Proceedings of 2017 IEEE
International Conference on Mechatronics and Automation
August 6 - 9, Takamatsu, Japan

Haptic Feedback in Robot-assisted Endovascular Catheterization

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***Abstract*-In teleoperated robot-assisted catheter intervenetional surgery, haptic feedback allows the interventionalist to perceive the remote contact force between the catheter and blood vessel. In this research, the haptic feedback in axial direction has been provided to the operator in master site to guide the remote catheter insertion. A remote catheter navigation system was presented, and the MR (Magnetorheological) fluids based haptic interface was as the master site. To evaluate the performance of the haptic feedback in catheter insertion, ten subjects were recruited to manipulate designed remote catheter navigation system. The patient catheter went through the blood vessel phantom, and the dynamic changes of the insertion resistance force can be measured by catheter manipulator in slave site which will be perceived by the operator through the master haptic interface. Experimental results showed that haptic feedback has a benefit to decreasing the contact force between the catheter and blood vessel phantom during the remote catheter navigation.**

Index Terms -MR fluids; Haptic Feedback; Catheter Interventional Surgery

I. INTRODUCTION

Short recovery time, a small incision to healthy tissue and little post-operative pain have facilitated adoption of endovascular surgical techniques to treat some cardiovascular and cerebrovascular disease. Despite these benefits, the high success rate of interventional surgery has lead to an increase in the number of procedures. Because of increasing the number of procedures, the long fluoroscopy times and X-ray radiation exposure to both patients and interventionalists are important factors to consider [1]. In recent two decades, the development of teleoperated surgical robot was motivated by the desire to reduce the radiation exposure. Unlike the conventional bedside technique, the remote catheter navigation system allows the interventionalist to offer traditional axial and radial action by master robot placed in a remote location. The control commands are processed by the computer console to control the catheter manipulator to insert, retract or rotate the patient catheter. Some commercial catheter navigation systems, all employ a master-slave control architecture, have demonstrated safety and efficacy in vascular and endovascular surgery, such as Magellan robotic catheter system (Hansen Medical) [2] and Niobe magnetic navigation system (Stereotaxis, St. Louis, Mo) [3]. Several research groups have developed remote catheter navigation systems. Srimathveeravalli et al. developed a novel remote catheter navigation system by using an input catheter placed in a radiation-safe location to control a second patient catheter [4]. The system for endovascular teleoperated access was presented to manipulate any guide wire and catheter in the range of 0.014-0.13 inches. A compact telerobotic catheter navigation system was presented that had the accuracy of 0.1 ±0.1mm and 7±6 deg over 100mm of axial motion and 360 deg of radial motion [5]. Teleoperated catheter surgery system has also been done by our lab from 2007 [6]-[19]. The Fig. 1 shows the schematic diagram of the teleoperated robot-assisted catheter interventional system.

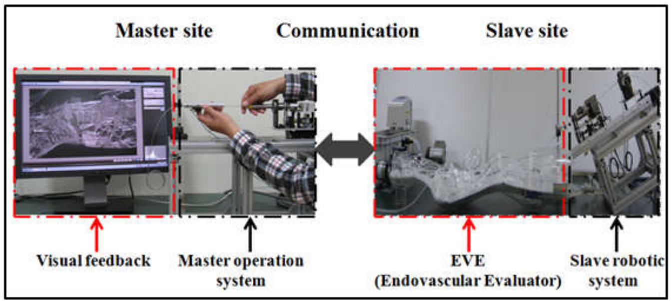


Fig.1 Master-slave catheterization system

Currently, interventionalists overwhelmingly rely on 2-D visual feedback, as one of their dominant information sources, during teleoperated robot-assisted surgery. However, the time delay caused by image transmitted from the remote site has not been solved [20].In addition, lack of the sensation of touch or haptic feedback from catheter-vessel contact to the operator is also a drawback in current master-slave robot-assisted catheter interventional system. The ideal teleoperated surgery scenario is viewed as a physical extension of the human body. A high level of transparency is essential to an operator to make a right decision in human-centered teleoperation system. To this end, recreating haptic sensation in master side becomes urgently in robot-assisted catheter surgery system. Some haptic devices have been developed, such as Sigma 7, HD2 and Premium 3.0 master hand-controller, which have been applied in teleoperated robot-assisted surgery system [21].The tactile sensation of the remote organ has been provided to the surgeon for teleoperated medical application [22]. Pacchierotti, C. et al.

integrated haptic sensation (kinesthetic and vibratory information) into the master system for a teleoperated steering flexible needle surgery [23]. The target of these researchers was to get high quality of transparency and enhance the performance of teleoperated robot-assisted surgery system.

Reduction of fluoroscopy times and X-ray radiation exposure to both patients and interventionalists, provided the haptic feedback to the operator and improved surgical safety are the motivation to develop the following system. In this study, the master haptic interface consists of two parts. MR fluids actuated haptic interface provides the haptic sensation to the operator. The operator can manipulate a 7 Fr catheter rather than a hand-controller or joystick to obtain the haptic sensation. The catheter goes through the MR fluids container, and the viscosity of fluids is controlled by the applied magnetic field. Another part is for motion measurement; the laser mouse's image sensor is utilized to measure the two DoFs linear and rotational motion of the catheter. The position commands of catheter manipulation from master robot can be replicated by the slave catheter manipulator. The resistance force at the proximal end of the patient-side catheter is collected by a load cell which is mounted on the catheter manipulator. The blood vessel phantom was utilized to evaluate the difference of catheter insertion performance under haptic feedback or not.

The remainder of this paper is organized as follows. The remote catheter navigation system is presented in section II. In section III, we used the cerebral vascular phantom to evaluate the effectiveness of haptic feedback in mock catheter surgery tasks. The experimental results are presented in section IV. Section V concludes this paper.

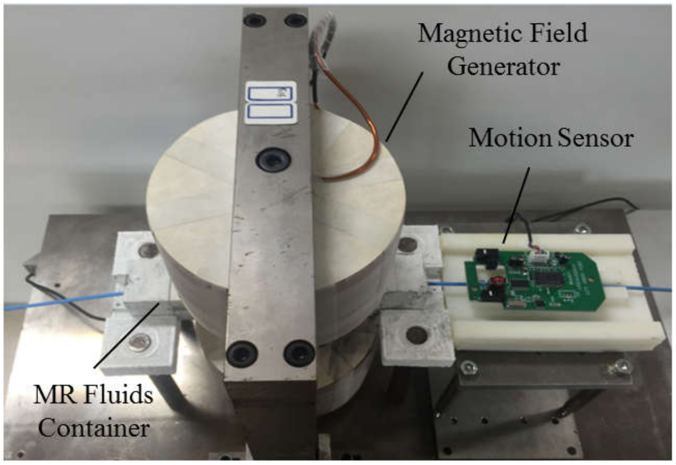
II. REMOTE CATHETER NAVIGATION SYSTEM

The remote catheter navigation system is shown in Fig. 2. The master device (to be placed at a local site) measures the axial and radial motions of an input catheter, and simultaneously provides the haptic feedback to the interventionalist during the operation. The catheter manipulator (to be placed at the patient table) replicates the motions measured by the sensor part of the master device.

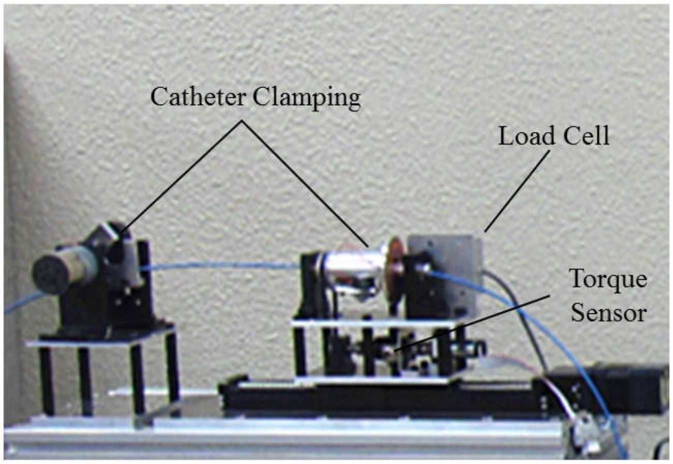
A. *Master Haptic Interface*

The design of master device should contain two kinds of capability, measuring the axial and radial motion of the manipulation catheter and displaying the passive force feedback from the slave device. The laser mouse's image sensor is used to measure the two DoFs linear and rotational motion of the catheter. This non-contact detection device can not only provide the high accuracy (1mm in axial motion over 100mm, and no more than 1deg in radial motion over 360deg), but also can increase the authenticity of the operation, its working principle is shown in Fig. 3.

The kinesthetic perception is presented by the MR Fluids actuated catheter haptic interface to the operators. The MR fluids fills the container, made of low permeability materials, which can never be magnetized during the external magnetic field. The container is placed in the center of two magnetic poles. The input catheter goes through the MR fluids. The MR



(a) Master haptic interface



(b) Catheter manipulator

Fig. 2 Remote catheter navigation system, master haptic device, the interventionalist can apply the conventional insertion, extraction or rotation motion to operate the input catheter, also can obtain the haptic feedback by adjusting the viscosity of MR fluids, and catheter manipulator replicates the motion along the patient catheter, and measures the axial force in proximal of catheter, simultaneously.

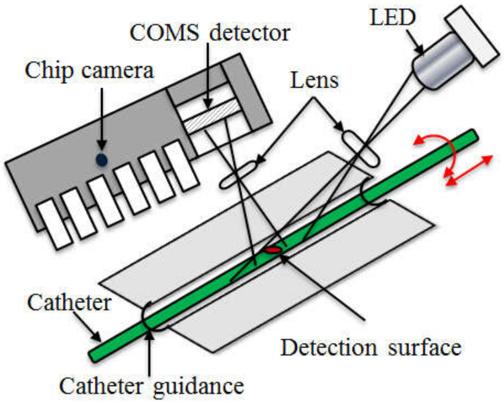


Fig. 3 Working principle of catheter motion measurement.

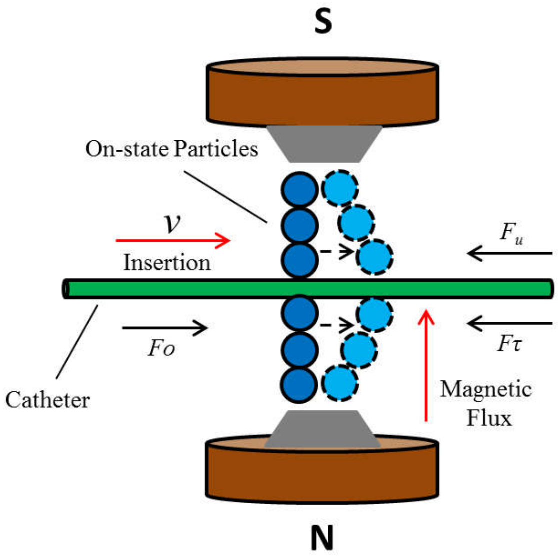


Fig.4 The force analysis of catheter during the insertion procedure, the total force, acts on the catheter, consists of the operating force, F_o, and whole resistance force F_r. The controllable force, F_τ and the uncontrollable force, F_u are made up of F_r.

fluids which is a kind of smart material, its actuated haptic interface was developed in the past decade [24]-[26]. The MR fluids fills the container, made of low permeability materials, which can never be magnetized during the external magnetic field. Haptic interfaces based on MR fluids have several advantages over traditional ones such as fast response time, low power consumption, and intrinsic passivity. In absence of an external magnetic field, MR fluids displays Newtonian-like behavior. When the fluids is activated, the particles are held together to chains parallel, aligning with the external magnetic line. In many cases, this effect is described as Bingham plastic model [27]. In our applications, we utilized Bingham plastic model to describe MR fluids field-dependent behavior [28]. The viscosity of MR fluids can be adjusted by an external magnetic field generator. The most important issue is that a passive force sensation can be produced by MR fluids based haptic interface to the operator. It matches with the traditional catheter interventional practice that the interventionalist actively operates a catheter, and the varied passivity force sensation will be continuously provided to their fingertips. Fig. 4 shows the force condition of catheter insertion when the magnetic field is generated. we embed two hall sensors in MR fluids container holder to obtain the magnetic field intensity in real time. This paper continues research based on the designed catheter haptic interface, the design detail and the performance evaluations were described by [29].

B. *Catheter Manipulator*

The slave manipulator is designed to actuate the patient catheter as transitional ways, push, pull, and twist. The two graspers were controlled by DC motors which fixed on the slide platform to hold the medical catheter for axial and radial motions. When the slide platform moves to the end, the distal grasper will be clamped by DC motor to keep the position of the catheter. To prevent slipping of the catheter, The axial gripping force is 4N, and the radial gripping torque is 6Nm, which is below the maximum value of force and torque applied by interventionalists during conventional interventional surgery. The stepping motor (ASM46AA, Oriental Motor, Japan) with built-in rotor-position sensor were the source of actuation. The high-performance micro-stepping driver (EN50178, Oriental Motor, Japan) system provided no missteps, even when the load changes suddenly. Load cell (TU-UJ, TEAC, Japan) was applied in this system to measure the force information in proximal of the catheter during the insertion and extraction. The accuracy of axial motion is 0.23mm (for a1m catheter) and the rotation motion is 1.2 deg (for 360 deg).

III. EXPERIMENTAL SETUP

A. *Experimental Design*

The experimental setup for validating the performance of the haptic feedback in catheter insertion is introduced. In the experiments, Ten right-handed subjects, no interventional experiences, or experience manipulated this remote catheter

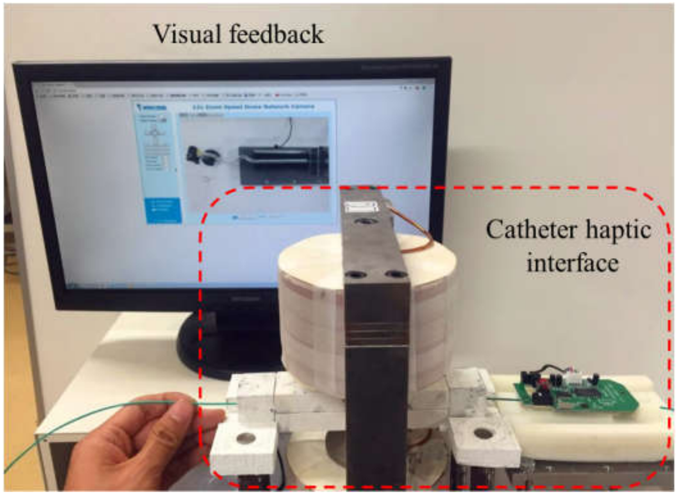


Fig. 5 Catheter operation process

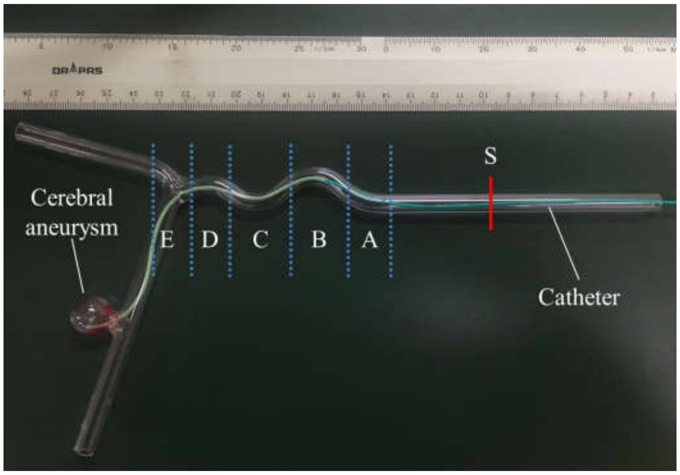


Fig. 6 Rigid model of cerebral vascular

navigation system, aged 22 to 28. Inexperienced operators were chosen because of their higher kinematics than experienced interventionalists in catheter manipulating [24].

The subjects were provided with 20 minutes of training on the master-slave system. The operators were instructed to navigate a 7-F input catheter through the master haptic device to guide the patient 5-F catheter. The patient catheter went through a rigid model of cerebral vascular and then directed the catheter tip into the wide neck aneurysm. The insertion speed of the catheter is 10mm/s, which meets the clinical demands of VIS [31]. In order to simulate 2D fluoroscopy guidance during the experimental process, a round view camera is mounted right above the vascular phantom, with the processed image information projected on a screen to be used by operators for navigation, and catheter operation process is shown in Fig. 5. Therefore, it needs hand-eye coordination when the operators do catheter interventional experiments.

The catheter is inserted into the blood vessel phantom to the disease target as shown in Fig.6. According to the physical geometry characteristics of the blood vessel phantom, the skill and collision discrimination are needed for the operators when the catheter encountered the tortuous blood vessel. Depending on the difficulty of the catheter manipulation (complexity of vascular phantom, the inner diameter is 5mm), the collision, between catheter tip and inner wall, and the contact, between the catheter body and inner wall, may be happened at bend position (section A, section B, section C, section D, section E) or not. The catheter interventional procedure path is from start position S to disease target (a cerebral aneurysm), and the total distance is about 170mm.

To evaluate the range of the contact force between the 5F catheter and vessel wall during the whole procedure, the applied insertion speed was 10mm/s. In order to obtain the maximum value of the contact force, the rotation motion was not utilized. The biggest contact force in ten times successful operation was shown in Fig. 7, the maximum value of those ten times is 0.45N, and the average value was 0.421N.

B. Experimental Control

The contact force, F_c between the catheter and blood vessel phantom can be measured by the load cell in slave side. The applied coils current, I is changed with the sensorized contact force. The generated resistance force can be described:

$$F_c = kF_r - 0.125 \tag{1}$$

where k is proportionality coefficient. The resistance force of input catheter manipulation is guided by the viscous drag of MR fluids which controlled by the generated magnetic field, as shown in Fig. 8. The relationship between the resistance force and magnetic flux density was present in our previous study [29]. The range of generated resistance force of input catheter insertion is 0.125N - 0.5N (magnetic flux density is from 0mT to 150mT, the seal friction is 125mN). Here we selected the proportionality coefficient k is 0.8.

C. Performance Metrics

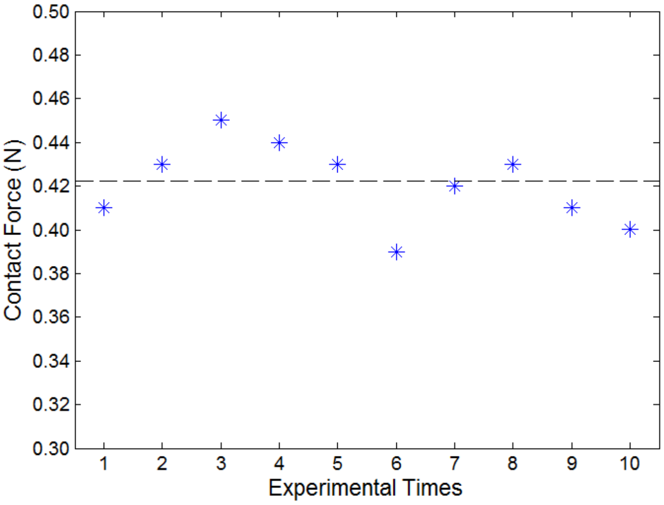


Fig. 7 The biggest contact force in ten times successful operation

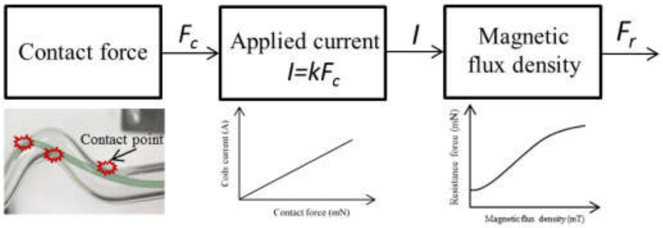


Fig. 8 Block diagram and schematic of the generation of haptic feedback

There were two modes were presented. In the mode 1, there was no force feedback in master site, just the visual feedback from the screen. The mode 2 was employed to provide the haptic feedback signal to the operator. All subjects were instructed to complete the same task under mode 1 and mode 2. The performance of the haptic feedback or not in the master-slave system was evaluated by measuring 10 trials in each mode by each subject. The measures were calculated based on data recorded during the experiments. The performance measures are as follows:

1) Task-completion time, representing the time is required to complete the catheter interventional task.

2) Sum of force, representing the resistance force of the patient catheter insertion.

3) Force per sample, defined as the ratio of the total force recorded by the load cell and the number of samples used to calculate the information at the slave side. To filter the noise at the catheter manipulator, when the total force at the sample was below at 0.01N, the force was set to 0N.

IV. EXPERIMENTAL RESULTS

Analysis of variance (ANOVA) was used to analyze the differences between mean values of performance measures and their corresponding procedure, and levels of $p<0.05$ are considered significant. Fig. 9 illustrates the mean value of task completion times (T_c) for two modes, while the operators performed each modes in ten times. Each bar shows the average of times taken for each operator to complete both mode 1 and 2. Mean completion times of 10 operators for

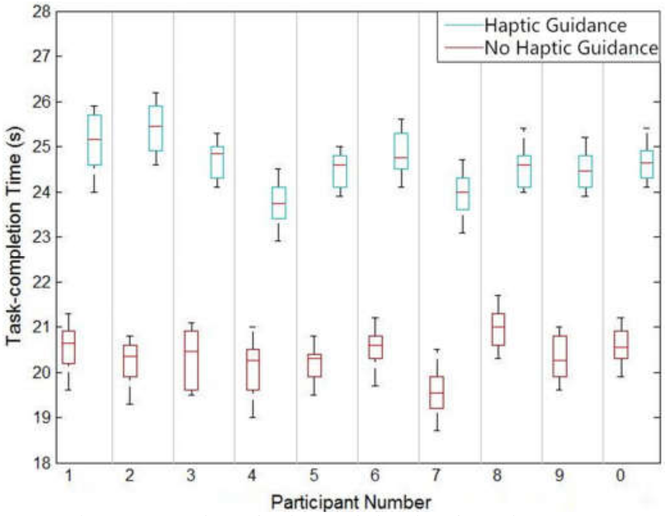


Fig. 9 Mean values of task-completion time for each operator.

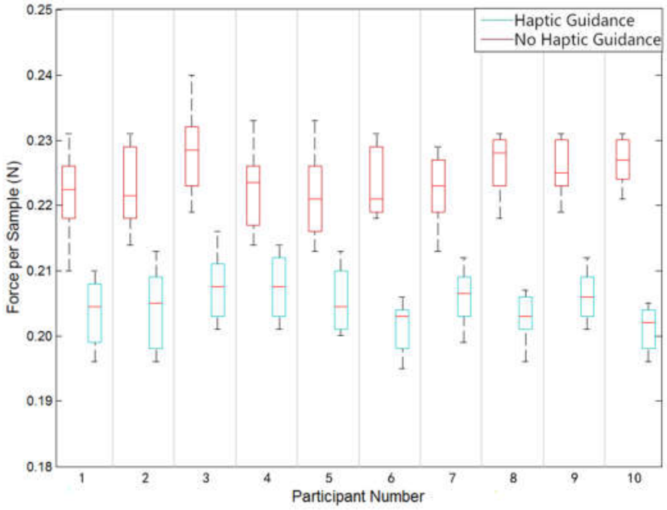
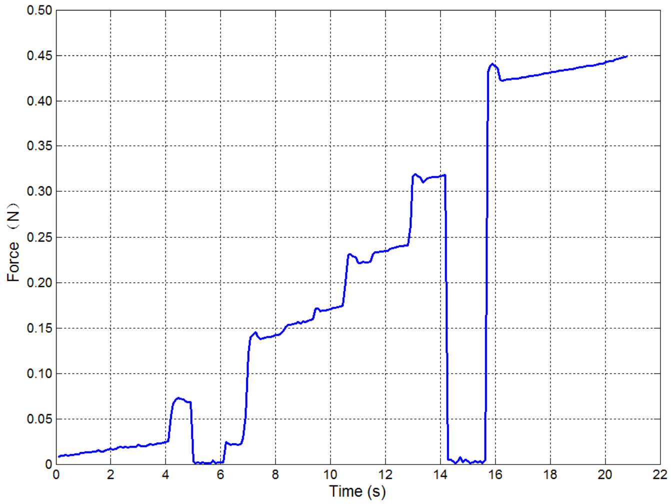
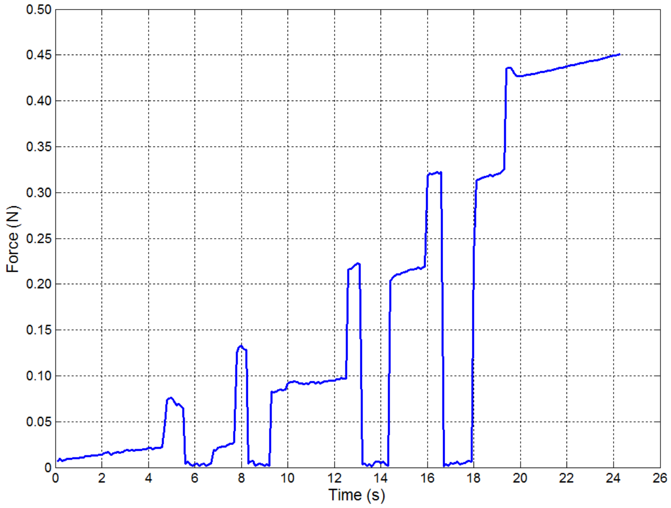


Fig. 10 Mean values of force/sample for each operator.



(a) The resistance force trajectories under mode 1



(b) The resistance force trajectories under mode 2

Fig. 11 The resistance force trajectories by subject#1.

mode 2 are higher than mode 1. The 2-way ANOVA was conducted to test whether the different modes have a significant effect on the task completion time. For the two modes, we detect a significant difference ($p=1.12\times10^{-7}$) in the mean completion times, which indicated that the value of the completion time was affected by the provided force feedback.

Fig. 10 illustrates the mean values of force per sample of each operator in mode 1 and mode 2. As observed, mean force/sample considering all operators in different modes were 0.224N and 0.205N, respectively. Mean force per sample of 10 operators for mode 1 is higher than mode 2. The 2-way ANOVA was conducted to test whether the different modes have a significant effect on the sum of force. For the two modes, we detect a significant difference ($p=1.25\times10^{-6}$) in the sum of force, which indicated that the value of the force per sample was affected by the provided force feedback.

Consider the individual subject; Fig. 11 displays the resistance force of the patient catheter navigation in the axial direction. These data were generated by the subject#1 in the first operation in mode 1 and mode 2, respectively. When the catheter tip meets the inner wall of blood vessel phantom, the resistance force will be increased. And then with the length of the path is increased, the contact force between the catheter body and inner wall will be also increased. In mode 1, the subject used the visual feedback to avoid the collision and made two times of rotation motion, which can be seen in Fig. 11(a), the resistance force is approximate to 0N in period of time. In mode 2, the haptic feedback was provided during the whole procedure, the subject can feel the changes of the resistance force, which will assist him/her to make decisions in avoiding the collisions or finding suitable directions to navigate the catheter and decrease the resistance force. In Fig. 11(b), the subject did four times of rotation motion in the whole procedure. The completion time in mode 1 was less than in mode 2. However, the resistance force per sample was lower in mode 2 than in mode 1.

V. CONCLUSION

In this paper, the haptic feedback has been utilized to assist the operator in decision making and improving catheter interventional skills during teleoperated robot-assisted catheter interventional neurosurgery practice. Experimental results illustrated that haptic feedback had a benefit for decreasing the contact forces between the catheter and blood vessel phantom when the operator encountered tortuous position during the experimental procedure. However, the MR fluids based haptic interface can be only responded to axial motions of the catheter. In the next study, how to reflect the torque information of radial motions in the master site should take into consideration.

ACKNOWLEDGEMENT

This research is partly supported by National Natural Science Foundation of China (61375094), National High Tech. Research and Development Program of China (No.2015AA043202).

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