Active Suppression Method of Dangerous Behaviors for Robot-Assisted Vascular Interventional Surgery

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***Abstract*— The procedure of vascular interventional surgery (VIS) is very complicated. It requires doctors to wear the protecting suits and manipulate the flexible instruments (catheters and guidewires) for a long time to complete the treatment, which may fatigue the doctors and lead to misoperation. Besides, the X-ray radiation in the operating room is also bad for doctors' health. So, to solve the above challenges, a novel robot-assisted system was developed for VIS, which realizes the separation of the doctor and the operating room; a preliminary method was used on the slave side to reduce the excessive collision force when the tip of the catheter travels through the curved blood vessel, and the active enhancing safety method of the robot-assisted system was proposed to reduce the danger caused by doctors' misoperation (dangerous behaviors) during the surgery. Finally, to verify the proposed methods, a series of experiments *in vitro* were conducted, and experimental results indicated that the method of assisting the deflection of the tip of the catheter has the potential to reduce the excessive collision force, the collision force at the tip of the catheter was reduced by 0.104 N when a misoperation occurred during the operation procedure under the condition of the active enhancing safety method, and the stronger sense of the tactile presence was generated by the master manipulator when the total force of the slave side was greater than 1.0 N. Therefore, based on the above results, we believe that the proposed methods are effective.**

***Index Terms*— Active enhancing safety method, active suppression method, collision force, flexible instruments, haptic force feedback, robot-assisted vascular interventional surgery (VIS).**

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I. Introduction

CARDIOVASCULAR disease is a serious threat to human health, usually leading to myocardial infarction or stroke. Open surgery will bring great pain to patients. With the development of medical technology, vascular interventional surgery (VIS) has brought good news to patients. VIS has been widely concerned due to its advantages of reducing patients' pain. Nowadays, the treatment method mainly includes manual operation and the emerging robot-assisted VIS. The flexible instruments (guidewires and catheters) are operated into the blood vessel branches and targets for diagnosis and therapy during the operation. VIS is a complicated procedure, in manual operation, the protecting suits, and the long-time operation, easy to fatigue the doctors and bring the dangers. Compared with the manual operation, the robot-assisted VIS has the characteristics of high accuracy and good stability, which can reduce the burden on doctors and avoid the damage of X-rays to doctors' health.

A. Current Research Status

As mentioned before, in manual operation, the protecting suits and long-time operation is a great challenge to a doctor's physical strength. Considering this point, the novel robot-assisted system was developed based on the "master–slave" structure [1]–[8]. The doctor operates the master device in the control room outside the operating room and controls the slave manipulator to complete the operation, which can prevent the doctors from being exposed to X-ray radiation. For the master–slave control system, keeping a good sense of presence is an important guarantee for the success of the surgery. Therefore, the master manipulator was proposed based on the magnetorheological fluids (MR fluids) [9]–[11], and the linear motor [12] to achieve the haptic force feedback. The image guidance technology [13], [14] was also integrated into the system to provide the doctor with accurate posture information of the surgical tools in the form of visual feedback. Besides, there are some studies devoted to improving the overall performance of the robot-assisted system from control methods. A noncontact detection method was proposed to reduce the detection error of the doctor's action [15], an adaptive system based on the motion control and the force modulation was designed to overcome the problem that the existing robot-assisted system has not consider the hysteretic behavior [16], a generalized predictive control and a terminal sliding mode controller were proposed to suppress the communication delay between the master side and the slave side, and improve the robustness of the robot-assisted system [17], a simplified piecewise linear model was proposed to compensate nonlinear hysteresis of the dead zone and the backlash [18], a generative adversarial imitation learning [19] and a supervised semi-autonomous control method [20] were proposed to improve the efficiency of the surgery and reduce the fatigue of the doctor for the repetitive task, and a fringe field navigation was proposed to realize the navigation of the flexible instruments in the deeper vascular regions [21]. The acquisition of the force on the surgical tools is a topic that cannot be ignored, which can be achieved by the methods of developing the fiber Bragg grating-based force sensor [22], [23] and the small and highly sensitive material-based force sensor [24]. Besides, in order to try to obtain the important force information without using the force sensor, a kinetic model prediction [25] and a sensor-less estimation [26] were proposed to obtain the distal force and the contact force during the surgery. Although the operation is very successful, the blood vessel may be damaged by collisions with the flexible instruments to some extent. The multilevel operation strategy [27] and the magnetic field-assisted navigation of the probe in the blood vessel [28] were presented to reduce the risk of the blood vessel suffering from the damage. In addition to the above studies, some studies have focused on the development of the specially manufactured catheters [29], [30], the new drive method of the catheter [31], and the analysis of the doctor's behavior [32].

By summarizing the current research, the study on the active suppression method of the dangerous behaviors for robot-assisted VIS still seems to be a challenge that needs to be addressed.

B. Challenges and Contributions

Safety performance has always been an important part of the emerging robot-assisted VIS. If the safety performance cannot be guaranteed, it is easy to cause the puncture of the blood vessels due to the doctor's misoperation and the sudden accident. So, the focus of this article is to address the challenge of how to actively avoid the dangerous behaviors during the operation through the proposed active suppression method for the robot-assisted VIS. The novelty and the detailed contribution of this article are listed below.

1) A novel robot-assisted system was conceived and developed to assist doctors in completing the surgery, which can provide a good sense of tactile presence to doctors, avoid the X-ray radiation of doctors, and reduce the fatigue of doctors.
2) A preliminary method was proposed based on magnetic field control to assist in the deflection of the catheter tip. This method can enable the catheter to travel through the more curved blood vessel with a relatively small collision force.
3) An active enhancing safety method was proposed to actively avoid the dangers caused by the doctor's misoperation and the sudden accident. The basic idea of the active enhancing safety method is to produce the different suppression behaviors at the master and slave sides according to the collision force and the total force. Compared with the passive method, it can suppress dangerous behaviors in time.
4) The experiments *in vitro* were designed and completed to evaluate the proposed methods. The results demonstrated that the deflection method based on magnetic field control of the catheter tip has the potential of reducing the collision force as the catheter travels through the more curved blood vessel. In addition, under the condition of the proposed active enhancing safety method, the collision force at the tip of the catheter was reduced by 0.104 N when a misoperation occurred. The sense of tactile presence was enhanced by the master manipulator when the total force from the slave side was greater than 1.0 N.

The robot-assisted system for VIS is conceived and developed in Section II. The principles and methods are used to improve the safety performance in robot-assisted VIS, which is described in Section III. The safety verification experiments are conducted in Section IV. The discussion is analyzed in Section V. The conclusion is given in Section VI.

II. System Description

The robot-assisted system for VIS is proposed to improve the stability, accuracy, and safety performance of the operation. The conceptual framework of the robot-assisted system is shown in Fig. 1, and the master manipulator collects the operating action of the doctor and provides the doctor with a good sense of presence. The slave manipulator operates the guidewire and the catheter to perform the operation. In the procedure of intervention, the total force of the guidewire and the catheter is detected, collected, and fed back to the master side in real-time through the force sensors integrated into the developed slave manipulator. In addition, the special contact force (the collision force) at the tip of the catheter is detected and collected in real-time through the self-developed force sensor attached to the tip of the catheter. In addition to the acquisition of force information during surgery, the acquisition of visual information is also important, and a camera is installed on the slave side to monitor the movement state of the catheter and the guidewire. The safety performance of the robot-assisted VIS can be guaranteed through force and visual feedback.

The active enhancing safety method proposed in this article is to make the robot-assisted system generate the active behavior according to the total force and the collision force during surgery, avoiding the danger caused by doctors' misoperation. Compared with the passive method, it can suppress dangerous behaviors in time.

A. Master Manipulator

The proposed master manipulator is shown in Fig. 2, which consists of the guidewire control unit and the catheter control

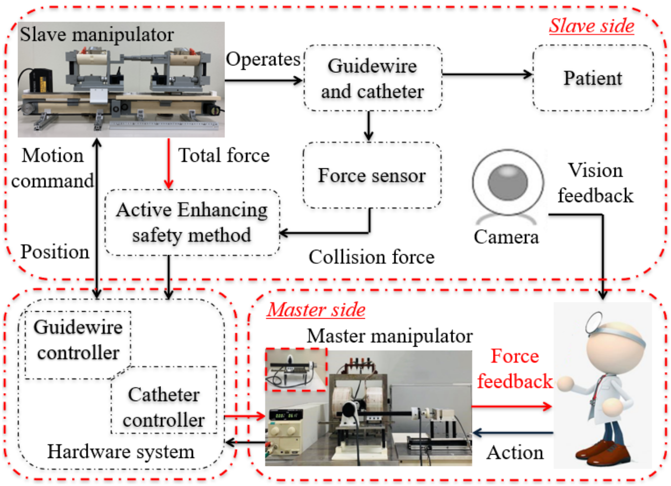


Fig. 1. Conceptual framework of the proposed robot-assisted system for VIS.

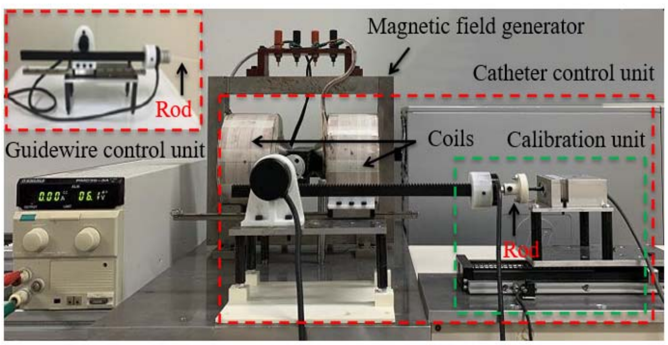


Fig. 2. Master manipulator with haptic force feedback [1], [2].

TABLE I
RELATED PARAMETERS OF THE MAGNETIC FIELD GENERATOR

The parameters of the coil			The copper wire	
Inner diameter	Outer diameter	Height	Number of turns	Diameter
30mm	120mm	68mm	1200T	1.6mm

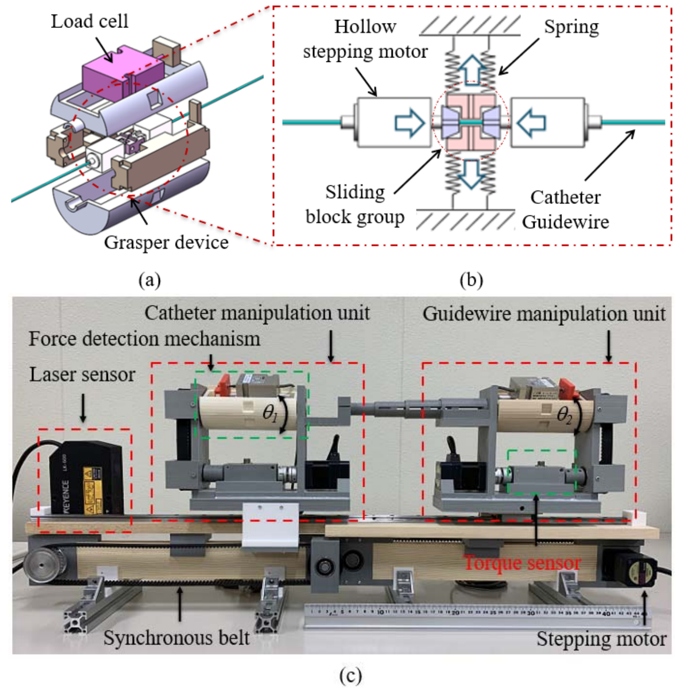


Fig. 3. Slave manipulator with the function of collaborative operation of the guidewire and the catheter. (a) Force detection mechanism. (b) Working principle of the grasper device. (c) Developed device.

unit. This device has two advantages: first, it respects the operating habit of the doctor by using two cylindrical rods (like a real guidewire or a real catheter) as inputs of the doctor's action, helping doctors to use their operating experience summarized from the clinical procedure. In addition, it is easy to be used, reducing the doctor's training time. Second, it realizes the haptic force feedback by using MR fluids, enhancing the doctor's tactile presence during the operation. In this design, the collection method of operating actions of the doctor is achieved by four encoders (MTL, MES 020-2000P, Japan), and the realization method of the haptic force is realized by the hybrid application of the magnetic field generator and the MR fluid. The main parameters of the designed magnetic field generator are listed in Table I. Each coil is made of 1200 turns of copper wire with a diameter of 1.6 mm. The inner diameter, the outer diameter, and the height of each copper coil are 30, 120, and 68 mm, respectively. The magnetic field generator is inspired by the electromagnet. So, two iron cores are inserted into the center of two copper coils. The master manipulator is a continuous work of the previous studies of our group [9]–[11].

B. Slave Manipulator

During the operation, the collaborative operation between the catheter and the guidewire is very important, but they must not interfere with each other. A novel slave manipulator is proposed to satisfy this requirement. Fig. 3(a) is the structure of the force detection mechanism, the output shaft of the load cell (TU-UJ5N, TEAC, Japan) is connected to the 3D-printed grasper device box, and the sliding rail is mounted on the bottom of the 3D-printed grasper device box to realize the transmission of the force to the load cell. Fig. 3(b) is the working principle of the grasper device, and the interaction between two hollow stepping motors (LIKO MOT OR, 20BYGH30-0604A-ZK3M5) and four springs control the opening and closing of the sliding block group, thereby realizing the clamping and releasing of the catheter or the guidewire. Fig. 3(c) is the developed device, where the slave manipulator has a catheter manipulation unit and a guidewire manipulation unit, which are independent of each other, so, it is easy to achieve the independent motion of a catheter or a guidewire, and the simultaneous motion of a guidewire and a catheter. Both the independent motion and the simultaneous motion are driven by the stepping motor with a resolution of 0.36° (ASM46AA, ORIENTAL MOTOR, Japan). The maximum motion distance of each manipulation unit is 40 cm, and the overall length of the slave manipulator is 92 cm.

C. Self-Developed Force Sensor

The self-developed force sensor is shown in Fig. 4, which uses the piezoresistive effect of the pressure-sensitive rubber to monitor the collision at the catheter tip during operation.

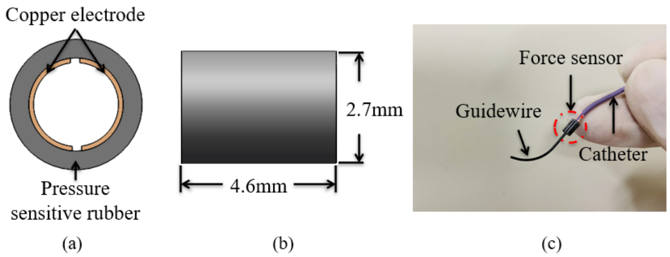


Fig. 4. Self-developed force sensor. (a) Front view. (b) Left view. (c) Force sensor is attached to the tip of the catheter.

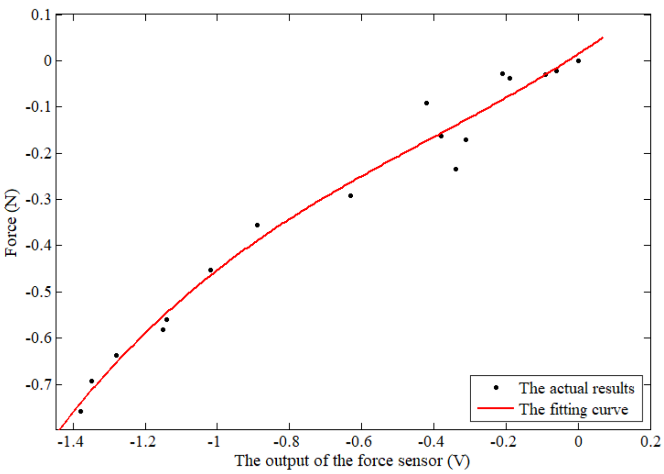


Fig. 5. Relationship between the output of force sensor and the force.

The calibration method between the self-developed force sensor and the load cell has been reported in [33]; the force sensor presented in this study is an improvement of the self-made force sensor presented in [33]. Compared with the previous design, it has a smaller size (outer diameter: 2.7 mm; length: 4.6 mm). Besides, the self-made force sensor and three resistors with a value of 1 kΩ form a single-arm measurement circuit to monitor the force at the tip of the catheter during the operation. The input voltage of the single-arm circuit is 5 V. The calibration of the self-developed force sensor is fitted by the MATLAB software. Its process is that the output value of the force sensor and the commercial load cell are imported into the MATLAB software, then the cubic polynomial is selected in the "curve fitting tool," and, finally, the fitting is done automatically. The results are shown in (1) and Fig. 5, in (1), the numeric values, such as 0.1849, 0.2279, 0.51, and 0.01437 are generated automatically by the MATLAB software. $F_{\text{pre.}}$ is the collision force at the catheter tip during the operation and U_0 is the output of the force sensor

$$F_{\text{pre.}} = 0.1849U_0^3 + 0.2279U_0^2 + 0.51U_0 + 0.01437. \quad (1)$$

Compared with commercial force sensors, the self-developed force sensor in our research has the characteristics of cost-saving and easy implementation.

III. Principles and Methods

The realization of the proposed active suppression method of dangerous behaviors will be described in this section, including the implementation of the haptic force feedback of the proposed system, the reduction method of the collision force at the catheter tip, and the active enhancing safety method of avoiding the danger caused by doctors' misoperation and sudden accidents during the operation.

A. Implementation of the Haptic Force Feedback

The haptic force feedback of the robot-assisted system is used to provide the doctor with a good sense of tactile presence and grasp the force state of the catheter in the blood vessels. Based on the previous studies of our group [9]–[11], the inspiration for the haptic force feedback comes from MR fluids. MR fluids are a kind of relatively active intelligent material. When there is no external magnetic field, it is characterized as the "Newtonian fluid" with low viscosity, and when an external magnetic field is applied, it is characterized as the "Bingham fluid" with high viscosity and low fluidity. The viscosity of the MR fluid is related to the intensity of the magnetic field. In order to provide the magnetic field for MR fluids, the magnetic field generator is integrated into the master manipulator. The relationship between the input current of the magnetic field generator and the haptic force generated by the master manipulator is shown in equations (2) and (3). It is worthy to emphasize that the calibration unit is shown in Fig. 2

$$f_{\text{te}} = -7.5i^3+8.464i^2+0.4357i+0.3686, \quad (0 \text{ A} < i < 0.7 \text{ A}) \quad (2)$$

$$f_{\text{th}} = 10.56i^3-11.33i^2+0.2183i - 0.37, \quad (0 \text{ A} < i < 0.7 \text{ A}) \quad (3)$$

where f_{te} is the haptic force (tension) generated by the proposed master manipulator, i is the electric current, and f_{th} is the haptic force (thrust) generated by the proposed master manipulator.

B. Reduction of the Collision Force at the Catheter Tip

The greater the collision force at the catheter tip, the higher the probability of the blood vessel being punctured. So, to reduce the probability of the blood vessel being punctured, a method for the deflection of the tip of the catheter is proposed in this study. The schematic of the method is shown in Fig. 6. As shown in Fig. 6(a), it is difficult for the catheter to access the blood vessel branch on the left with a small collision force when there is no magnetic field. However, compared with Fig. 6(a), the magnetic field generator composed of two energized coils in Fig. 6(b) will generate a uniform magnetic field, and the magnet at the tip of the catheter will deflect toward the magnetic induction line under the action of the uniform magnetic field. The related parameters of the developed magnetic field generator have been introduced in Section II and listed in Table I.

A Tesla meter was used to detect the magnetic field intensity with the increase of the input current, and its detection method is shown in Fig. 7. The relationship between them is given in Table II, and it is not difficult to find that the magnetic field intensity increases in a nearly linear trend when the input current increases with a step of 0.2 A. However, the magnetic

TABLE II
CHANGE IN MAGNETIC FIELD INTENSITY AS THE INPUT CURRENT INCREASES IN A STEP OF 0.2 A

I (A) / B (mT)	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8
N-pole	0.0	13.2	26.6	40.8	54.4	67.7	81.3	94.2	108.1	123.5	134.3	134.3	134.3	134.3	134.3
S-pole	0.0	-13.2	-26.6	-40.8	-54.4	-67.7	-81.3	-94.2	-108.1	-123.5	-134.3	-134.3	-134.3	-134.3	-134.3

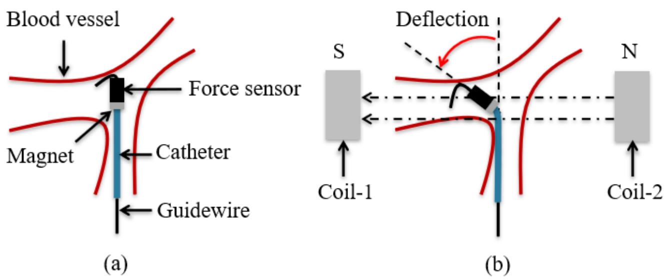


Fig. 6. Schematic for the deflection of the tip of the catheter. (a) In the absence of the magnetic field. (b) In the presence of the magnetic field.

TABLE III
CLASSIFICATION OF THE FORCE LEVELS DURING THE OPERATION

The type of force	Level	The robot-assisted system for VIS	M/S
Total force	A (<1.0N)	Haptic force feedback	M
	B (>1.0N)	Enhanced haptic force feedback	M
Collision force	C (>0.342N)	automatically retract the catheter	S

M: Master side S: Slave side

field intensity does not increase when the input current is 2.0 A, because it reaches the saturation state, the maximum value of magnetic field intensity can reach 134.3 mT. The maximum deflection of the tip of the catheter is about 15°, and the minimum deflection of the tip of the catheter is about 0° when there is no magnetic field.

The test results are shown in Fig. 7. In the initial state, the tip of the catheter was placed parallel to a Tesla meter in the center of the two cores [see Fig. 7(a)]. When the input current of 2.0 A was applied to the two coils, the magnetic field of 134.3 mT was generated, and the tip of the catheter was deflected obviously in the direction of the magnetic field [see Fig. 7(b)]. The power supply that provides the current was then turned off, and the tip of the catheter returns to the initial state due to its own stiffness [see Fig. 7(c)]. Finally, the input current of 2.0 A was applied to the two coils once again, and the tip of the catheter was deflected again like the first time [see Fig. 7(d)]. In the procedure of testing, the relationship between the change of the magnetic field intensity and the time is shown in Fig. 7(e).

C. Realization of the Active Enhancing Safety Method

During the operation, the catheter is subjected to a variety of forces. Only two forces, namely the total force and the collision force, are studied in this article. The total force is the sum of all types of forces, and it is detected by the load cell installed on the slave manipulator. The principle of the force detection mechanism is shown in Fig. 8. The collision force is the force after the catheter tip collides with the blood vessel, and it is confirmed and detected by the self-made force sensor described in Section II-C. The structure diagram of the self-made force sensor is shown in Fig. 4.

The active enhancing safety method can directly guarantee the safety performance of the robot-assisted VIS during the surgery. Based on our previous studies [9]–[11], the master manipulator can generate the haptic force and provide the doctor with tactile presence by using the state change of MR fluids. In addition to the haptic force feedback of the robot-assisted system, two other active enhancing safety methods are proposed in this study. As shown in Table III, the total force of the slave side can be classified into three levels and listed below.

1) *Level A:* When the total force during the operation is less than 1.0 N, the active enhancing safety method of the robot-assisted system will occur on the master side, and its behavior is to provide the doctor with conventional haptic force feedback.
2) *Level B:* When the total force during the operation is greater than 1.0 N, the proposed active enhancing safety method will occur on the master side, and its behavior is to provide the doctor with enhanced haptic force feedback.
3) *Level C:* When the collision force is greater than 0.342 N, the proposed active enhancing safety method of the robot-assisted system will occur on the slave side, and its behavior is to control the slave manipulator to automatically retract the catheter by 5 mm, which purpose is to prevent the blood vessel wall from being punctured due to the excessive collision force.

It is worthy to emphasize that the threshold listed in Table III is set by us. The safety threshold is set to provide the condition for validation of the proposed active enhancing safety method, and it can be adjusted according to patients' individual information.

The active enhancing safety method that occurs on the master side is used to remind the doctor whether the operation belongs to a safe area. The schematic of the active enhancing safety method that occurs on the master side is shown in Fig. 9, where x_m is the input of the doctor on the master side, x_s is the output of the slave manipulator, F_s is the total force of the slave side, F_h is the haptic force of the master manipulator, a is the coefficient, and i is the input current. The safety threshold of the total force is preset as 1.0 N, when the total force of the catheter is less than 1.0 N, a equals 1, the robot-assisted system will provide the conventional haptic force feedback to the doctor, when the total force of the catheter is greater than 1.0 N, a equals 1.2, the robot-assisted system will provide the

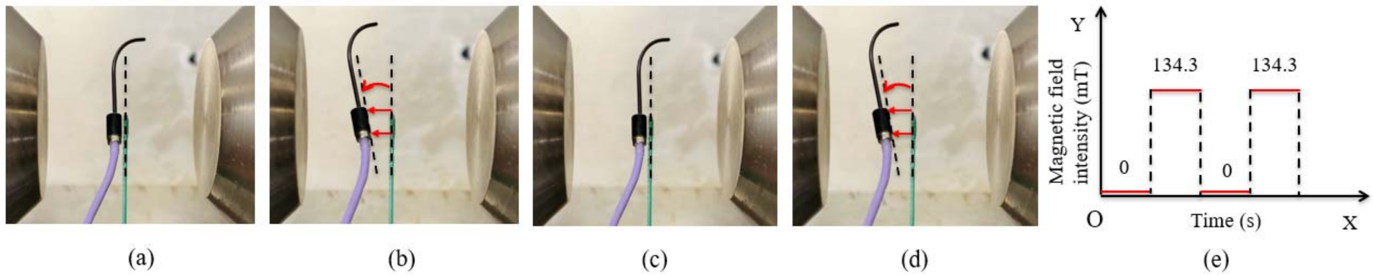


Fig. 7. Test results. (a) In the initial state. (b) Input current of 2.0 A was applied to the two coils. (c) Power supply that provides the current was turned off. (d) Input current of 2.0 A was applied to the two coils. (e) Relationship between the change of the magnetic field intensity and the time.

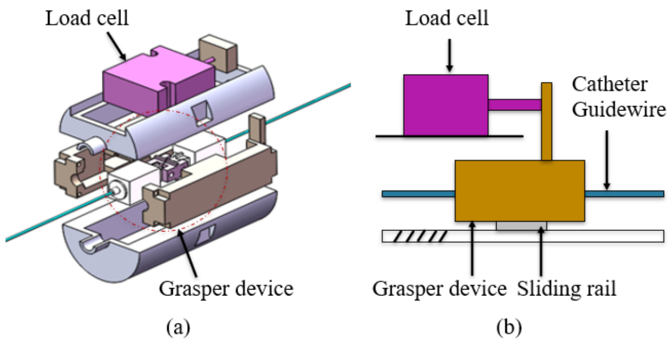


Fig. 8. Principle of total force detection when the developed robot-assisted system in the linear motion. (a) Structure diagram. (b) Schematic.

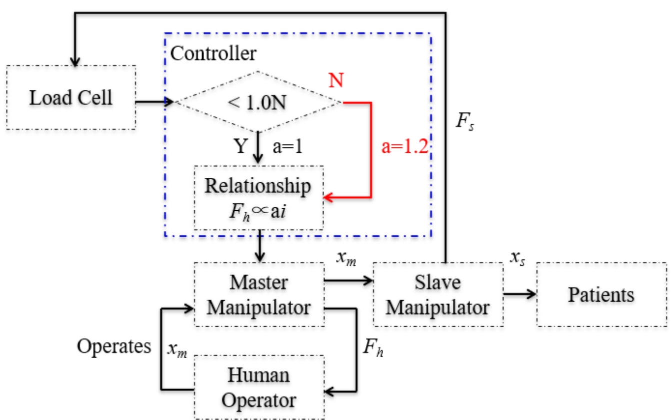


Fig. 9. Schematic of the active enhancing safety method that occurs on the master side.

enhanced haptic force feedback to the doctor. So, the doctor will obtain a stronger sense of tactile presence.

In addition to the active enhancing safety method that occurs on the master side, an active enhancing safety method that occurs on the slave side is used to reduce the danger caused by doctors' misoperation. A self-developed force sensor proposed in Section II is used to monitor the collision force at the tip of the catheter and keep the collision force maintained at a safe range. The schematic of the active enhancing safety method that occurs on the slave side is shown in Fig. 10, where $F_{\text{pre.}}$ is the collision force, the safety threshold of the collision force is set to 0.342 N, when the output of the force sensor is less than 0.342 N, the current status will be regarded as a safe area; otherwise, the current status will be regarded as an unsafe area, the slave manipulator will retract the catheter by 5 mm automatically, which can reduce the dangers caused by the

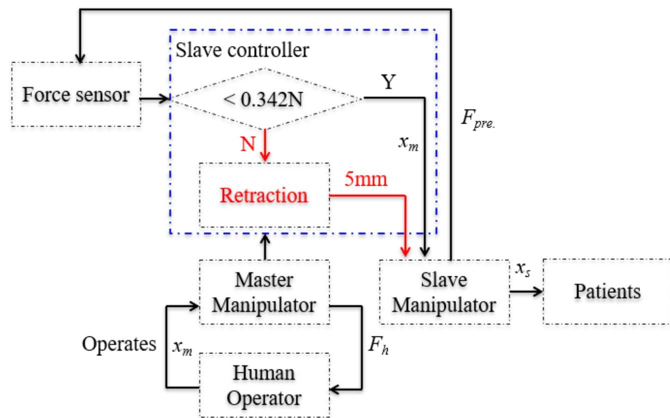


Fig. 10. Schematic of the active enhancing safety method that occurs on the slave side.

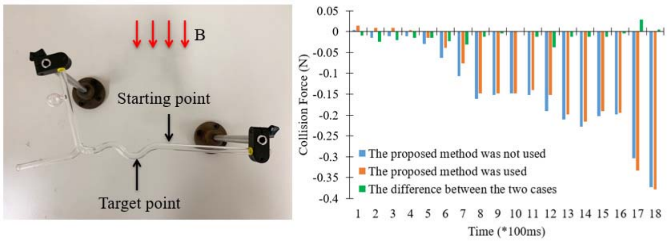
doctor's misoperation in time, and also prevent the tip of the catheter from piercing the blood vessel wall.

IV. Experiments and Results

The experiments *in vitro* will be carried out in this section to evaluate the proposed active suppression method in this study. There are two experiments: 1) to evaluate the method proposed in Section III-B can effectively reduce the collision force at the tip of the catheter, the experiment will be performed in Section IV-A, and 2) to verify the active enhancing safety method proposed in Section III-C can effectively reduce the danger caused by the doctor's misoperation and the sudden accident, the comparative experiment will be performed in Section IV-B. The experimental setup and the results will be given in each part, respectively. In addition, the experimental results will be analyzed in detail.

A. Evaluation Experiment of the Method of Reducing the Collision Force at the Tip of the Catheter

1) Experimental Setup: To verify the effectiveness of the method proposed in Section III-B, a comparison experiment from the starting point of the blood vessel model to the target point of the blood vessel model was performed under the condition with or without the magnetic field. The inner diameter and the outer diameter of the blood vessel model are 5 and 7 mm, respectively. The starting and target points and the direction of the applied magnetic fields were marked in Fig. 11(a). In the experiment, the catheter was a 4 Fr ($\Phi \approx 1.3$ mm) catheter, the guidewire was a long guidewire



(a) (b)

Fig. 11. Evaluation of the method to reduce the collision force at the tip of the catheter. (a) Experimental setup. (b) Experimental results.

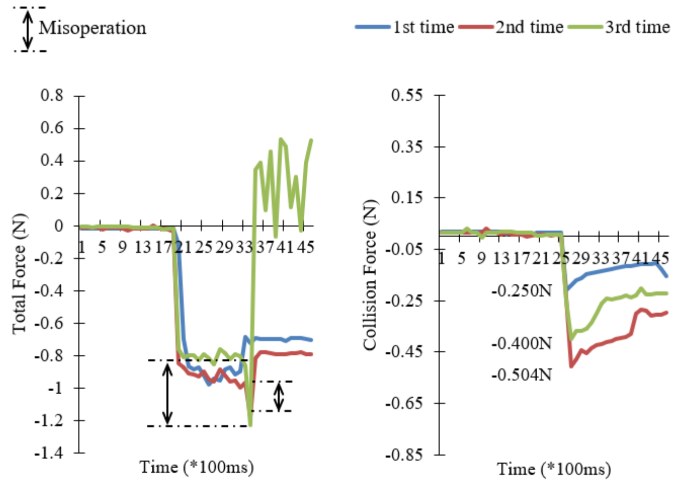
with an angle type of 45°, and the sampling time of the self-developed force sensor was 100 ms.

2) Experimental Results: As shown in Fig. 11(b), there are three sets of histograms: the blue one is the experimental results obtained in the condition without a uniform magnetic field of 134.3 mT, the red one is the experimental results obtained in the condition with a uniform magnetic field of 134.3 mT, and the green one is the difference value between the two cases. Before 500 ms, the collision force at the catheter tip fluctuated within a small range because there is no obvious collision. From 500 to 1600 ms, the collision force at the tip of the catheter is significantly reduced under the action of the magnetic field. But after 1600 ms, the experimental results are contrary to the results before 1600 ms. The reason may be that the direction of the tip of the catheter is opposite to the direction of the uniform magnetic field. Experimental results demonstrated that the deflection method based on the magnetic field control of the catheter tip has the potential of reducing the collision force as the catheter travels through the more curved blood vessel.

B. Safety Evaluation Experiment of the Robot-Assisted System Under the Different Conditions

1) Experimental Setup: To verify the method proposed in Section III-C can enhance the safety of the robot-assisted system, the experiments *in vitro* were completed in the blood vessel model [see Fig. 11(a)]. The experiments were repeated three times under different conditions. First, the experiment was completed without the misoperation. Second, the experiment was completed with the misoperation. Third, the experiment was completed with the misoperation under the condition of the active enhancing safety method. And the "misoperation" refers to the sudden feed of the catheter due to the fatigue of the doctor and accidents when the catheter was in contact with the blood vessel wall. Similarly, the catheter was a 4 Fr ($\Phi \approx 1.3$ mm) catheter, the guidewire was a long guidewire with an angle type of 45°, and the sampling time of the self-developed force sensor was 100 ms.

2) Experimental Results: As shown in Fig. 12, it is the sample of the total force of the catheter and the collision force at the tip of the catheter. It is not difficult to find from Fig. 12(a) and (b) that when there is a misoperation in the procedure, both the collision force and the total force will suddenly increase, which is dangerous behavior. In the first experiment, the collision force at the tip of the catheter is −0.250 N; in the second experiment, the collision force is −0.504 N; and in the third experiment, the collision force is −0.400 N. It is obvious that under the condition of the active enhancing safety method, the collision force in the third experiment is reduced by 0.104 N compared to the collision force in the second experiment, indicating that the proposed active safety-enhancing method can inhibit the doctor's misoperation behaviors to some extent.



(a) (b)

Fig. 12. Samples of the total force of the catheter and the collision force at the tip of the catheter. (a) Total force. (b) Collision force.

TABLE IV

STATISTICAL RESULTS OF THE EXPERIMENT WERE COMPLETED UNDER THREE DIFFERENT CONDITIONS

NO.	Force		First	Second	Third
1	Total force	Maximum (N)	-0.954	-1.176	-1.230
		Average (N)	-0.891	-0.934	-0.834
2	Collision force	Maximum (N)	-0.250	-0.504	-0.400

As shown in Table IV, it is the statistical result of the experiment that was completed under three conditions (the conditions have been described in the Experimental Setup). The misoperation will bring danger during operation, and it is inevitable, but the active safety-enhancing method can inhibit the misoperation behavior to some extent. For instance, the collision force and average total force of the catheter are reduced by 0.104 and 0.1 N, respectively, under the condition of the active enhancing safety method.

As shown in Fig. 13, it is the sample of the total force of the catheter from the slave side and the haptic force generated by the master side when there is a misoperation. The enhanced part is marked in (a) and (b). In Section III-C, we introduced that if the total force is greater than 1.0 N, the conventional haptic feedback of the master side will be changed to the enhanced haptic force feedback. In Fig. 13, compared with the conventional haptic force feedback, the enhanced haptic force feedback has increased by 0.28 and 0.27 N, respectively, which provides a stronger sense of tactile presence to the doctors.

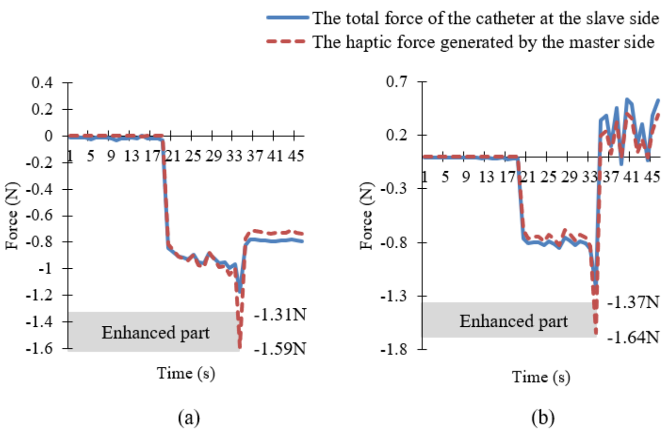


Fig. 13. Samples of the total force and the haptic force when there are misoperations. (a) Second time. (b) Third time.

V. Discussion

Considering the challenges presented in Section I, this article proposed the active suppression method of dangerous behaviors for improving the safety performance of the robot-assisted VIS. To evaluate the effectiveness of the proposed active suppression method, comparison experiments *in vitro* were conducted. For "the evaluation experiment of the method of reducing the collision force at the tip of the catheter," the results indicated that the method of reducing the excessive collision force at the tip of the catheter through a magnetic field has potential, however, changing the direction of the magnetic fields through a program needs to be studied, so that the robot-assisted system can face the different environment in the future. For "the safety evaluation experiment of the robot-assisted system under the different conditions," the experimental results indicated that the collision force at the catheter tip was reduced by 0.104 N when there is a misoperation during the procedure under the condition of the active-enhancing safety method. The stronger sense of tactile presence was provided by the master manipulator when the total force was greater than 1.0 N. However, the self-developed force sensor was used to confirm, detect, and collect the collision force at the tip of the catheter, and it will be replaced by a commercial force sensor with high precision in the future. To sum up, the contribution of this article is to focus on the active suppression method of dangerous behaviors for improving the safety in robot-assisted VIS, which has been verified to be effective through the experiments.

VI. Conclusion

In this article, the active suppression method of the dangerous behaviors was proposed for robot-assisted VIS. Compared with the passive methods, it can reduce the dangers of the surgery in time. The active suppression method mainly includes the reduction of the collision force at the tip of the catheter, the enhanced haptic force feedback that occurs on the master side, and the identification and suppression of dangerous behaviors that occur on the slave side. To verify the effectiveness of the proposed active suppression method, a series of experiments *in vitro* were carried out. The experimental results indicated that the collision force at the catheter tip was reduced by 0.104 N when a misoperation occurred during the procedure under the condition of the active-enhancing safety method. The stronger sense of the tactile presence for the doctor was generated by the master manipulator when the total force of the slave side was greater than 1.0 N. Based on the above results, we believe that the proposed methods can improve the safety of operation.

The future work will focus on the evaluation of the developed robot-assisted system *in vivo*.

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