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TECHNICAL PAPER

# Design and performance evaluation of a haptic interface based on MR fluids for endovascular tele-surgery

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**Abstract** In this paper, a magnetorheological (MR) fluids based haptic interface has been developed in master site to provide the haptic sensation to the interventionalist during endovascular tele-surgery. The novel design of haptic interface allows the interventionalist to apply conventional axial and radial motions to a rigid catheter which goes through the MR fluids. In addition, the haptic feedback in the axial direction can be generated by altered the viscosity of MR fluids. The actual force measurement is provided to assess the effectiveness of this haptic feedback. While to evaluate the performance of this master device, the virtual-reality (VR) simulator is as the slave side to execute the replicated motions, pull, push and twist of the virtual catheter, which is applied by interventionalist in master site. The ten operators are recruited to navigate a catheter through virtual cerebral-vessel. Experimental results indicate that the use of the proposed haptic interface has a benefit to avoiding the collision and improving the safety of endovascular tele-surgery.

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## 1 Introduction

Minimally invasive surgery (MIS) has been widely utilized to diagnose and treat endovascular disease, especially cardiovascular diseases and cerebrovascular diseases (Saliba et al. 2016; Song 2015). In the last few decades, remote-controlled catheter technology and master–slave catheter navigation systems have seen a growing interest in the field of endovascular tele-surgery (Arai et al. 2002; Zakaria 2013). It had been shown some merits, such as increasing the precision of motion, removing the surgeons from the exposure of X-ray radiation, providing the comfortable operating environment to the surgeons (Thakur et al. 2009a). 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) and Niobe magnetic navigation system (Stereotaxis, St. Louis, Mo). Several research groups have developed remote catheter navigation systems. Yogesh 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. Figure 1 shown the master–slave catheterization system of our lab (Xiao et al. 2012; Guo et al. 2012; Wang et al. 2015).The surgeon is able to manipulate a hand-controller with force feedback in the remote site. At the same time, the control commands will be sent to slave site to guide the slave robot do the surgery (Van Oosterhout et al. 2015).

Now, haptic technology in teleoperated surgery is a promising research area. Some commercial haptic hand-controllers were developed, like Sigma 7, HD2and Premium 3.0; they have been applied in teleoperated surgery (Zareinia et al. 2015).The tactile sensation of the remote organ was

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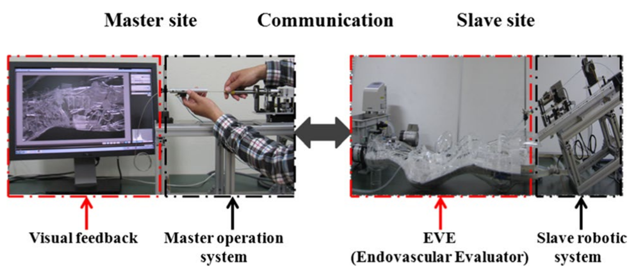


**Fig. 1** Master-slave catheterization system

provided to the surgeon for teleoperated medical application (Nakajima et al. 2014). Pacchierotti integrated haptic sensation (kinesthetic and vibratory information) in the master system for a teleoperated steering flexible needle surgery (Pacchierotti et al. 2014). The target of these researches is to enhance the performance of teleoperated surgery system by introducing haptic technology. There are still some challenges in recreating the effective haptic sensation to the local operator. The first one is lacking effective and passive haptic feedback when rigid instruments or actuators are used. The damping, inertia, and friction of electrical motors based haptic devices will significantly reduce the transparency of the system (Shafer and Kermani 2011). Secondly, the stability of haptics-enabled tele-surgery is a major obstacle in introducing haptic into medical applications (Lawrence 1993). The medical professionals strongly rely on the sense of touch and their intuitive skills during endovascular surgery. However, the employment of these remote navigation systems removes the catheter from the interventionalist's hands, also removes the direct contact between the clinician and patient. So it is necessary to increase the natural haptic feedback in the master site by catheter-based haptic interface (Gerovich et al. 2004; Okamura et al. 2011).

In recent years, Magnetorheological fluids based actuators have been used as haptic devices (Carlson et al. 1996; Najmaei et al. 2014). MR fluids, controllable fluids, are capable of changing its rheological behavior when an external magnetic field is applied. It has three components (Ashour et al. 1996): magnetizable micro-sized particles, additives, and carrier fluids (such as mineral oil, synthetic oil, water, ethylene glycol or vegetable oil).The magnetizable micro-sized particles can be polarized by the magnetic field in several milliseconds, and then be the plastic viscosity fluids (Yin et al. 2016a). The viscosity of MR fluids is proportional to an external electromagnetic power. These characteristics have motived the design of haptic devices based on MR fluids (Rizzo et al. 2007). An encountered-type of the haptic interface using MR fluids has been designed and evaluated for surgical simulation (Blake and Gurocak 2009). MRFs-based actuators were used to develop the 2-DoF haptic interface for medical applications, the devices showed great potential about stability and transparency on master–slave teleoperation (Najmaei et al. 2016). MR fluids actuated miniature tunable stiffness haptic interface has been designed and fabricated (Yang et al. 2010).

As a result, based on our previous work (Yin et al. 2016b), a new design of a haptic interface based on MR fluids was proposed in master site for endovascular telesurgery. A master-salve catheter manipulation system is provided to evaluate the performance of proposed haptic interface. The master haptic interface is located at a console site. The slave site is a VR platform that contained vascular geometrical mode and physical mode, and the virtual catheter can insert into vascular lumen freely (Wang and Guo 2016). The position and velocity commands of catheter tip are generated by manipulating the rigid catheter in master site. At the same time, the virtual catheter in VR platform will replicate the axial and radial motions as accurate as possible. Meanwhile, the VR platform will send different warning signals to the haptic interface when the virtual catheter tip meets the "dangerous area" or impacts on the vascular wall. The viscosity of MR fluids will be changed to reflect different levels of resistance forces through the catheter which can be perceived by the operators.

The remaining of the paper is organized as follows. In Section II, the MR fluids actuated haptic interface is presented. The generation of haptic force is proposed in Section III. To evaluate the performance of the proposed haptic interface, the master–slave system is established in Section IV. Section V provides the experimental results which show the performance of the proposed haptic interface. Finally, Section V concludes the paper.

## 2 MR fluid based haptic device

The structure of haptic interface is shown in Fig. 2.The rigid catheter goes through the MR fluids, and it is coaxial with MR fluids container. The viscosity of MR fluids can be controlled by energizing the electromagnetic coils. Subsequently, the resistance force of catheter insertion

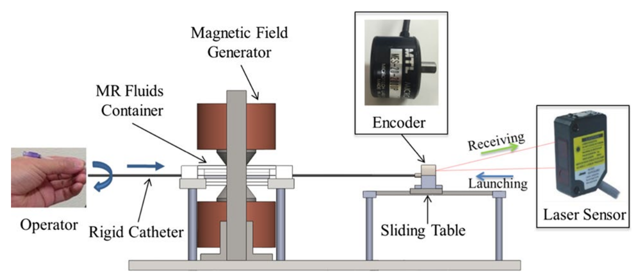


**Fig. 2** The structure of MR fluids based haptic interface

can be altered. The interventionalist can apply axial (push and pull) and radial (twist) motions to the one end of the rigid catheter. Radial motion is measured by an encoder (MES-20-2000P, MLT Corp, Japan), and its rotating shaft connects with the other end of this rigid catheter. Axial position measurement is obtained by the laser sensor (LK 5000, Laser displacement sensor, KEYENCE Corp, Japan), and the encoder is played as a laser receiver. The encoder is fixed on the sliding table above the guideway and moved with the catheter together. The MR fluids was exploited to provide haptic sensation (kinesthetic sensation) to the operator during catheter interventional surgery. The operator will manipulate a real rigid catheter (same diameter with a 7 Fr catheter) rather than a hand-controller or joystick. The most important issue is that MR fluids actuated haptic interface can produce a passive force during the catheter manipulation. This dynamic resistance force will be generated by the interaction between the catheter and blood vessel wall.

## 3 MR fluids container

The MR fluids fills the container, as shown in Fig. 3, which can never be magnetized by the external magnetic field. The container is placed in the center of two magnetic poles. The catheter goes through the MR fluids container, and the viscosity of fluids is controlled by the applied magnetic field.Here, we embed two hall sensors in MR fluids container holder to obtain the magnetic field intensity in real time. As observed, when the magnetic field is applied, magnetic lines are evenly distributed in the middle of two poles. Meanwhile, it has the great effect on the shear stress of MR fluids and directly affects the resistance force of catheter insertion. The actual placement of hall sensors in practice is affected by the size and maximum measurement range. The small hall sensors are much more desirable in order to have minimum effect on the strength of the magnetic field. Thus, we choose TLE4990 programmable liner hall sensor, continuous measurement ranges between 0 and 400mT. The use of hall sensors provides a reliable, compact, and a non-contact force measurement.

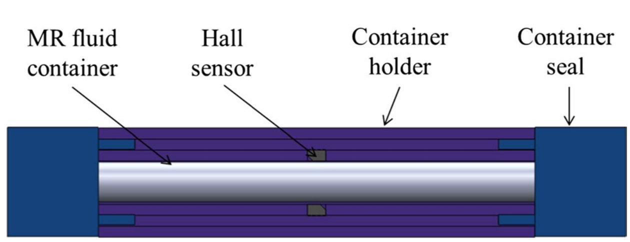


**Fig. 3** The MR fluids container

**Table 1** Characteristics of the MRF-122EG

| Main characteristics | Values |
|---|---|
| Viscosity | 0.42 ± 0.0020 (Pa.s, 40 °C) |
| Density | 2.28–2.48 (g/cm$^3$) |
| Solids fraction | 72% |
| Flash point | >150 °C |
| Operating temperature | −40 to +130 °C |
| Maximum magnetic permeability saturation | 200–250 (kA/m) |

The shear stress of the MR fluids can be accurately controlled by controlling the intensity of an applied magnetic field. In absence of an external magnetic field, MR fluids displays Newtonian-like behavior (Yin et al. 2016a). When the fluids is activated, the particles are held together by chains parallel, aligning with the external magnetic line. In many cases, this effect is described as Bingham plastic mode (Bossis 2002). In our applications, we utilized Bingham plastic mode to describe MR fluids field-dependent behavior. When the operator inserts the catheter through MR fluids, the structure of some particles, are arranging along the magnetic field lines, will be changed inevitably. Meanwhile, the operator will perceive the viscous force (kinesthetic haptic sensation) by applied external magnetic field. Here, we utilized a kind of commercial MR fluids named MRF-122EG produced by Lord Crop, USA. Its main magnetic and rheological characteristic shows in Table 1.

## 4 Magnetic field generator

MR fluids actuated system is a coupled analysis problem: electromagnetic analysis and fluids system analysis. Reliable control is a critical issue in haptic interfaces for delivering precision and high fidelity feedback. MR fluids based devices suffer from nonlinear hysteretic relationships between the input current and magnetic field. The nonlinear behavior of MR fluids actuated device is due to the use of ferromagnetic materials in the magnetic circuit of the device. The presence of hysteresis leads some problems in control system, like tracking errors and instability (Hughes and Wen 1997). This relationship also reflects on the output force behavior with respect to the input current. However, the hysteresis of the MR fluids is small enough to be neglected that due to the soft irons used in the fluids suspension (Najmaei et al. 2014). The hysteresis in the magnetic field is mainly associated with magnetic field generator (Rakotondrabe 2011). In order to reduce the hysteresis, the soft iron cores inside two coils separately are assembled together to generate the electromagnetic field, so the

**Table 2** Characteristics of the magnetic field generator

| Main characteristics | Values |
|---|---|
| Cooper wire diameter | 1.6 (mm) |
| Inner diameter of the coil | 30 (mm) |
| Outer diameter of the coil | 120 (mm) |
| Height of each coil | 68 (mm) |
| Coil turns | 1200 (T) |
| Coil resistance | 2.45 (Ω) |
| Distance of two magnetic poles | 300 (mm) |

magnetic field intensity changed quickly by the actuator. The magnetic circuit was analyzed in previous work (Song et al. 2016). The major geometrical dimensions of the magnetic generator are shown in Table 2.

The MR fluids actuated haptic interface minimizes the use of contact measuring requirements to provide high fidelity of haptic sensation. The only necessary measurement is the encoder that connects with the distal end of the catheter to record the rotation signal. The catheter goes through the MR fluids container, and the passive force sensation can be produced by MR fluids. It matches with the traditional catheter interventional practice. Operators actively manipulate catheter, and the varied passivity force sensation will be continuously provided to their fingers, which can make the operators completely immersed in operation. Not only the system should reflect the dynamic changes of the insertion resistance forces, but also can reproduce the collision situation between the catheter tip and the vessel.

## 5 Generation of haptic force

The haptic force is generated by insertion the rigid catheter through the MR fluids. It is just like a stick inserting into the 'sticky clay with some of the water.' In theory, the generated force cannot be affected by the insertion frequency because the generated force is viscosity dependent. In traditional force control strategy, the resistance force of catheter insertion will be measured by the direct force measurement device. In addition, the relationship between the viscosity of MR fluids and the intensity of magnetic field can be established. However, the resistance force is a kind of passive force, which can hardly be measured in real time during the catheter insertion.

When the operators insert or extract the catheter through haptic interface under the external magnetic field, they will feel the resistance force by the viscosity of fluids. In this case, the total force, acts on the catheter, consists of the operating force, $F_o$, and whole resistance force $F_r$, as shown in Fig. 4. The controllable force, $F_\tau$ and the uncontrollable force, $F_u$ are made up of $F_r$, as shown in Fig. 3. The operation force is acted by the operator. The uncontrollable force is the friction force between the catheter and MR fluids container seal. The controllable force is controlled by varying stress of MR fluids. Although the particles of MR fluids provided the friction force, $F_f$, changed with the strength of the magnetic field, to the rigid catheter. $F_\tau$ can not be described an opposing force independent of the velocity of catheter insertion or extraction. When the MR fluids displays Newtonian-like behavior, the viscous force, $F_v$ is proportional to velocity of catheter manipulation, $v$ and it is zero when velocity is zero. But when the fluids is magnetized, the particles of fluids are held together by chains parallel, the fluids plays a plastic behavior, and the $F_f$ and $F_v$ compose the $F_\tau$.

The resistance force of the operation can be written by

$$F_r = F_\tau + F_u \tag{1}$$

$$F_\tau = (\mathrm{sgn})F_f + F_v \tag{2}$$

$$F_v = \alpha_v \cdot v \tag{3}$$

$$\mathrm{sgn} = \begin{cases} 1, & (Warning) \\ 0, & (No\ Warning) \end{cases} \tag{4}$$

where $\alpha_v$ is the viscosity parameter. The operating force should be governed by

$$\begin{cases} F_o \geq F_r, & \mathrm{sgn} = 0 \\ F_o < F_r, & \mathrm{sgn} = 1 \end{cases}. \tag{5}$$

In this study, the controllable force is generated when the master side received the feedback warning signal from slave side. In the remote catheter navigation system, the warning signal is sent when the catheter tip has a collision with the inner vascular wall. This impact force is captured by the catheter manipulator or catheter tip force sensor. The recreated force must be established rapidly in master site when the real danger happened, and the reaction should be in a short time. Here, in order to find the relationship between resistance force of rigid catheter manipulation and the applied magnetic field. We utilized the load cell (TU-UJ, TEAC, Japan) to measure the resistance force of rigid catheter manipulation in the axial direction. The one end of the rigid catheter is connected to the load cell, which navigated by the stepping motor (ASM46AA, Oriental Motor, Japan) in the horizontal direction. Another end is fixed with the encoder. The manipulation velocity of the rigid catheter has an influence on resistance force. Here, the set speed is from 10 to 150 mm/s, with a step 10 mm/s, which according to the surgeon's experience, catheter insertion frequency can reach up to 3–5 Hz, and motion profile is no more than 30 mm (Speich et al. 2005). The experimental setup is shown in Fig. 5.

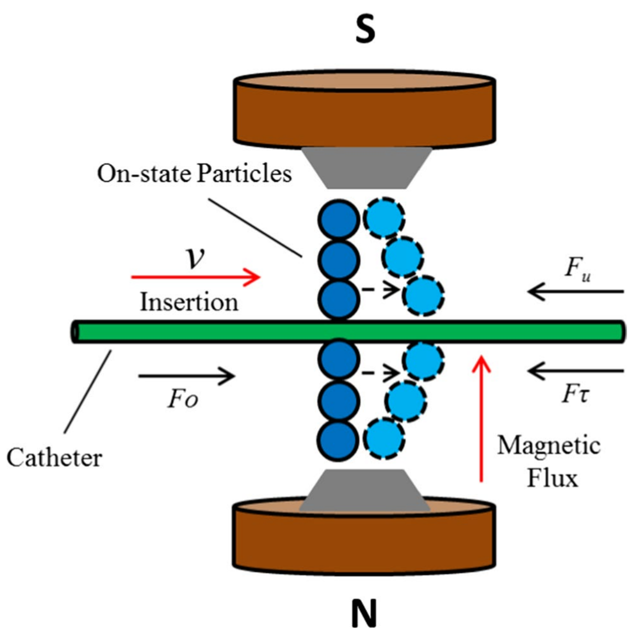


**Fig. 4** The force analysis of catheter insertion

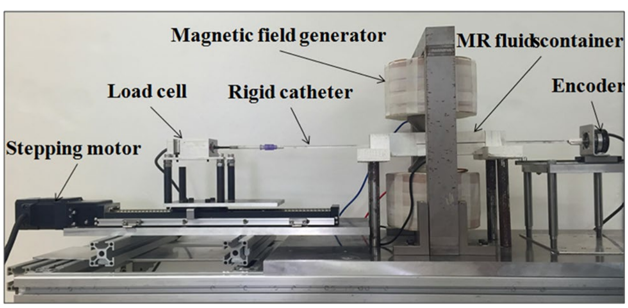


**Fig. 5** The setup of output resistance force measurement

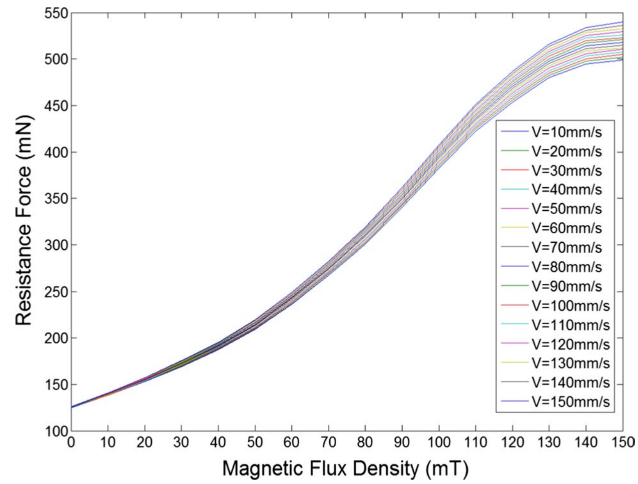


**Fig. 6** Applying the constant currents to the coils, the relationship between resistance force and applied magnetic field

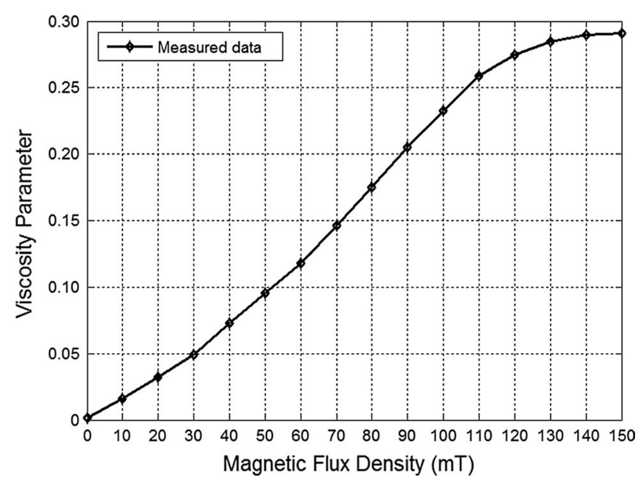


**Fig. 7** The values of viscosity parameter in different magnetic field

The insertion force is measured ten times with each applied constant currents. The enough time is provided to establish the steady state magnetic field in the certain constant current. Magnetic field density is measured by the embedded hall sensors, and the results are shown in Fig. 6. From the results, the off-state resistance force is dominated by the seal friction (125 mN).When the magnetic field was applied, the resistance force of catheter insertion was increased rapidly, but not linearly. The velocity of the catheter inside the MR fluids has an influence on the resistance force of rigid catheter manipulation. The values of viscosity parameter in different magnetic field are shown in Fig. 7. The difference of resistance force between maximum velocity (150 mm/s) and minimum velocity (10 mm/s) in the same magnetic field intensity is not more than 50 mN (the percentage rate for the whole resistance is less than 10%).

Figure 8 shows the experimental results (full lines) of resistance force by different insertion speeds obtained with various input currents. The insertion speed has a bigger influence on resistance force of catheter insertion when the MR fluids was applied the strong magnetic field than the weak magnetic field. However, these differences of viscous force coursed by the different velocities can hardly be distinguished by the operator in certain applied magnetic field. In conventional bedside technique, only the sudden increase of resistance force of patient catheter manipulation can be perceived by interventionalist, just like the catheter has a collision or contact with the vascular wall. Tan and Durlach found a JND (just noticeable difference) that lied between 100 and 200 mN for pinching motions between finger and thumb with a constant resistance force (Pang et al. 1991). Considering the resistance force of catheter

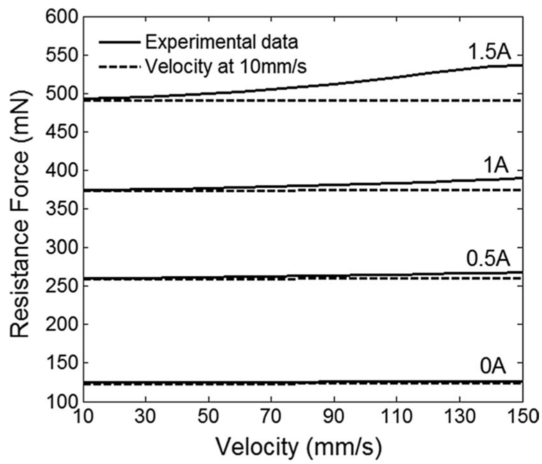


**Fig. 8** Experimental resistance force/velocity curves for rigid catheter going through the MR fluids container for various input currents

manipulation is just provided when the different warning signals sent from the slave site. Specifically, we derive JNDs for force using this haptic feedback interface. So we utilized the specific values of resistance force as the haptic feedback to the operator, and the difference between set values can be just noticeable by the operator.

## 6 Experimental setup

The experimental setup for validating the performance of the developed MR fluids actuated haptic interface is introduced. We utilized the VR simulator as the slave side to evaluate its efficiency during the endovascular tele-surgery.

## 7 Master–slave system

Figure 9 presents the block diagram of the mater-slave system. The master site was described in section II. Here, we use the VR simulator as the slave site to simulate the real catheterization environment. The operation information of rigid catheter can be transferred to VR simulator console (3.07 GHz, 4 processors, and 16 GB RAM), which replicates the motion along the virtual catheter. Control software was implemented using C++; multithreading was used to enable simultaneous motion control. The communication delay can be neglected.

The virtual cerebral-vessel structure was established by the MRI images of DICOM header, and the individual images were processed by OpenGL. These volume data were imported to Bullet 2.8. The virtual catheter is a chain of cylinders (1 mm diameter and 3 mm long) with angularly limited joints. The angle between the catheter body and catheter tip is set to 30 degrees. The minimal

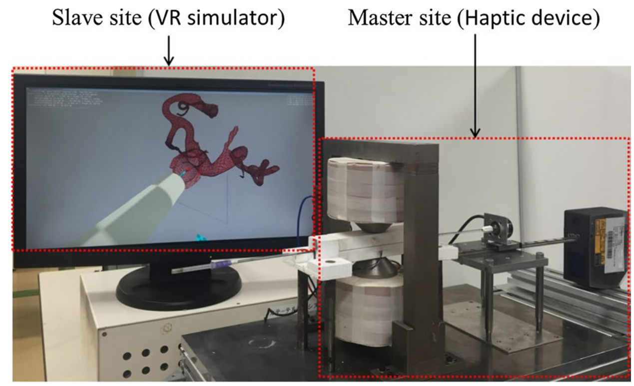


**Fig. 9** The block diagram of the master–slave endovascular catheterization system

distance between the virtual catheter tip and vascular wall can be calculated by the program in real-time (Wang and Guo 2016), as shown in Fig. 10. The axial motion of the virtual catheter is the motion replication of rigid catheter which obtained by the laser sensor. The interventionalist can apply conventional rotational motion of rigid catheter to guide the virtual catheter tip.

Here, we just pick one branch of cerebral vessel from common carotids artery (CCA) to middle cerebral artery (MCA) (length along the middle line is 200 mm, and the diameter is between 5 and 9.5 mm) to evaluate the performance. According to the minimal distance of catheter tip and vascular wall, virtual vascular can be divided into three parts in view of the cross section, safe area (*dmin* > 0.5 mm), dangerous area (0 mm > *dmin* ≥ 0.5 mm), and forbidden area (collision, *dmin* ≤ 0 mm), as shown in Fig. 11. When the catheter tip moves into dangerous or forbidden area, different

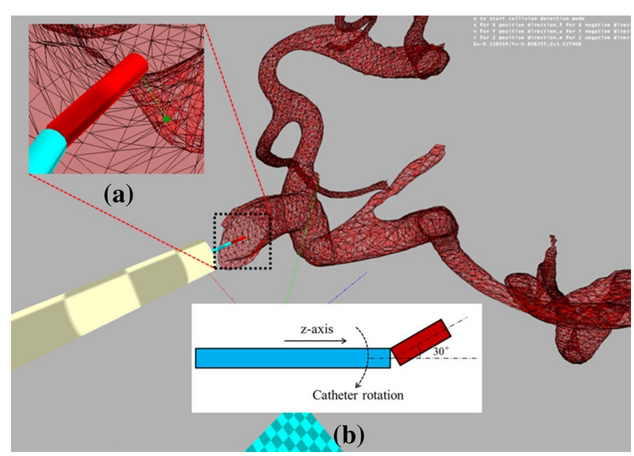


**Fig. 10** The operation environment of VR simulator, **a** the minimal distance between the virtual catheter tip and vascular wall, **b** the catheter tip at a 30-degree angle to the z-axis

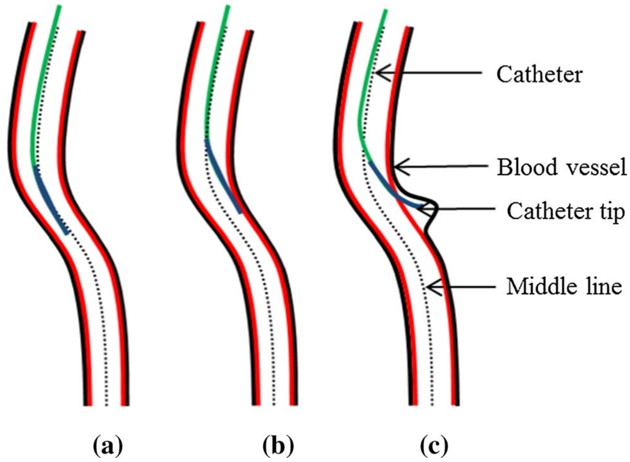


**Fig. 11** Three different situations of the catheter tip in blood vessel, **a** catheter tip in the safe area, **b** catheter tip in dangerous area, **c** catheter tip in forbidden area

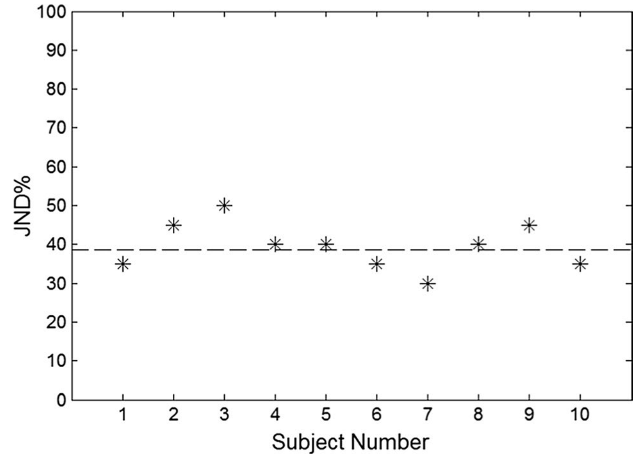


**Fig. 12** JNDs per subject. The *dashed line* lies at the average JND

warning signals will be sent by VR simulate to the haptic interface, which will provide different levels of haptic sensation (two values of resistance force, the difference is based on the JNDs) to operators immediately. For both master and the salve site the forces, time and positions are recorded at 1 kHz.

## 8 Task performance description

In the experiments, two modes were presented. In the mode 1, there was no force feedback in master site, just the visual feedback from the VR simulator. The mode 2 was employed to provide the haptic feedback signal to the operator. The minimal distance between the virtual catheter tip and the vascular wall was detected in real-time. Moreover, the positions of virtual catheter tip were recorded during the procedure. To verify the efficiency of the proposed MR fluids actuated haptic device in catheter interventional performance. Ten right-handed subjects, no interventional experiences, or experience using this catheter navigation system, aged 22–28 participated in the experiment. Before the experiments, two different values of constant resistance force were provided to each subject as the distinction which they can be perceived. The base resistance force value is chosen when the applied magnetic field is at 150 mT, and the resistance force is about 500 mN. The JNDs of 10 subjects were shown in Fig. 12. From the results, a JND lies between 30 and 50% for insertion the rigid catheter between finger and thumb with a constant resistance force. According to the relationship between resistance force and applied magnetic field in Sect. 3, we selected the resistance forces when the magnetic field is at 70 and 150 mT.

The subjects were provided with 20 min of training on the master–slave system. All subjects were instructed to complete the same task under mode 1 and mode 2. Inexperienced operators were chosen because of their higher kinematics than experienced interventionalists in catheter manipulating (Thakur et al. 2009b). The performance of 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. At the master site, the following parameters were recorded: Time (s), the position of the catheter (mm) and angular displacement of the catheter (°). At the slave site, the position of the virtual catheter tip along three axes (mm) and minimal distance between the virtual catheter tip and vascular wall (mm) were recorded. Task performances are evaluated by three main metrics:

1. Task-completion time ($T_c$), representing the time is required to complete the catheter interventional task in a selected branch of virtual cerebral-vessel.
2. Percentage of the catheter tip in the safe area ($P_t$), representing the percentage of time that catheter tip spent in the safe area during the whole operation.
3. Number of collision ($N_c$), representing the number of times the collision happens.

## 9 Results

This section presents the results of three performance measures, as shown in Fig. 13. All results are presented as mean value and standard deviation (SD). Analysis of variance (ANOVA) was used to analyse the differences between mean values of performance measures and their corresponding procedure, and levels of $p < 0.05$ are

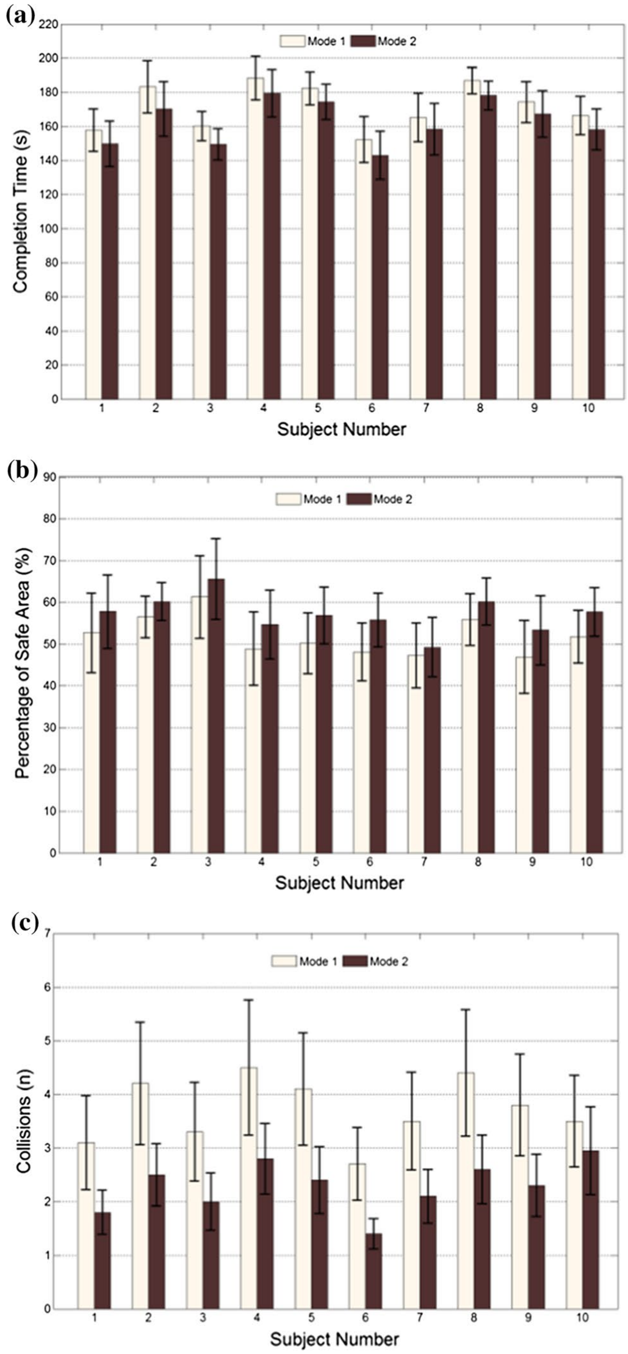


**Fig. 13** The results of three performance measures. **a** Mean values of task completion times ($T_c$) of each operator; **b** Mean values of time percentage of catheter tip spent in safe area; **c** Mean values of collisions between the catheter tip and vascular wall

considered significant. Figure 13a 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 mode 1 are higher than mode 2. The 2-way ANOVA was conducted to test whether the different

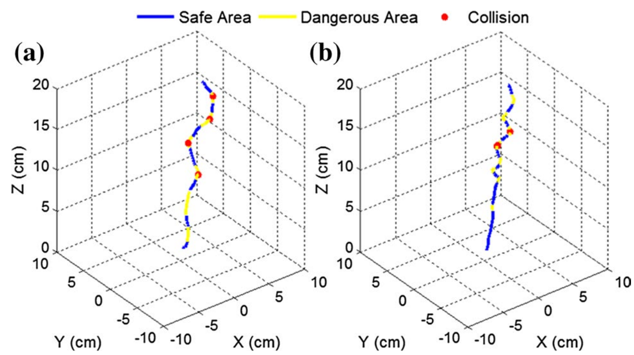


**Fig. 14** The catheter tip trajectories under mode 1 (**a**) and mode 2 (**b**)by subject#1

modes have a significant effect on the task completion time. For the two modes, we detect a significant difference ($p = 1.08 \times 10^{-7}$) in the mean completion times, which indicated that the value of the completion time was affected by the provided force feedback in master site.

Figure 13b illustrates the mean value of the percentage of time that catheter tip spent in the safe area during the whole operation for each operator in two modes. This measure was used to investigate the improvement in operator performance as the haptic force was provided in the master site. In addition, using 2-way ANOVA, the significant difference was detected ($p = 3.7 \times 10^{-6}$). As observed, mean percentages considering each operator under mode 2 are higher than mode 1, respectively. In another word, the operators spent less time to meet the dangerous area under the mode 2. Therefore, applying the haptic feedback in the master site can affect the time that catheter tip spent in the safe area.

Mean values of collisions between the catheter tip and vascular wall under two conditions ($N_c$) of each subject are shown in Fig. 13c. This measure was used to investigate the improvement in surgery safety when the fewer collisions happened. In addition, the study showed that the number of the collision has decreased when the operators were under mode 2 than mode 1.

Figure 14 was the catheter tip trajectories under mode 1 and mode 2 by subject#1 in the first operation. The blue and yellow dots signify the safe and danger areas respectively, and the red mark expresses as the collision points. In mode 1, the subject met the 4 collision points. However, the collision times decreased to 2 in mode 2. Apparently, the time of catheter tip spent in the dangerous area in mode2 was less than mode 1.

## 10 Conclusion

In this paper, an MR fluids actuated haptic interface is presented in master site for endovascular tele-surgery.

The interventionalists can apply conventional bedside technology, axial (push and pull) and radial (twist) motions, to guide the patient catheter. What is more, the passive haptic sensation can be perceived by operating a rigid catheter rather than a manipulator or rod to obtain a passive haptic sensation. To evaluate the performances of proposed master site in catheterization tele-surgery, the virtual-reality (VR) simulator was as the slave side to execute the control commands from the haptic interface. In the experiments, two modes were conducted. The system was evaluated by 3 performance measures, describing task completion times, time percentage of catheter tip spent in safe area and number of the collision. According to the performance measures, the results showed that after provided the haptic feedback the subjects need shorter time and meet less number of collision to conduct the task, and also the time percentage of catheter tip spent in safe area was increased.

The main application of this paper is intended to be in avoiding the collision of the catheter tip and the vessel wall. Here, we utilized the minimal distance of catheter tip and vascular wall to reflect this dynamic interaction in VR simulator. However, how to measure the distance and interaction force between the catheter and the inner wall of the blood vessel during actual vascular operation must be the next step of this research. It is very important and necessary to conduct a new method for extending the range of the controllable force, $F_\tau$ to provide more different levels of passive force. That will help to reflect the dynamic interaction between the catheter and vessel during interventional surgery.

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**Compliance with ethical standards**

**Conflict of interest** The authors declare that they have no conflict of interest.

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