Design and experimental evaluation of a teleoperated haptic robot–assisted catheter operating system

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Abstract
Minimally invasive surgery and therapy is popularly used both for diagnosis and for surgery. Teleoperation, a promising surgery, is used to protect the surgeon from X-ray radiation as well as to address the problem of lacking experienced surgeons in remote rural areas. However, surgery success ratio should be considered because the surgeon was separated from the patient remotely. A most effective addressing method to improve success ratio is design of a haptic interface as a master console, which can provide the “immersive” operation to the surgeon. In this study, a haptic catheter operation system for teleoperation through exploiting magnetorheological fluids is proposed to solve the safety problem. The haptic sensation is provided by varying the viscosity of the magnetorheological fluids by adjusting the magnetic field, which is dependent on the force measured in the slave manipulator. Therefore, three parts of the haptic interface were designed and fabricated: magnetic field, magnetorheological fluids container and haptic performance calibration mechanism. Some preliminary experiments have been done to verify the effectiveness of this kind of haptic interface. Experimental results illustrated that the designed haptic catheter operation system can be used for teleoperation and for training the surgeon for the non-experience.

Keywords
Magnetorheological fluids, haptic interface, teleoperated haptic system, minimally invasive surgery, transparency, stability, catheter operating system

Introduction
The word “haptic” refers to something that is associated with the sense of touch while interacting with simulated objects in a virtual world or operating haptic interface through feedback control in teleoperated system. In open surgery, the surgeon can directly feel the interaction of the instrument and the tissue characteristics of the patient, which can provide haptic cues. However, in manual minimally invasive surgery and therapy, the haptic cues may be masked. The lack of significant haptic feedback in intraoperative injury is often reported (Xin et al., 2005). A haptic interface conveys a kinesthetic sense of presence to a human operator. Haptic interaction has a basic characteristic of kinesthetic energy flows bi-directionally, from or to the human operator and is different with human–computer operation only with an artificial sense of kinesthetic presence in a virtual world to human. The primary application field of haptic interfaces is to provide a realistic sense of forces to human and make them immersed into a virtual world or teleoperated scenario. An ideal haptic interface should provide a high fidelity “immersive” sensation of interaction with virtual world or teleoperated world to human operator (Adams et al., 1998; Adams and Hannaford, 1998). Recently, haptic devices have been designed to increase the effectiveness of human–machine interaction. Teleoperation naturally indicates that operator is operating at a distance, which extends the human capability to manipulate objects remotely by providing the human operator with similar conditions as those at the remote location to protect them from injury due to harmful radiations. Such use includes diverting radiation in nuclear reactor, protecting physician from X-ray radiation during the surgery, and so on. A telerobotic system consists of five
subsystems: master manipulator (master subsystem), slave manipulator (slave subsystem), local control systems in master site and slave site, and information exchange channel. However, in teleoperated robot–assisted minimally invasive surgery (TRMIS), all types of haptic feedback are eliminated because the surgeon no longer manipulates the instrument directly (Okamura, 2009). The lack of haptic feedback is a major limitation of current TRMIS systems.

There are several challenges to successful MIST. On one hand, current catheters do not have the dexterity, speed and force calibration. Therefore, catheter intervention needs full experience of physicians. On the other hand, the risks of injury or penetrating the blood vessel is exists. In order to address these limitations, researchers have developed robot-assisted catheter intervention system. Current commercial products such as remote-controlled catheter navigation system, Niobe® magnetic navigation system (Stereotaxis, USA) and Sensei® robotic navigation system (Hansen Medical, USA) have improved the operating environment for surgeons (Fu et al., 2011). Except these commercial products, a robot-assisted cardiac catheter operating system for heart surgery was proposed (Kesner and Howe, 2011, 2014).

Teleoperated surgical systems have the ability to assist and improve the surgeon's precision and dexterity (Ding et al., 2013). A teleoperated robot–assisted catheter surgery has been done in our laboratory from 2007 to now (Guo et al., 2012; Xiao and Guo, 2012; Yin et al., 2013). However, it suffers the drawback of lack of haptic sensation in the master site. Therefore, it is urgent to design a haptic interface as a master console incorporated into teleoperated robot–assisted catheter system.

As the development of smart materials, some haptic devices have been provided based on these materials. Rizzo et al. (2007) developed the Haptic Black Box I and II (HBBI and HBB II) based on a freehand concept, in which the surgeon can put his or her hand within a box and freely interact with the suitably controlled fluid. Tsuita et al. (2013) designed and evaluated an encountered type of haptic interface using magnetorheological (MR) fluid, which can be used in surgery simulation.

Therefore, a teleoperated haptic robot–assisted master system based on smart materials was proposed in this article. Catheter minimally invasive surgery requires that insertion of catheter or extraction of the catheter into (from) the blood vessel system during cerebrovascular system surgery. During the operation process, when catheter tip goes from the main blood vessel into the branch vessel, in order to avoid penetrating the blood vessel wall, the surgeon will retreat a little or rotate the catheter to change the direction of the catheter tip until it enters into the smaller diameter branch vessel. Therefore, the slave manipulator robotic system has 2 degrees of freedom (insertion and rotation). According to the surgeon’s experience, the safety of catheter minimally invasive surgery is depended on good controlling of the insertion force. Although the slave-assisted robot has 2 degrees of freedom, the proposed haptic interface by exploiting MR fluids only needs to consider the insertion haptic providing.

The characteristics of the proposed haptic system include the following: It is possible to (1) improve the success ratio of catheter minimally invasive surgery by large of training based on the proposed haptic catheter interface; (2) mimic the surgeon’s catheter operating gesture and process; and (3) operate a real catheter not a stick or rod to provide a kind of realistic sensation. The core idea of proposed catheter haptic operating system is shown in Figure 1. In developed catheter haptic interface, the surgeon practices the catheter minimally invasive surgery just like (he/she) operating a catheter insertion into the patient blood vascular system. When catheter was inserted into the developed catheter haptic interface, the surgeon will feel subtle resistance caused by good controlling of the viscosity of the MR fluids.

**Working principles of teleoperated robot–assisted surgery**

Haptic interface was integrated into the robot-assisted surgery system, which enables the surgeon to feel the force experienced by the tool tip of the robot, and could render these limitations obsolete by making the robot more like an extension of the surgeon’s own body (L’Orsa et al., 2013).

Teleoperated robot–assisted catheter operation system with haptic feedback control diagram block is shown in Figure 2, which describes the general
structure of teleoperated haptic robot–assisted surgery system (Vision information and interaction force fed back to the surgeon will increase the “telepresence” of surgeon. Vision information processed by the image processing technology is transmitted to the surgeon. Interaction force information was recreated by operating haptic interface. The haptic rendering (interaction force recreating) method is shown in Figure 3.). This article focuses on the kinesthetic haptic realization and does not consider time delay. Although time delay that occurs on the networks is a serious problem from the perceptive of stability and performance of haptic system (Natori et al., 2010), catheter tip position image displays in the local site may improve maneuverability of catheter minimally invasive surgery.

Haptic force-generated principles
MR fluids application technology utilizes the shear stress of MR fluids. MR fluid is kind of smart materials that undergo in rheological behavior change when an external magnetic field is applied. This mutual interaction among the magnetizable of particles form into a kind of chain-like structures aligned parallel to the applied magnetic field. This kind of rheological state changes from the free flow state into the semi-solid state in several milliseconds (Carlson and Jolly, 2000; Sapinski and Horak, 2013), as shown in Figure 4. The strength of chain-like structures depends on the magnitude and distribution of the magnetic field (Jolly et al., 1996; Wang and Hou, 2013). Therefore, chain-like state

Figure 2. Scheme of kinesthetic sense and visual sense feedback diagram block of teleoperated robot–assisted surgery. TCP: transmission control protocol; IP: internet protocol.

Figure 3. Teleoperated robot–assisted catheter operating system control diagram block through exploiting MR fluid. The relationship in the diagram block represents “current versus haptic force” and the relationship for the developed system has been determined experimentally and it will be discussed in section “Experiment IV: haptic force measurement at different insertion frequencies”. (Yin, et al., 2014)

can be controlled by adjusting the application of magnetic field.

A simple Bingham plastic model effectively describes the MR fluid viscosity dependent on the magnetic field (Ashour et al., 1996; Juning and Kwon, 2003; Wang and Hou, 2013; Weiss et al., 1994). In this model, the total shear stress can be expressed by equation (1). The first term in this equation is the dynamic yield stress, which is the function of magnetic induction ($B$). The second term is the shear stress related to the viscosity of MR fluids. The model equation is expressed as follows

$$\tau = \tau_0(B) + \eta \cdot \dot{\gamma}$$

where $\dot{\gamma}$ is the shear strain rate, and $\eta$ is the field-independent plastic viscosity defined as the ratio of the shear stress versus the shear strain rate relationship. Figure 6 shows the relationship between shear stress and shear rate based on equation (1).

The simple physical relationship can be used to feel this viscosity change. For example, we use a stick inserted through the MR fluid, the higher the viscosity, the slower of the stick insertion, when insertion through the MR fluid with a certain force. That is to say, the higher the viscosity and the same speed of the stick insertion, the larger the force when the stick goes through MR fluids. Therefore, the kind of viscosity change can be used to simulate the force change during catheter surgery process. When trying to change the chain-like structure, you will feel the resistance force generated by the interaction of adjacent particles, as shown in Figure 5. This kind of haptic sensation is encountered often in daily life, just like stirring soup or coffee. This kind of viscosity can be perceived by stirring with the hand and or a stick (Bicchi et al., 2005; Tiest et al., 2013). Based on this idea, the catheter haptic interface was designed.

The haptic force is generated by insertion of catheter through the MR fluid. It is just like a stick inserted into the “sticky clay with some of water.” In essence, the catheter insertion motion in the MR fluid will change the chain structure of the MR fluids under the magnetic field exciting condition. Therefore, the magnitude of force is generated by the easiness of this kind of chain structure change.

During the catheter operation surgery, the frequency of catheter insertion can be divided into two situations: high frequency (a little faster) and low frequency. When catheter goes through the main blood vessels, catheter can smooth insertion through it. According to the surgeon’s experience, catheter insertion frequency can reach up to 3–5 Hz. In this article, this is so-called high frequency. In another condition, the catheter goes through from the main blood vessel to blood branches. The catheter tip direction will be adjusted to avoid penetrating the blood vessel wall. In this condition, the catheter will need rotating and...

Figure 4. Chain structures of magnetorheological particles upon application of magnetic field: (a) magnetorheological fluids in “off state,” (b, c) magnetorheological fluid in “on state” and the magnitude of magnetic field (b) is smaller than (c) (Park et al., 2010). MR: magnetorheological.

Figure 5. Haptic sensation generated process caused by interaction of magnetorheological particles in “on state” (MR fluid particles are a few microns). MR: magnetorheological.

Figure 6. Relationship between shear stress and shear rate in two states (Tsujita et al., 2013).
slowing down of the insertion frequency. Therefore, the catheter insertion frequency will slow down to 1–2 Hz. It is so-called low frequency insertion. Figure 7 shows the MR fluids’ shear state in high and low frequency. The difference is the catheter insertion velocity $v$, which depends on insertion frequency. In theory, the generated force cannot be affected by the insertion frequency because the generated force is viscosity dependent. The effect of the high and low frequency on the magnitude of generated haptic force will be determined experimentally in section “Experiment IV: haptic force measurement at different insertion frequencies.”

### MR fluids choose

In the designed catheter haptic interface, the haptic sensation is provided through controlling viscosity variations of MR fluids. Therefore, the MR fluids choice is significantly important to achieve good results of the haptic sensation provided to the surgeon. Electro rheological fluid is also a smart material. Some haptic devices based on electrorheological (ER) fluids are reported in the literature (Butz and Von Stryk, 2002; Carlson et al., 1996). The characteristic comparison between MR fluids and ER fluids is given in Table 1.

In this article, a semi-active passivity encountered type of haptic catheter interface (based on MR fluids MRF-122EG, a product of the Lord. Corp., USA.) is fabricated. The felt force is subtle during the catheter minimally invasive surgery practice.

Therefore, the viscosity parameters are most important in this kind of smart material choose. Except this, density and particle fraction also need consideration. The typical characteristic of the MR fluid (Lord. Corp.) is shown in Table 2.

### System design

Teleoperated robot–assisted haptic catheter minimally invasive surgery system consists of human operator, haptic master subsystem, communication channel, slave manipulator subsystem, and the patient environment. In this article, a haptic catheter operation subsystem based on exploiting MR fluids was proposed, which consists of electromagnetic design, haptic catheter interface design, and haptic calibration mechanism design.

#### Electromagnetic design

The catheter haptic interface and electromagnetic design idea is shown in Figure 8, in which two coils are assembled together to generate the magnetic field, the MR fluids container is placed between two coils, and the catheter goes through the MR fluids.

The important goal in the design of the magnetic circuit is to increase the magnetic field intensity applied to the MR fluids as much as possible. The relationship between the haptic force generated through catheter insertion and rotation motion by applying the coil current and the corresponding magnetic field intensity is given by Ampere’s law (Nam and Park, 2009)

$$ NI = \oint H \cdot dl = H_f l_f + H_s l_s $$

where $N$ is the number of the coil turns, $I$ is the coil current, and $l$ is the length of the magnetic flux path. The subscripts $f$ and $s$ represent the physical properties related to the MR fluid and the yoke, respectively. Here, the haptic force $NI$ can be controlled to display the catheter interaction force by adjusting the current. In order to increase magnetic field intensity, iron core was placed into the bobbins. Not only the nonuniform magnetic field is formed by this kind of design, but also the haptic resolution can be improved.

The magnitude optimization design was conducted using the magnetic software (Photon magnetic simulation software, http://www.photon-cae.co.jp). The simulation results are shown in Figure 10.

Three spacers (each of spacer is 4 mm, made of SS 400 steel, Japanese industrial standards (JIS)), which gave MR fluids annular duct design more freedom according to the requirements, were designed to adjust...
the gap between two coils to further adjust magnetic field intensity through the MR fluids container. Diameter of the copper wire of the coil is 1.6 mm and each of coil turns is 1200 T. The bobbin of the coil and the stage are made of aluminum. Iron core (cylinder with circular truncated cone made of SS400 steel, JIS) is used to increase the magnetic field in the center. The yoke used to support the coils is also made of SS400 steel, and all other components are made of non-magnetic material. The fabricated magnetic field generator is shown in Figure 12. The major geometrical dimensions of the designed magnetic generator are shown in Table 3 and Figure 9.

### Table 2. Typical characteristics of the MR fluids (Lord. Corp.)

<table>
<thead>
<tr>
<th>MR fluids species</th>
<th>MRF-122EG</th>
<th>MRF-140CG</th>
<th>MRF-132DG</th>
<th>MRF-132LD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>Dark gray liquid</td>
<td>Dark gray liquid</td>
<td>Dark gray liquid</td>
<td>Dark gray liquid</td>
</tr>
<tr>
<td>Viscosity (Pa·s at 40°C)</td>
<td>0.042 ± 0.020</td>
<td>0.280 ± 0.070</td>
<td>0.112 ± 0.02</td>
<td>0.94</td>
</tr>
<tr>
<td>Density (g/cm³(lb/gal))</td>
<td>2.28(2.48)</td>
<td>3.54–3.74</td>
<td>2.95–3.15</td>
<td>3.055</td>
</tr>
<tr>
<td>Solids content by weight (%)</td>
<td>72</td>
<td>85.44</td>
<td>80.98</td>
<td>80.74</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>&gt;150</td>
<td>&gt;150</td>
<td>&gt;150</td>
<td>&gt;150</td>
</tr>
<tr>
<td>Operating temperature (°C)</td>
<td>-40 to +130</td>
<td>-40 to +130</td>
<td>-40 to +130</td>
<td>-40 to +130</td>
</tr>
</tbody>
</table>

MR: magnetorheological.

**Figure 8.** Show the major geometrical dimensions of the developed catheter haptic interface: (a) front view, (b) top view, and (c) left view.

**Figure 9.** Idea of haptic catheter interface.
Design of catheter haptic interface

In teleoperated robotic haptic system, to improve maneuverability and safety of the robot-assisted catheter operation surgery, some of the key practical design considerations will be introduced in this section. Scheme of catheter haptic interface is shown in Figure 11 and the fabricated catheter haptic interface is shown in Figure 12. The surgeon can obtain the realistic operation scenario and sensation through grasping the catheter insertion or rotation into the MR fluids. However, MR fluids are will flow out from the holes, which is used for catheter insertion, when the magnetic field is in “off state.” Therefore, MR fluid seal is important to this catheter haptic interface.

In this haptic interface, the haptic force sensation consists of two parts: one is the force generated through adjustment of the MR viscosity and the other is the friction force caused by the seal of MR fluids and the contact between the catheter and the MR fluids container. In catheter surgery, the total force is very small as well as the force change is very small. Hence, it is important that friction force was reduced to minimum in the whole design. The following are used as representations of the design: coil fixator, coil support, MR fluids annular duct support, permanent magnetic, MR fluids annular duct, magnetic coil, catheter, magnetic sensor fixator, sensor fixator.

In general mechanism design, “O-ring” was used to prevent overflow. However, this kind of seal will increase the friction and worsen the maneuverability. A new dynamic seal method was presented to prevent overflow of MR fluids with minimum friction. The details are shown in Figure 13.

Four permanent magnets were fixed at both ends of container. Four sponges, which were used to absorb the MR fluids flowing out from the container, were placed between the catheter and the permanent magnets. The magnetic field generated by the permanent magnets was used to alter the viscosity of the flow out MR fluids. In order to get the minimum friction

Table 3. Dimensions of the designed magnetic generator.

<table>
<thead>
<tr>
<th>Parameter item</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper wire diameter (mm) (AIW)</td>
<td>Ø1.6</td>
</tr>
<tr>
<td>AIW is a kind of enameled round copper wire, with polyesterimide resin as under coating and polyamide-imide resin as over coating.</td>
<td></td>
</tr>
<tr>
<td>Inner diameter of the coil (mm)</td>
<td>Ø30</td>
</tr>
<tr>
<td>Outer diameter of the coil (mm)</td>
<td>Ø120</td>
</tr>
<tr>
<td>Height of each coil (mm)</td>
<td>68</td>
</tr>
<tr>
<td>Coil turns (T)</td>
<td>1200</td>
</tr>
<tr>
<td>Coil 1 resistance (Ω)</td>
<td>2.435</td>
</tr>
<tr>
<td>Coil 2 resistance (Ω)</td>
<td>2.448</td>
</tr>
</tbody>
</table>

Figure 10. Simulation results of magnetic field generation (vector form). Simulations parameters: the input current is set at 1 A and \( \mu_r = 300 \); the relative permeability ferromagnetic materials (\( \mu_r = 200 - 400 \)).
of the catheter operation, the magnitude of the permanent magnets were only used to prevent MR fluid flow out.

**Design of haptic evaluation mechanism**

Although the force can be displayed to the surgeon through adjusting the current, this is only a feeling. During force-reflecting teleoperated robot–assisted surgery system, however, it is important to know the magnitude of the force. Therefore, a dynamic force measurement device is designed. We called it as the haptic calibration mechanism shown in Figure 14.

During the calibration process, catheter operation technology is realized as the calibration system. It mainly consists of stepping motor \( \oplus \) and load cell \( \oplus \) (TEAC Corp., Japan). The stepping motor, which is controlled forward and backward, is used for insertion of the catheter instead of physician operating. The load cell is fixed on the load cell bracket, which is assembled on the ball screw. The motor stage \( \oplus \) is used for fixing the stepping motor. The catheter \( \oplus \) is assembled to the sensitive axis of the load cell \( \oplus \) by a linker \( \oplus \).

**System evaluation**

In order to provide a precise haptic sensation to the surgeon in the master side during the teleoperated robot–assisted catheter surgery, it is necessary to improve the kinesthetic control precision. Therefore, it is significantly important to find out the relationship between the haptic force and the current input. Some experiments have been done to verify the efficiency and maneuverability of the proposed catheter haptic interface.

**Experiment I: magnetic field intensity and distribution measurement**

The Gauss meter (TM701; KANETEC, Japan) was put into the gap of two coils and adjusted in radial and
vertical directions step by step from the center. Each step is 5 mm. And the input current is increased step by step from 0 to 1.5 A, with each step being 0.5 A. The radial direction measurement results are shown in Figure 15 from center to outer direction. The results show that the magnetic field distribution in the gap is a nonuniform magnetic field. The magnetic field reduced from the center to the outer edge. The vertical direction measurement results are shown in Figure 16. The results show that MR fluids is in nonuniform magnetic field space.

**Experiment II: haptic interface system friction measurement**

The experimental setup block diagram is shown in Figure 17. It consists of three parts: the first part is the magnetic field generation and control. The magnetic
field intensity is controlled through adjustment and amplifying the current to supply the magnetic generator, which was implemented by DSP controller (TI TMS320F28335) and current amplifier (AQMD3610NS; Chengdu AIKONG Electronics, China). The second part is the haptic calibration system, which consists of a catheter insertion stepping motor system (VEXTA, ASM46AA, DC: 3.42 V, 0.9 A, Oriental Motor Corp., Japan) control. The current control signal is amplified by the stepping motor driver and controller (EMP400 Series Controller, Oriental Motor Corp., Japan). The third part is the resistance force (haptic sensation), which included a force measurement device load cell and strain amplifier (SA-570ST; TEAC, Japan).

When the MR fluids are in “off state,” a 7Fr catheter was inserted through the designed catheter haptic interface. The small force will be felt by the operator, which is called system friction of haptic interface. It contains two parts: one is the friction caused by the relative motion between the catheter and the MR fluids, which is in the Newtonian fluid state and the other part of friction is caused by the dynamic seal of MR fluids, as shown in Figure 12. Force measurement experiments have been conducted six times. The catheter insertion frequency is set at 2 and 5 Hz. The results of system friction are shown in Table 4.

The average of the system friction is about 0.014 N. For teleoperated surgical system, it is good for assessing the system transparency that the operation motion frequency is set in the range of 0.5–10 Hz (Speich et al., 2005). Based on the experiments have been conducted at the catheter insertion frequencies of 2 and 5 Hz, conclusion can be drawn that the minimum haptic sensation force is 0.014 N. When the MR fluids are in “on state,” haptic force caused through controlling of the input current will be increased.

### Experiment III: Haptic force calibration

In order to find the relationship between haptic force and input current, different coil currents in the range of 0–2 [A] with a step 0.20 [A] are applied to each coil. Experimental setup is shown in Figure 17. In order to control the haptic force accurately according to reference force measured by the patient-manipulator, force feedback control between haptic interface and patient-manipulator is indispensable (shown in Figure 4). Before the current applied to magnetic coils, MR fluids were injected into the MR fluids container. The force was measured five times with each step of current increase experiments setup is shown in Figure 18. The relationship between the haptic force and the input current is shown in Figure 19. The measured force consists of three parts: the first part is the system dynamic friction caused by catheter surface contacted with MR fluids seal. The system dynamic friction is a constant and its value is about 0.014 N, which is measured in a condition that the input current is 0 and magnetic field intensity is controlled through adjustment and amplifying the current to supply the magnetic generator, which was implemented by DSP controller (TI TMS320F28335) and current amplifier (AQMD3610NS; Chengdu AIKONG Electronics, China). The second part is the haptic calibration system, which consists of a catheter insertion stepping motor system (VEXTA, ASM46AA, DC: 3.42 V, 0.9 A, Oriental Motor Corp., Japan) control. The current control signal is amplified by the stepping motor driver and controller (EMP400 Series Controller, Oriental Motor Corp., Japan). The third part is the resistance force (haptic sensation), which included a force measurement device load cell and strain amplifier (SA-570ST; TEAC, Japan).

![Figure 17. Experimental setup (Yin et al., 2014).](image1)

![Figure 18. Haptic force calibration experimental setup.](image2)

### Table 4. System friction force measurement.

<table>
<thead>
<tr>
<th>Experiments times</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion frequency</td>
<td>2 Hz</td>
<td>13</td>
<td>14</td>
<td>16</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>5 Hz</td>
<td>15</td>
<td>16</td>
<td>18</td>
<td>13</td>
<td>11</td>
</tr>
</tbody>
</table>

Force unit: (10^{-3} N). Magnetorheological fluids in “off state,” that is, Newtonian fluid.
is 0 as well as MR fluids are in a Newtonian-like state. From Figure 20, an approximated curve can be obtained and can be expressed as follows

\[ f = 1.7 \times 10^{-5}i^3 + 2.1 \times 10^{-3}i^2 - 3.6 \times 10^{-3}i + 0.019 \]  

(3)

where \( f \) and \( i \) are the displayed force (called haptic force) and the input coil current, respectively. The scaling capability of the proposed haptic catheter interface depends on system friction caused by dynamic seal of the MR fluid, which prevents the MR fluid overflow from the holes of the MR fluid container (the holes are used to catheter goes through) and the viscosity when the MR fluids in "off state" and provides the smallest magnetic field intensity excited by the smallest current supply. When operating the developed haptic catheter interface, the smallest kinesthetic force

**Figure 19.** Relationship between the haptic force and the input current.

**Figure 20.** Relationship between haptic force and the input coil current at the different insertion frequencies.
provided to the surgeon is 0.01 N with the input of 0.1 A current. Its value can be reduced by changing the seal of design of MR fluid.

**Experiment IV: haptic force measurement at different insertion frequencies**

In catheter surgery practice, when the catheter advance is difficult at the branch of the blood vessel, it will be rotated or will be retreated. After moving into the small branch of the blood vessel, the speed of the catheter insertion will be slowed down to avoid penetrating the blood vessel. Therefore, in the whole catheter insertion practice, the surgeon will change the insertion frequency, according to the kinesthetic sensation and image information, such as that obtained by computerized tomography (CT). However, in actual catheter minimally invasive surgery, the catheter insertion velocity has no fixed relationship with insertion frequency. In the experiment, the catheter insertion frequency is controlled through the stepping motor. Three kinds of frequencies were adopted: 2 Hz (4.23 mm/s), 5 Hz (6.10 mm/s), and 8 Hz (7.18 mm/s). And the input current increased from 0 to 2 A with a step of 0.20 A. These insertion frequencies are usually used according to the physician experience. The experiment of each insertion frequency was done five times to measure the force. The results are shown in Figure 21.

**Experiment V: hysteretic characteristics test of MR fluids**

Figure 21 shows the experimental results conducted to examine the hysteretic characteristics of the catheter haptic interface. The whole catheter insertion displacement is set to 120 mm. When catheter insertion frequency is set at the frequency of 2 and 5 Hz, the current is varied from 0 to 2.0 A and then to 0 A and increasing or reducing with a step of 0.20 A, respectively. Figure 21(a) shows catheter insertion frequency at 2 Hz. The maximum of deviation between the actual measurement value and the curve fitting value is about 0.014 N. The maximum of deviation between the current increase and decrease is 0.009 N, which is caused by the hysteretic characteristic of MR fluids (Wang et al., 2003). Figure 21(b) shows catheter insertion frequency at 5 Hz. The maximum of deviation between the actual measurement value and the curve fitting value is about 0.012 N. The maximum of deviation between the current increase and decrease is 0.016 N.

**Discussion**

These experimental results demonstrate that the designed teleoperated robot-assisted catheter haptic minimally invasive surgery master operating system can provide a haptic sensation to the surgeon for improving the safety of surgery as well as maneuverability. The haptic operating master system is designed based on the MR fluids, which provides a new method for the surgical haptic simulation device as well as console device design of teleoperated haptic robot-assisted surgery system.

One insight from this work is obtaining the relationship between haptic force and the magnetic field intensity, because the variation of viscosity of the MR fluids is controlled by adjusting the magnetic field intensity. The magnetic field intensity is changed with the changed input current. Haptic calibration experiments based on the designed catheter haptic operation system and hysteretic characteristics test of MR fluids have been done. The relationship between the haptic force and the input current was obtained. The hysteretic characteristics of MR fluids have no impact on the haptic force.

The surgeon can obtain a kinesthetic sensation based on the slave system measurement by precise control of the current generated magnetic field intensity. The system transparency can be increased by optimization control of force information. Therefore, the safety of telesurgery can be improved through the designed catheter haptic operating master.

Although the experimental results demonstrate that the robotic catheter haptic operation master system is able to provide a kinesthetic sensation to the surgeon to ensure the safety of catheter minimally invasive surgery, there are a number of limitations in this validation evaluation due to the challenges of accurate operation of this catheter haptic operating master system.

As the system dynamic friction experiment describes, in order to prevent the MR fluids flowing out from the MR fluid container, the dynamic seal will increase the dynamic friction force, and the resolution of the catheter haptic operation system will be reduced. Especially, in cerebrovascular disease surgery, a little more force applied on catheter will penetrate the blood vessel wall, which will cause the cerebrovascular surgery accident, although image information is also given to the surgeon. Therefore, it is important to improve the resolution of this kind of haptic device design.

During catheter surgery practice, surgery safety depends not only on the quality of the tools but also on the skill of the surgeon. In this research, a haptic catheter interface was designed to provide an “immersive” surgery practice. Therefore, it is possible to improve surgery practice through large of haptic catheter operating surgery training based on proposed haptic teleoperated robotic catheter operating system. Moreover, it will improve the success rate of surgery. It will be confirmed in the future research of this project.

The future work in this project will focus on the demonstration and evaluation of teleoperated robot-assisted catheter minimally invasive surgery in an in...
vivo setting. In order to realize the teleoperated robot-assisted catheter operation surgery evaluation, a motion measurement part will be added to the designed catheter haptic operation master. A catheter slave manipulator with a force sensor attached on the end-effector will be designed.

**Conclusion**

TRMIS is a promising surgery technology. For improving the success ratio of teleoperated robot-assisted catheter minimally invasive surgery practice, this article presents a haptic operation master system based on MR fluids for catheter cerebrovascular surgery. Through the electromagnetic analysis and design, catheter haptic operating master system structure design and haptic force calibration mechanism design as well as some experiments, its effectiveness is verified. The designed catheter haptic master operation system can be used not only as a console used in teleoperated robot-assisted surgery scenario but also for non-experienced surgeon training.

**Figure 21.** Hysteretic characteristics at different insertion frequencies: (a) insertion frequency 2 Hz (insertion velocity: 4.23 mm/s) and (b) insertion frequency 5 Hz (insertion velocity: 6.10 mm/s).
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