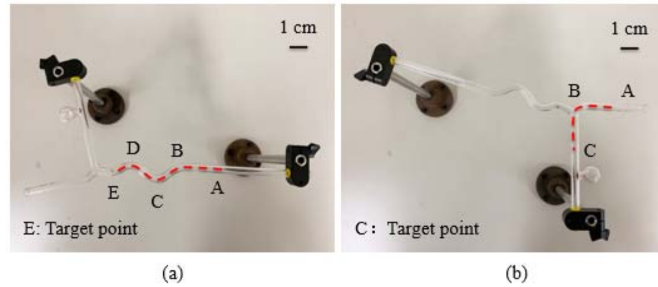

Fig. 12. Experimental setup. (a) Task I. (b) Task II.

B. The Determination of the Force Between the Inner Wall of the Catheter and the Outer Wall of the Guidewire

1) Experimental Setup: The force between the inner wall of the catheter and the outer wall of the guidewire is also mainly due to the friction. Just like the last experiment "The determination of the force between the catheter and the sheath". To determine the friction force between the inner wall of the catheter and the outer wall of the guidewire, a reciprocating motion was repeated three times at the velocity of 10.90 mm/s, the guidewire was held straight, and the distance was 43.60 mm. The behavior includes guidewire insertion and retraction. The other condition of this experiment was that the catheter was clamped by the slave manipulator and without any movement, the guidewire passed through the catheter. The tip of the catheter is in the same position as the tip of the guidewire, the guidewire used in this experiment was a long guidewire with an angle type of 45 degrees.

2) Experimental Results: Fig.11 (b) is the statistical result of the friction force between the inner wall of the catheter and the outer wall of the guidewire. For the guidewire insertion, the average value was 0.040 N after the experiment was repeated three times. And for the guidewire retraction, the average value was -0.077 N. after the experiment was repeated three times.

C. The Safety Evaluation of the System in Two Tasks

1) Experimental Setup: Fig.12 is a blood vessel model used in this paper has an outer diameter of 7 mm and an inner diameter of 5 mm. Two surgical tasks were designed to verify the safety of the system by using the proposed method (Combined with the force feedback of the system and the collision detection of the catheter tip). In Fig.12 (a), the starting and target points of the task I are points "A" and "E", respectively, and the path of the catheter and the guidewire is "A-B-C-D-E". In Fig.12 (b), the starting and target points of the task II are points "A" and "C", respectively, and the path of the guidewire and the catheter is "A-B-C".

Each task was repeated three times by the slave manipulator at the velocity of 10.90 mm/s. In addition, the operation process of these two tasks is different. As for the task I, the catheter and the guidewire were inserted twice to navigate the target position. And as for the task II, the catheter and guidewire were inserted once to navigate the target position. Compared with the surgical task I, the path of the task II was relatively short. The sampling time of all experiments was 100 ms.

2) Experimental Results: As shown in Fig.13, it is the sample of the force detection in real time and the contact force between the blood vessel and the catheter. According to the analysis in Section III, the total force on the catheter during the operation mainly includes the contact force between the catheter and the blood vessel (F_{i}), the friction force between the outer wall of the guidewire and inner wall of the catheter (F_{fs}), the friction force between the catheter and the catheter sheath (F_{e}), and the viscous force (F_{v}). In this study, we defined the sum of F_{fs}, F_{e}, and F_{v} as the disturbance force. There are four dotted black borders. "GW-FI" indicates the guidewire was inserted for the first time, "C-FI" indicates the catheter was inserted for the first time, "GW-SI" indicates the guidewire was inserted for the second time, and "C-SI" means the catheter was inserted for the second time. In the "C-FI" of Fig.13 (a), it is not difficult to find that the disturbance force is significantly greater than the contact force during the operation, and the disturbance force accounts for 72% of the total force. If the total force is used as the reference force to achieve the haptic force feedback, it will affect the judgment of the surgeons and bring some operational difficulties. Therefore, the total force after the disturbance force is eliminated, that is, the contact force is used as a reference force to realize the haptic force feedback of the system. The accuracy of the force feedback will be improved. Similarly, in the "C-SI" of Fig.13 (a), the disturbance force accounts for 44% of the total force, in the "C-FI" of Fig.13 (b), the disturbance force accounts for 55% of the total force. In this experiment, the total force was detected by the load cell on the slave manipulator (As shown in Fig.4), and the contact force was calculated by eliminating the disturbance force.

The experiments were completed at a constant speed of 10.90 mm/s. According to the experiments in the part B and C of this section, the friction force between the catheter and the catheter sheath (F_{e}) was -0.513 N, the friction force between the outer wall of the guidewire and inner wall of the catheter (F_{fs}) was -0.077 N, and the viscous force was 0 N because no liquid was injected into the blood vessel model in the experimental setup (as shown in Fig.12). So, the disturbance force during the operation can be approximately replaced by a constant value of -0.590 N.

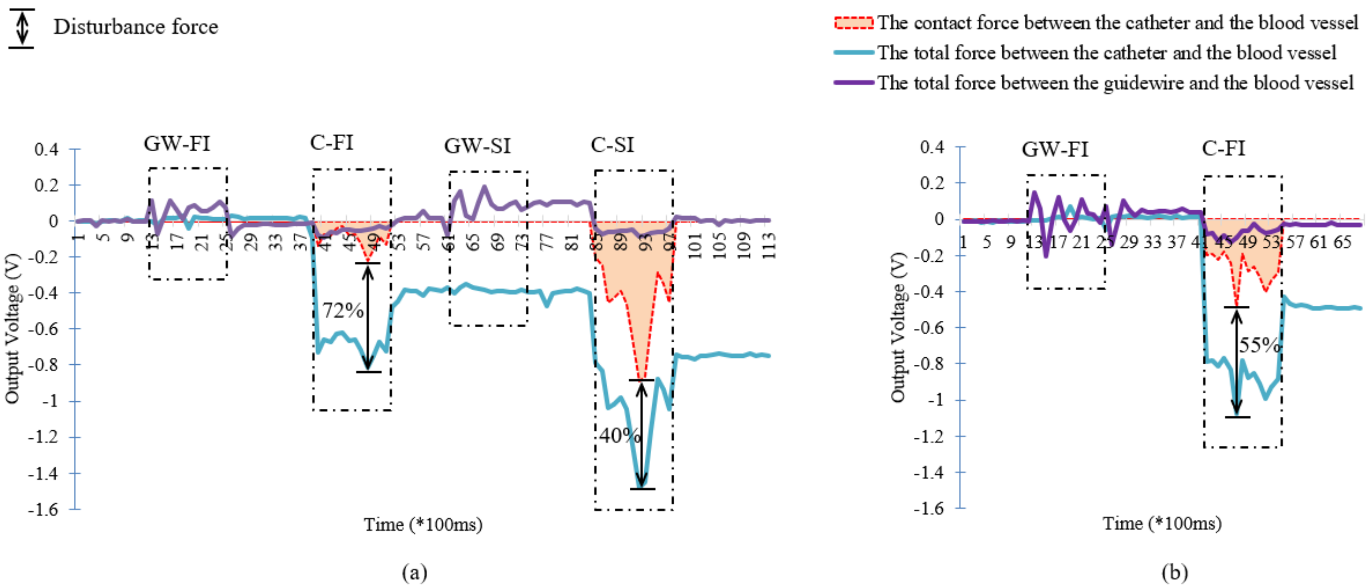

Fig. 13. The samples of the force detection in real time and the contact force between the catheter and the blood vessel. (a) In task I. (b) In task II.

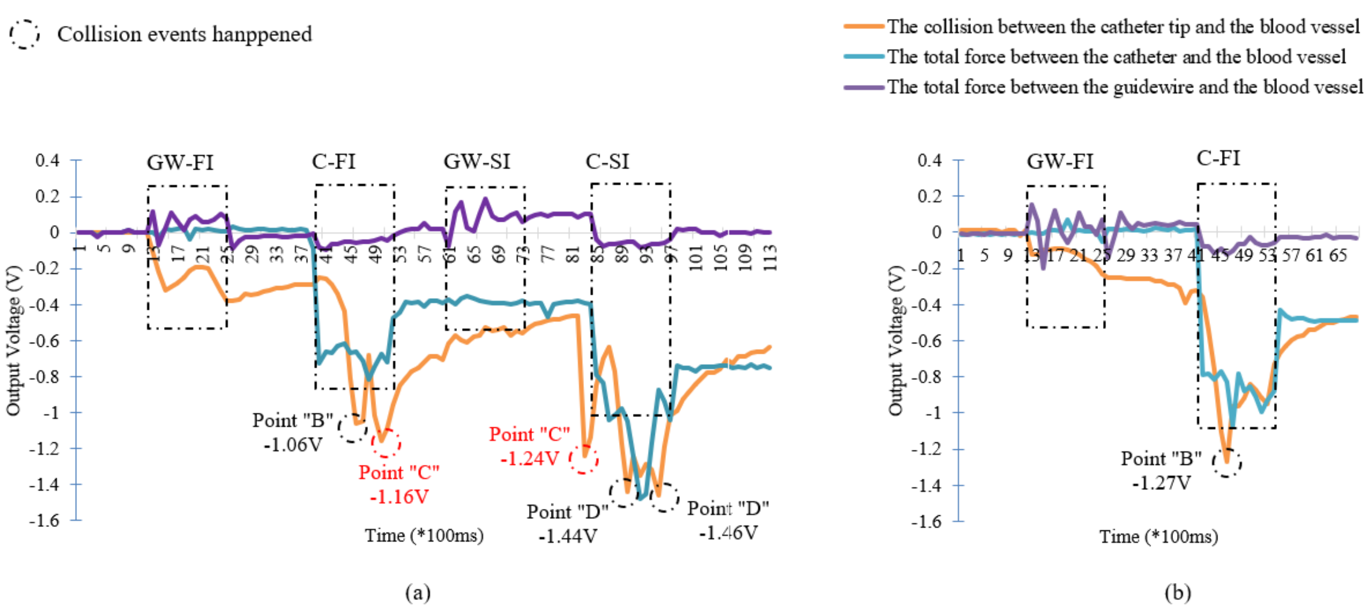

Fig. 14. The samples of the force detection in real time and the collision between the tip of the catheter and the blood vessel. (a) In task I. (b) In task II.

As shown in Fig.14, it is the samples of the force detection in real time and the collision between the tip of the catheter and the blood vessel. Similar to Fig.13, the "GW-FI" indicates the guide wire was inserted for the first time, "C-FI" indicates the catheter was inserted for the first time, "GW-SI" indicates the guidewire was inserted for the second time, and "C-SI" means the catheter was inserted for the second time. At point "B" in Fig.12 (a), the tip of the catheter collided with the blood vessel wall for the first time, and the collision force was −1.06 V (−0.490 N). Besides, at point "C", the tip of the catheter collided with the blood vessel twice, and the collision forces were −1.16 V (−0.559 N) and −1.24 V (−0.620 N), respectively. At point "D", the tip of the catheter also collided with the blood vessel twice, and the collision forces were −1.44 V (−0.800 N) and −1.46 V (−0.820 N), respectively. In Fig.12 (b), at point "B", the tip of the catheter collided with the blood vessel once, and the collision forces was −1.27 V (−0.644 N). It is not difficult to find that the change of the collision force was relatively obvious in comparation with the total force acting on the catheter at the same time. Based on the analysis of above results, it was indicated that the contact force between the tip of the catheter and the blood vessel can be well reflected by a force sensor designed in this study, and the safety of the robot- assisted system can be improved by combining the force feedback of the system with the collision detection of the self-developed force sensor.

TABLE I
THE STATISTICAL RESULTS OF THE MAXIMUM FORCE AND THE AVERAGE FORCE AFTER THE EXPERIMENT WAS REPEATED FOR THREE TIMES IN TASK I AND TASK II

NO.	Forces	Task I				Task II	
		GW-FI	GW-SI	C-FI	C-SI	GW-FI	C-FI
1	Maximum (N)	0.131	0.121	-0.856	-1.555	0.208	-1.044
	Average (N)	0.062	0.063	-0.721	-1.093	0.073	-0.888
2	Maximum (N)	0.115	0.190	-0.827	-1.493	0.222	-0.921
	Average (N)	0.061	0.079	-0.660	-1.083	0.108	-0.753
3	Maximum (N)	0.136	0.194	-0.826	-1.548	0.205	-1.122
	Average (N)	0.051	0.087	-0.728	-1.091	0.052	-0.902

TABLE II
THE STATISTICAL RESULTS OF THE COLLISION FORCE AFTER THE EXPERIMENT WAS REPEATED FOR THREE TIMES IN TASK I AND TASK II

NO. Force \ Points	Task I					Task II
	"B"	"C"		"D"		"B"
1	-0.490	-0.559	-0.620	-0.800	-0.820	-0.670
2	-0.545	-0.696	-0.678	-0.862	-0.820	-0.644
3	-0.538	-0.612	-0.644	-0.884	-0.741	-0.670
Average (N)	-0.524	-0.622	-0.647	-0.849	-0.794	-0.661

Table I is the statistical results of the maximum force and the average force after the experiment was repeated for three times in task I and task II. It was indicated that the developed system has good stability in force measurement, because the experiment results of the three groups were similar. After comparison, the difference is that the force of the second insertion of the catheter and the guidewire was significantly greater than the force of the first insertion. The reason is that as the catheter or the guidewire was inserted, the contact point between the catheter or the guide wire with the blood vessel increased.

Table II is the statistical results of the collision force after the experiment was repeated for three times in task I and task II. It was indicated that the self-developed force sensor has the good stability in detecting the collision between the tip of the catheter and the vessel wall. The points B, C, D in Fig.12 (a) and the point B in Fig. 12 (b) have different angles, so that the collision force of each point was very different. However, after the experiment was repeated for three times, the output of the force sensor was similar. The collision force is greatly influenced by the direction of the tip of the catheter, and it can be reduced by adjusting the direction of the tip of the catheter.

V. Discussion

Aiming at the challenges mentioned in Section I. This paper developed a tactile sensing robot-assisted system for VIS based on the design requirements, analyzed the total force between the surgical tools and the blood vessel by modeling, and developed a force sensor to confirm the collision force between the catheter tip and the blood vessel wall. To verify the analysis method and the safety of the system, the experiments in "Vitro" were carried out by combining the force feedback and the collision detection.

In the determination of the force between the catheter and the catheter sheath, and the determination of the force between the inner wall of the catheter and the outer wall of the guidewire. A constant speed of 10.90 mm/s was set to perform the experiments, the forces Fe and Ffs were also regarded as a constant value. In the safety evaluation of the system in two tasks. The disturbance force accounts for a large proportion in the total force (as shown in Fig.13), and it can be eliminated by using the analysis method. So, the accuracy of the force feedback can be enhanced. Besides, the collision cannot be well reflected in the total force (as shown in Fig.14), and it can be confirmed by the self-developed force sensor. By combining the force feedback and force sensor, the safety of the robot-assisted system can be improved. But in the actual operation, F_e and F_{fs} may also be affected by other factors. Therefore, the effect of other factors should be fully considered in the future. Moreover, although the structure and performance of the force sensor have been greatly improved compared with previous studies of our group, its detection accuracy still needs to be improved. For example, the frequency of the noise signal will be analyzed through the spectrogram, and the filter will be used to eliminate the noise signal.

VI. Conclusion

In this paper, a tactile sensing robot-assisted system for VIS was developed to assist the doctors to complete the surgery, the total force on the guidewire and the catheter during the surgery was analyzed in detail by modeling and a force sensor based on pressure sensitive rubbers was designed to confirm the collision between the tip of the catheter and the blood vessel. To verify the proposed analysis method and the self-developed force, a series of experiments were performed by combining the force feedback of the robot-assisted system and the self-developed force sensor. It was indicated that the accuracy of the force feedback can be enhance by using the proposed analysis method, and the collision force can be detected by the self-developed force sensor, which is helpful for surgeons to make accurate judgments and improve the safety performance of the system. Therefore, we believe that the robot-assisted system proposed in this paper has high safety.

In the future, the tactile sensing robot-assisted system will be verified through the experiments in "Vivo".

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