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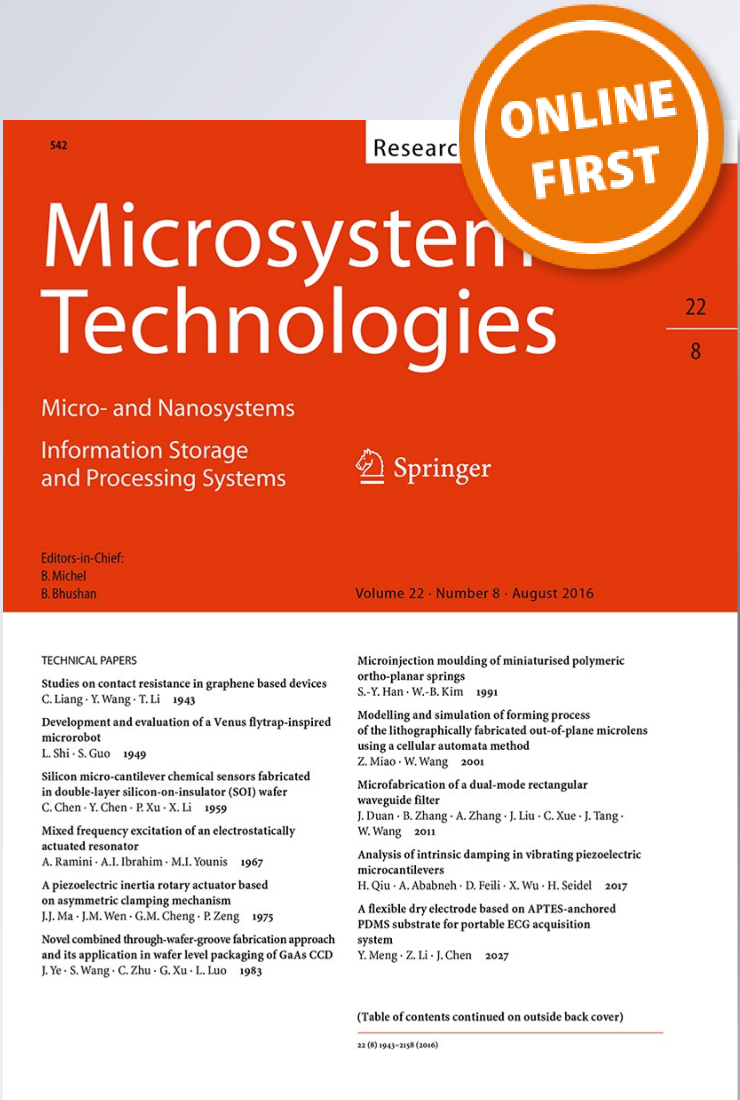

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TECHNICAL PAPER

Design and characteristics evaluation of a novel VR-based robot-assisted catheterization training system with force feedback for vascular interventional surgery

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Abstract Vascular interventional surgery has been become a specialized surgical technique because it can minimize the trauma and shorten the recovery time, but it needs more accurate operation and image to guide the surgery. In the meantime, it needs that the doctor has a great deal of experience. Moreover, it needs to train the novice because of the lack of experienced neurosurgeons. In order to solve aforementioned problems, the training system for vascular interventional surgery was proposed. A novel VR-based robot-assisted catheterization training system is designed to solve these problems. This system is composed of the virtual environment and the haptic device. The virtual environment included a catheter model and a vascular model to realize the synchronous movement with the haptic device. In order to imitate soft tissue deformation, mass-spring model has been proposed in physical modeling. In this paper we established a dynamics equation of the moving catheter. We analyzed the elasticity distribution of the wall of vascular according to the previous research. The haptic interaction device based on magneto-rheological fluid as the master manipulator was applied to control the movement of the catheter model in the virtual environment and realize haptic feedback. At the same time, a force feedback calculation model for the novel master manipulator has been proposed. Ten times experiments both in axial movement direction and in radial movement respectively, are carried out, there was within 0.74 mm error in axial movement direction and 3.5° error in radial movement direction. When the moving speed of the catheter is 5 mm/s, the force error between the virtual environment and the feedback force of the damper is within 0.3 mN. The error is in the range which is permitted during VIS. The proposed method improved accurate operability and traceability in this novel VR robotic catheter training system. It offers users better visualization and control. The experimental results indicate that the performance of the synchronous movement and the force feedback can meet our design requirement. The developed training system can be used to train novice for VIS.

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1 Introduction

Vascular diseases is one of the main diseases that threatening human health. The VIS because of many advantages such as less blood loss, smaller trauma and shorter recovery time are getting more attentions in recent years. However, it requires high operation skills, error or repeat process will lead to damage of blood vessels.

The traditional training method has its own limits. With the continuous development of science and technology, virtual reality (VR) technology has been used in health care (Gallagher et al. 2005), and the virtual reality simulators in medicine are becoming more widely (Cecil et al. 2014). And many systems have proved to be significant practical value in training and in evaluating user responses in situation specific problem solving (Anderson et al. 2002). The purpose of the training system is to improve the doctors' surgery accuracy for real patient (Sebastyan et al. 2016; Freschi et al. 2014). And characteristic of VR is used to

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imitate the way to the user to create a virtual environment, through the behavior such as vision, hearing and touch, let users have a feeling of immersion. In the meantime, many simulators can protect the surgeons from X-ray radiation (Wissel et al. 2015).

A typical research is a robotic catheter placement system called Sensei Robotic Catheter System offered by Hansen Medical (Seymour et al. 2002), the system mainly improve the accuracy and prevent the doctor from radiation, but multiple degrees of freedom and force detection is not ideal. Gong et al. proposed an approach based on Chai3D to set up a virtual reality training system (Gong et al. 2014). The approach can achieve the flexible body modeling of catheter and the collision force feedback algorithm. And the results of collision force feedback algorithm match well with the data collected by sensors. Gao et al. presented a mechanical analysis and haptic simulation of the catheter and vessel model for the MIS VR operation training system (Gao et al. 2013). And the experimental results show that the system can be used for surgery training. Hasegawa et al. have developed a catheter simulator using a 3D heart model to improve doctors' skills (Hasegawa et al. 2006). The simulator enables doctors to measure the electricity of the heart, especially some particular parts, such as high right atrium (HRA), bundle of His (HIS), and right ventricular apex (RVA). In addition, doctors confirm how electricity is transmitted within the heart by comparing normal hearts and abnormal hearts using the electrocardiogram. Zhang et al. have proposed an active contour method (snake) to track changes in vessel geometry (Zhang et al. 2014). And the experiment indicates that the proposed approach is feasible for liver vessel centerline extraction from 3D ultrasound images. Mi et al. have presented a 3D virtual reality simulator for core skills training in minimally invasive surgery (Hou et al. 2014). The system can generate realistic 3D vascular models segmented from patient datasets, including a beating heart, and provide a real-time computation of force and force feedback module for surgical simulation. These above mentioned researches also have some disadvantages: some systems don't have the function of force feedback, some systems only realize the virtual reality environment while not connecting with the master side, and some systems cannot make the surgeon inherit the skills acquired in the traditional surgery.

In this paper, we proposed a VR-based robotic catheterization training system for vascular interventional surgery. This training system integrates the VR system and the master–slave robotic catheter system (Guo et al. 2012). When master side process some kinds of operation (radial movement and axial rotation), we can see the image and data on the integrated screen. So it can realize the catheter remotely control to train the novice. MRF is used in the master side to provide haptic feedback. We have done some experiments to evaluate the system and to verify the stability and veracity of the synchronous movement and the force feedback. In the meantime, the results indicate that the veracity and the stability of the system can meet our design requirement. And the combination of the haptic device and virtual environment, gives a lot of convenient for novice in the actual use of minimally invasive surgery, and this system applied VR technique to increase the immersive simulation, give novice a better training effect.

2 Method

2.1 Overview of the whole system

In order to realize operation training, the VR-based robotic catheter training system is proposed. The Fig. 1 shows the concept diagram for VR-based robotic catheter training system. The master–slave robotic catheter system can realize remote catheter control (Guo et al. 2012). The haptic device using MRF is applied as the master side. The surgeon operates the real catheter to move along axial direction and rotate along radial direction. At the same time, the control commands will be transmitted to the PC of the slave side. Then the controller of the slave side controls the slave manipulator to clamp the catheter to insert and rotate the catheter, as if the surgeon operated the real catheter just beside the patient to finish the surgical process. The master manipulator is used to collect the movement information of the catheter and to realize the force feedback to the operator. The movement information will be transmitted to the VR environment to realize the synchronized movement of the catheter between the real environment and the virtual environment.

To ensure the safety of the remote control, a force sensing system is applied. When the catheter contacts the blood

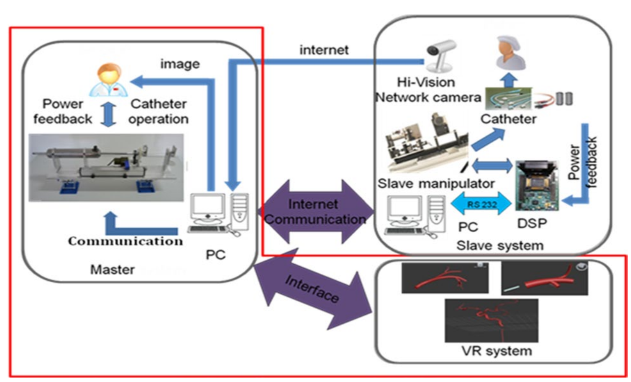

Fig. 1 The concept diagram for VR- based robotic catheter training system. The master–slave robotic catheter system can realize remote catheter control

vessel wall, it can transmit the force feedback information to the master side (Shimojo et al. 2004). The operator can feel the feedback force actually through the master side (Wang et al. 2008). Besides, the monitoring interface is gained by the IP camera will be transmitted to the operator.

A novel virtual reality surgery training system is proposed based on the master–slave robotic catheter system (Gao et al. 2013). We build a virtual surgery environment with the three-dimensional reconstruction method, and finish the visual effect rendering using three-dimensional software to simulate real surgery scene. The catheter in the virtual environment can realize insertion along axial direction and rotation along radial direction under the control of the master manipulator. The movement of the catheter in the virtual environment is in accordance with the movement of the real catheter on the master side. When catheter contacts the blood vessel wall in the virtual environment, the model can produce deformation based on mass-spring model, and the intern will feel the feedback force through the master manipulator applying MRF (Ahmadkhanlou et al. 2005; Yan et al. 2007). The feedback force is consistent with the force calculated in the virtual environment. The real surgery procedure is simulated in this way. During the process of training, the intern operates the catheter on the master side to control the movement of the catheter in the virtual environment. If the catheter contacts the vessel, a feedback force will be transmitted to the intern through the haptic device, the master manipulator, and then the intern can adjust the operation according to the visual and force feedback.

When the catheter collides the vascular wall the model could produce deformation and a feedback force. The haptic device is the main hardware platform. Utilizing it the interaction between the virtual environment and the operator can be realized.

2.2 Structure and principle of the VR System

In order to achieve the goal of training interns, the VR Robotic Catheter System must imitate the actual medical procedure. The software design is aimed at building the virtual environment, which includes the catheter model and the vascular model. When the catheter collides the vascular wall the model could produce deformation and a feedback force. The haptic device is the main hardware platform. Utilizing it the interaction between the virtual environment and the operator can be realized. The operator can control the movement of the catheter in virtual environment and the feedback force can be transmitted to the operator.

The hardware platform and the software design should be combined perfectly, only in this way the VR system can be integrated successfully (Thakui et al. 2009). The Fig. 2 shows the functional block diagram.

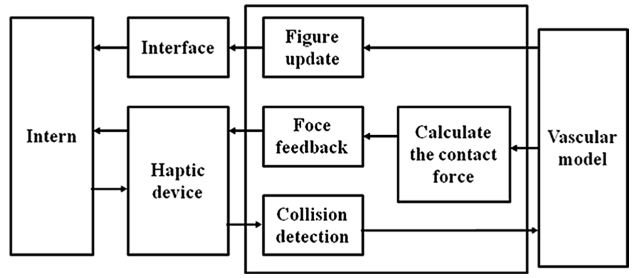

Fig. 2 The Functional block diagram of the developed system

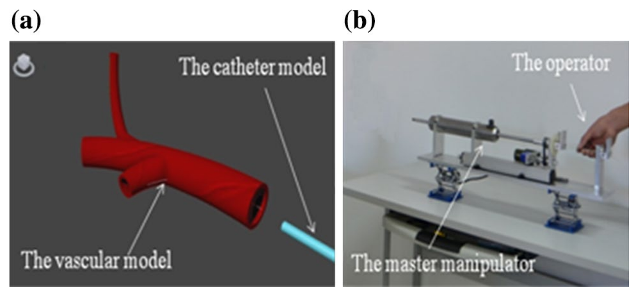

Fig. 3 **a** The vascular and the catheter model. **b** The master manipulator. The developed master manipulator based on MRF damper

2.3 Hardware platform

In recent research, many research institutions use PHANTOM as the haptic device (Silva et al. 2009). However, the handle of this device is a thick cylinder, the progress of operating the handle is different from inserting the catheter. This will reduce the effect of the operation training. In order to improve this situation, our research team have designed a novel master operator based on magnetorheological fluid. This novel operator can take the place of PHANTOM in the virtual reality system. The platform using the novel manipulator based on MRF damper is shown in Fig. 3.

The master manipulator is the operating platform of the doctor who operates the catheter interventional surgery. On the master side, the motion of the catheter operated by surgeon has two degrees of freedom, one is axial motion, and the other is radial motion. In order to acquire the axial motion of the catheter, a linear displacement sensor has been adopted. The radial motion of the catheter is acquired by the optical encoder which installed on the torque motor. In order to realize the force feedback, a damper is used based on the intelligent fluid-MR fluid. MR fluid is in the free flowing liquid state when magnetic field is absence. But it can change reversibly from free-flowing, linear viscous liquids, to semi-solids with the yield strength swiftly and continuously controllable (milliseconds scale dynamics) when exposed to a magnetic field (Song et al. 2009).

The viscosity of the MR fluid can be controlled by applying an external magnetic field.

Compared with the PHANTOM device, the novel master haptic device based on MRF can simulate surgeon's operating skill to insert and rotate catheter more realistic (Gao et al. 2014), the best advantage of this system is that the surgeon can operate a real catheter. The novel system accords with the requirements of ergonomic and can make full use of natural catheter manipulation skills obtained in conventional catheter navigation.

2.4 Software design

2.4.1 Establishment of the virtual environment

The virtual environment of the virtual vascular interventional surgery system includes vascular model and catheter model. In order to make the vascular model reach high consistency with the real vascular, three-dimensional reconstruction method has been applied to set up geometric model (Suh et al. 2014). 3DS MAX 2012 software on windows platform have completed rendering of the virtual environment. The model built using three-dimensional reconstruction method has high complexity, which will increase the computational complexity. In the experimental stage, in order to simplify the computation, we have established a simply environment including vascular model and catheter model. The vascular model is part of the vascular, which has some branches. The catheter model is in cylindrical shape. These models are all built in mm.

2.4.2 Software flow design

The programming language of Visual C++ 6.0 has been chosen to complete the whole procedure, in order to realize control and perception of the virtual object by applying the haptic device.

3 Experiments and results

The movement control of the virtual catheter plays an important role in the representation of real operation procedure. The physical model was established in our previous research (Guo et al. 2014). We will analyze the movement of the catheter in this part. In real operation procedure, the movement of the catheter has 2° of freedom, they are moving along the axis direction and rotating along the radial direction (Yin et al. 2016). So, from the haptic device we obtain axial displacement by the linear sensor and the rotation angle by the optical encoder. According to the proper proportion relationship, the two movement

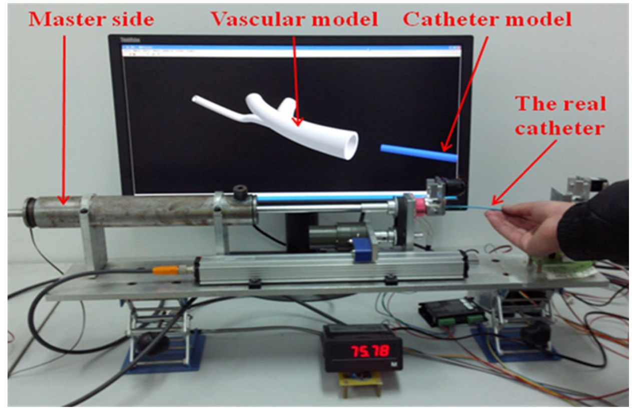

Fig. 4 The VR-based robotic catheter training system

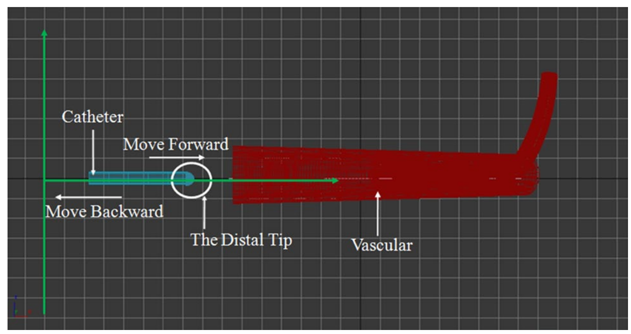

Fig. 5 Catheter insertion along *axial* direction

information can be transmitted to the virtual catheter, and the movement control of the virtual catheter can be realized. Figure 4 shows the physical map of the experiment. The operator inserts the catheter while the virtual catheter in the VR environment can realize the synchronous movement. The experimental data can be acquired through the sensors.

As the Fig. 5 shows, one degree of freedom is that the catheter model moves forward and backward along axial direction. This figure is the front viewpoint of the vascular model in 3DS Maxs. On the master side, a linear displacement sensor is installed on the installation board. During the catheter operation, the motion of the catheter along axis direction can be obtained. The axial displacement information of the real catheter on the master side is set as the control signal, and we set it as quantity information in mm. Positive number represents the catheter moving forward, and negative number represents the catheter moving backward. In order to improve the operability of the VR system, the relationship between the movement amount of the catheter model and the control variable is built as follows.

$$S = k_1 \cdot x \quad (1)$$

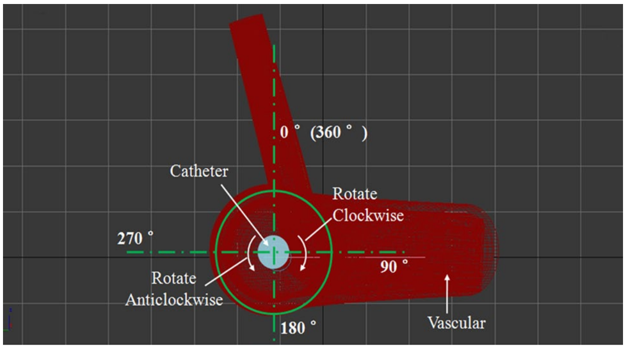

Fig. 6 Catheter rotation along *radial* direction

where, S means the displacement of the catheter model in virtual environment, k_1 is the proportional coefficient, x means the displacement of the catheter on the master side.

The other degree of freedom is that the catheter rotates along radial direction. As Fig. 6 shows, an optical encoder is installed on the torque motor. This figure is the left view of the vascular model in the 3DS Maxs. Using it the radial motion of the catheter on the master side can be obtained. We set the radial information as the control variable. Positive number represents the catheter rotates clockwise and negative number represents the catheter rotates anticlockwise. The relationship between the rotation angle of the catheter model and the control variable is as follows.

$$\omega = k_2 \cdot \omega_0 \qquad (2)$$

where, ω means the rotation angle of the catheter in virtual environment, k_2 is a proportional coefficient, ω_0 and means the rotation angle of the catheter on the master side.

Utilizing the experimental platform of the virtual reality system, we carry out a series of experiments. As Fig. 5 shows, the operator is doing virtual vascular interventional surgery. The haptic device based on MRF is used as the human–computer interaction interface device. When the operator operates the catheter to move along axial direction, the catheter model in virtual environment will realize the synchronous movement with the real catheter. Likewise, when the operator rotates the catheter, then the catheter model will rotate in radial direction correspondingly. At the same time, a feedback force can be transmitted to the operator through the haptic device.

The insertion and rotation of the real catheter in the experiment is shown in the Fig. 7. The experimental results of axial movement are shown in Fig. 8. In Fig. 8a, Y-axis represents the displacement, and X-axis represents time. We take the range of linear displacement sensor as a measurement cycle, and insert the catheter along X-axis direction slowly in a constant speed. The total displacement of the catheter is 150 mm. The green curve shows the displacement of the catheter on the master side (haptic device).

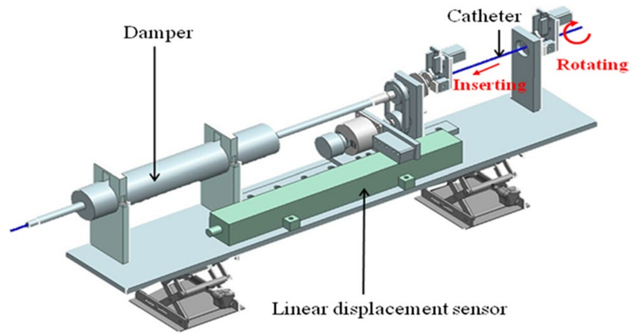

Fig. 7 Insertion and rotation of the real catheter in master side

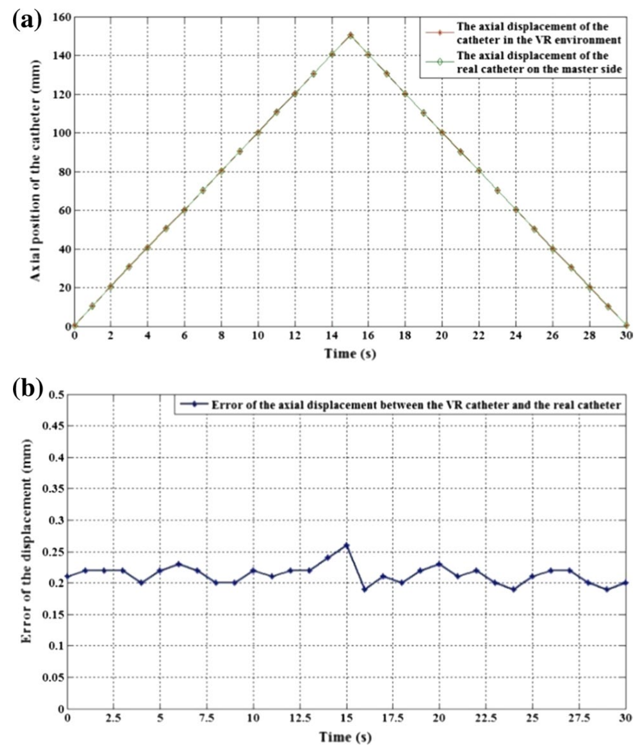

Fig. 8 Experimental results of the axial insertion. **a** The axial movement curve of the real catheter and the catheter model. **b** Error analysis

And the displacement of the catheter in the virtual environment is obtained in software program. The red curve shows the axial movement of the catheter in real environment. And it is obtained by the displacement sensor. The rising curve represents the forward motion, and the falling curve represents the backward motion. From Fig. 8a we can see that the movement between the virtual environment and the reality has good consistency. In Fig. 8b is the error curve of the displacement between the real catheter and the virtual catheter. The maximal error is less than 0.27 mm. Because of trembling of the hand during operation, the accidental error exits, the precision of the operation can be improved after enough training. This will not affect the stability of the system. The data curve has proved the operability of axial movement.

Figure 9 has shown the results of radial movement. In Fig. 9a, Y-axis represents the angle of the catheter, and X-axis represents time. We take 0°–360° as a measurement cycle, and rotate the catheter on the master slowly in a constant speed. The rotation data of the catheter in the real environment and the virtual environment will be acquired to draw the curve. The green curve shows the angle of the real catheter, which is obtained by the optical encoder. The red one shows the rotation angle of the catheter in virtual environment, which is obtained by the software program. The rising curve represents the catheter rotating clockwise, and the falling curve represents the catheter rotating anticlockwise. The two data curves have high consistency. Figure 9b is the angle error between the real catheter and the catheter model. The absolute error is less than 3.5°. During experiment, accidental error exits. After a lot of training, this situation can be reduced. This case does not affect the stability of the entire system. The data curves have proved the operability of rotation.

Based on the above experimental results, we can get the conclusion that the catheter in virtual environment is able to move along axial direction and rotate along radial direction under the control of haptic device. The catheter model in the virtual environment can realize the synchronous movement with the real catheter. This system conforms to the requirement of freedom. Moreover, it realizes more accurate movement control. The traceability of the virtual reality system conforms to the surgical requirement.

In human–computer interaction, position control is the fundamental function. The transfer of feedback force is the key step for the virtual reality system. The force in the virtual environment is transmitted to the operator through the master manipulator. On the master side, the piston-cylinder structure has been applied according to the characteristics of mangnetorheological fluid. As Fig. 10 shows, the viscosity of the MR fluid can be controlled by applying an external magnetic field. When different current flow in the coil, different magnetic will produce (de Abreu et al. 2013). It means that the magnetic will enhance when increasing the current of the coil. Then different shearing resistance will be applied to the piston body when it moves.

The Fig. 11 shows the MR fluids which is a kind of smart material, there are non-homogenous suspension of micro-sized ferromagnetic particles in a carried fluid, which undergo in rheological behavior change when an external magnetic field is applied. This mutual interaction among the magnetizable of particles from into columns (chains) aligned to the direction of the applied external magnetic field that (Yin et al. 2016).

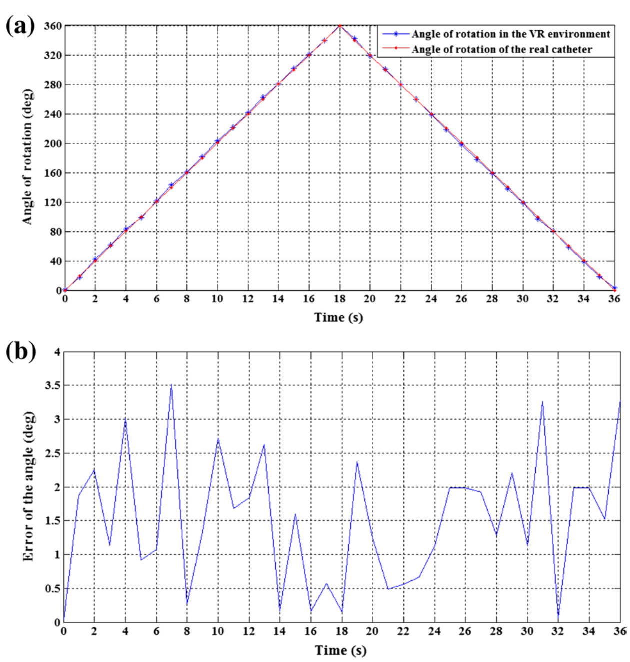

Fig. 9 Experimental results of the radial rotation. **a** The rotation tracking curves between real catheter and catheter model. **b** Error analysis in VR environment

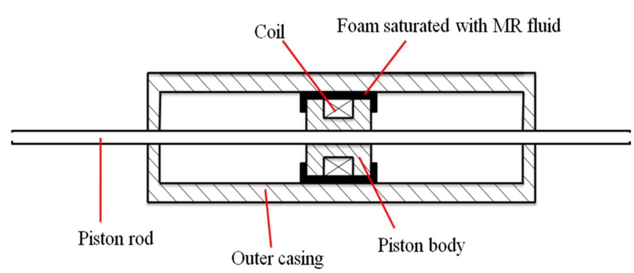

Fig. 10 The conceptual diagram of MR fluid damper assembly

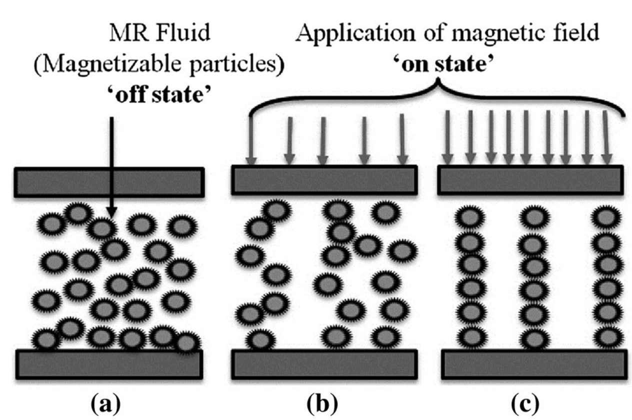

Fig. 11 Chain structures of magnetorheological particles **a** magnetorheological fluids in 'off state,' **b**, **c** magnetorheological fluid in "on state" and the magnitude of magnetic field (**b**) is smaller than (**c**)

According to the previous research in our lab, we have achieved the relationship equation between the resistance and the input voltage value. The resistance of the damper increased as the input voltage increased. The resistance and the input voltage have a good linear relationship. The researchers in our lab carried out a series of experiments. According to the data of correlation between the input voltage and the resistance of the damper, they have established a fitting curve equation (Guo et al. 2014). The relationship between the resistance and the input voltage is as follows:

$$\mathrm{F} = AU^2 + BU + C, \tag{3}$$

where F represents the damping force produced by the damper, A, B and C all represent constant value, U represents the value of input voltage.

In the virtual reality system, the feedback force is calculated according to the Eq. (4). According to the previous research, when the temperature is 37 °C, the viscosity coefficient of blood is $\rho_{\mathrm{blood}} = (2.0\text{–}4.0) \times 10^{-3}$ (N S/m^2). Based on the research of our team which has been stated in reference we set the Young modulus E = 1.17 × 107 (N/m^2) (Wang and Guo 2014), the thickness of the vessel wall is 0.1 mm, deformation is in degree of 0.01 mm, area S is $(0.01 \times 10^{-3})^2$ (m^2).

$$F = \mathrm{F}_{\mathrm{collision}} + \rho_{blood} \cdot \upsilon \cdot l \tag{4}$$

We set the calculation model into the software, assuming that the catheter have collided the vascular wall and the vascular wall is not broken, the collision force is a constant value. The moving speed of the catheter v = 5 mm/s. Then the relationship between force F and displacement of catheter is linear correlation. The resistance of blood is in degree of μN, but the force can be realized by the master manipulator is in degree of mN. Then we amplify the virtual force in virtual environment to feedback. In the experiment, we will get the resistance by the Load Cell. We can get the feedback force. Figure 12a shows the experimental results. The red curve is the force in the virtual environment. The blue curve is the resistance of the damper on the master side, it is the damping force to the operator, when the operator insert the catheter. We have analyzed the force error between the virtual environment and the feedback force of the damper. The Fig. 12b shows the error curve between the real catheter and the virtual catheter. The maximal error is less than 0.37 N. From the data we can see that there exists instability in this VR system, when feedback force being realized. That is because the force in virtual environment is too small to be realized by the master manipulator based on MRF. In the meantime, we have done the ten times experiments to verify the stability of the force feedback of the system. Figure 13 shows the results of the experiments. The Fig. 13a shows the data cure of force feedback experiment for ten times. And the Fig. 13b shows the error curve while the Fig. 13c shows the average and the variance of the error for ten groups. From the Fig. 13b, we can see that the maximal error of the ten groups is less than 0.3 N. As the Fig. 13c shows, the maximum average error is less than 0.2 N. The variance of the error is very small, which indicates that the change of the error is very small. Therefore, the stability of the system can meet our design requirement according to the experimental results.

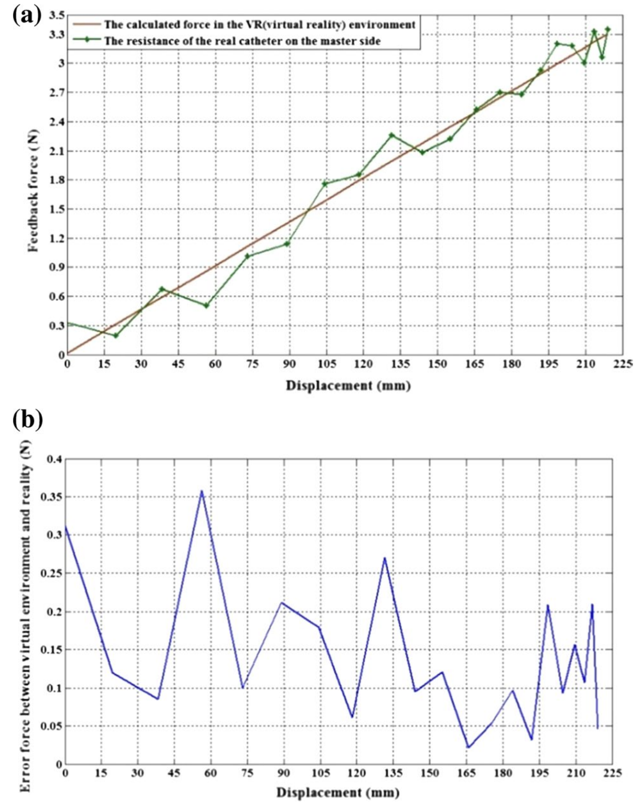

Fig. 12 The experimental result of feedback force. **a** The force curves between catheter resistance and calculated force in VR. **b** Force error analysis

From the force data curve, we can see that the feedback force on the master side is in accordance with the force in the virtual environment in the overall trend. The virtual reality system which applies the MR fluid in the master side can realize force feedback accurately. During the training process, when the catheter collides the vascular wall, the operator can feel the force feedback, the operator can adjust his operation according to this information. Then the training process can be simulated. In this VR system, we will set a threshold value, when the collision force exceeds it, the insertion motion will be stopped automatically, which can ensure the safety of operation. On the whole, the experiment results indicate that the force feedback of the system is stable after multiple use of the system.

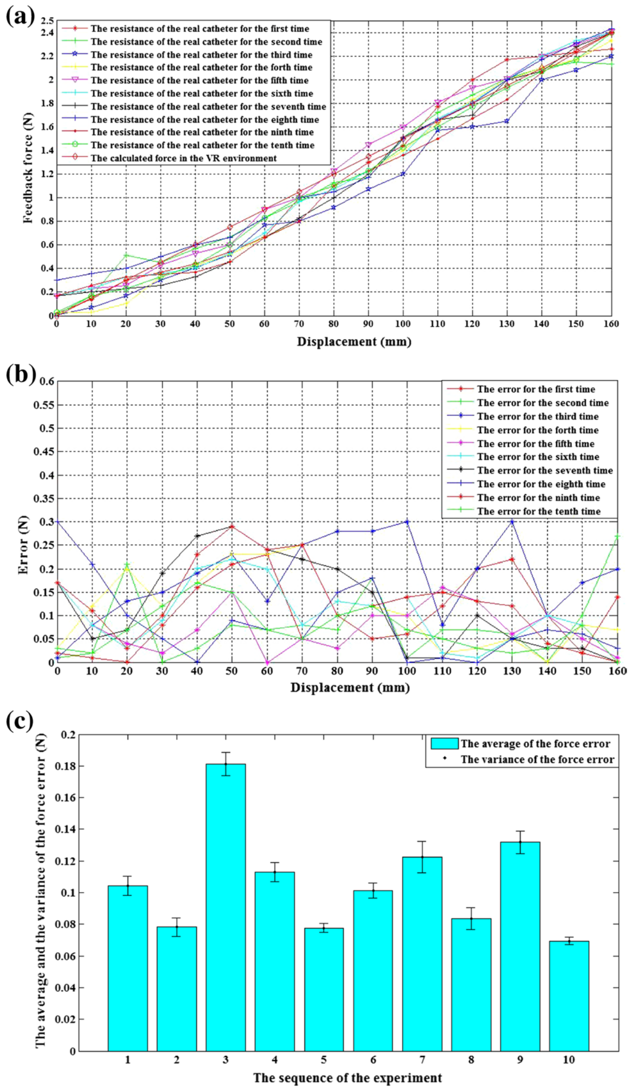

Fig. 13 The force feedback experiments for ten times. **a** Force feedback experiments for ten times. **b** The error curve of the force feedback experiments. **c** The variance and the average of the force error

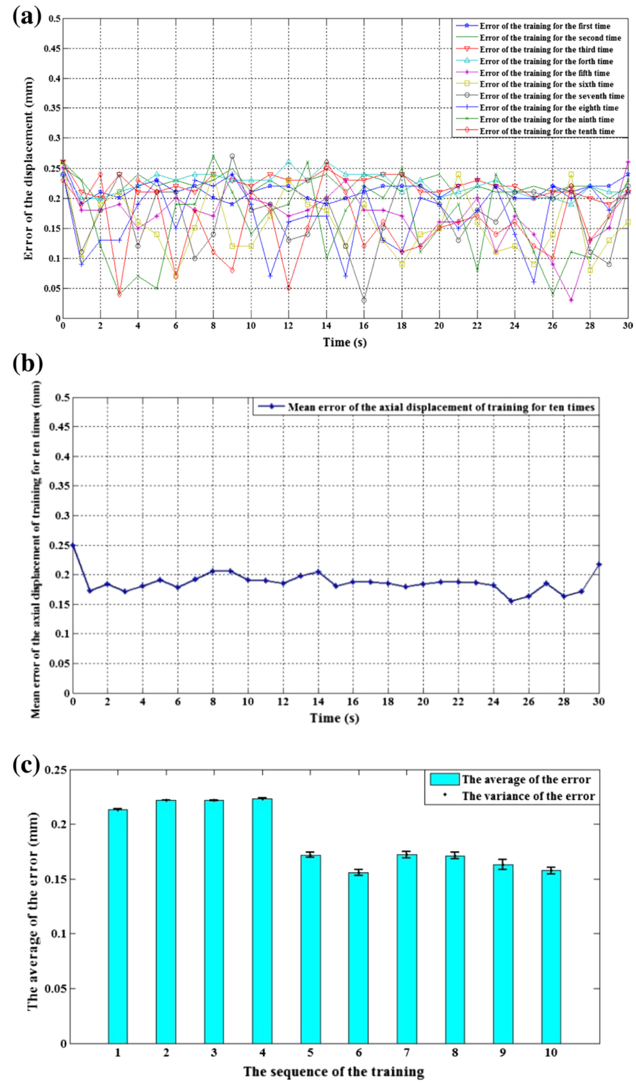

Fig. 14 Experimental results of axial movement. **a** The axial error of 10 experiments. **b** The axial average error of 10 experiments. **c** The variance and the average of the displacement error

In order to verify the stability of the axial synchronous movement, we have done 10 experiments by ten different people. The Fig. 14 shows the results of the axial synchronous movement. The Fig. 14a shows the axial error of 10 experiments and it shows the ten error curves, and the maximal absolute error is less than 0.27 mm, and the average error changes smoothly. And the Fig. 14b shows axial average error of the ten experiments, we can see that the maximal average error is less than 0.25 mm. Figure 14c shows the variance and the average of the displacement error. From the Fig. 14c, we can see that the average error of every group changes between the 0.15 mm and the 0.25 mm. The variance of the displacement error is very small, which indicates that the change of the error is very small. The variance is smaller, the changing range of the error is smaller, which indicates that the error is stable in a very small range. Therefore, the stability of the axial movement can meet our design requirement.

Similarly, The Fig. 15 shows the results of the radial synchronous movement. The Fig. 15a shows the rotation error of 10 experiments, there are ten error curves of ten experiments. From the Fig. 15a, we can see that the maximal absolute error of the ten experiments is less than 3.5°. And the Fig. 15b shows radial average error of the ten experiments. Figure 15c shows the variance and the average of the rotation error. As is shown in the Fig. 15b, we can see that the maximum average error is less than 1.9°. Compared with the axial error curve, the rotation error curve's change scope is large. From the Fig. 15c, we can see that the average error of every group changes between

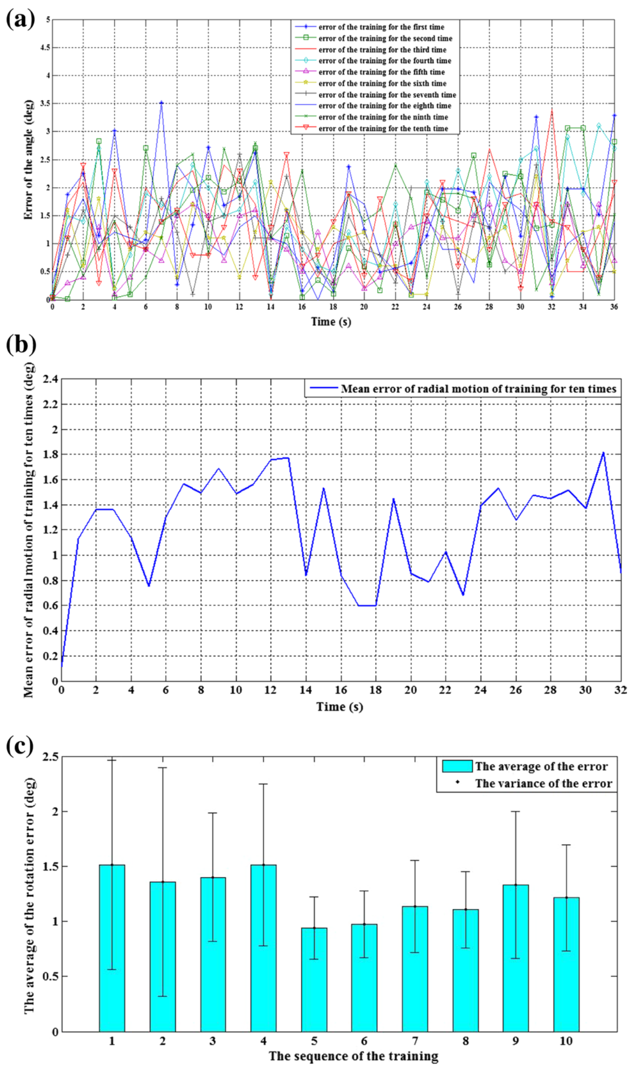

Fig. 15 Experimental results of rotation experiment. **a** The radial error of 10 experiments. **b** The radial average error of 10 experiments. **c** The variance and the average of the rotation error

the 1.0° and the 1.6°. The variance of the rotation error is very small, but compared with the axial error, the variance of the rotation is larger. On the whole, the stability of the radial movement can meet our design requirement. As a whole, the performance of the axial movement is better than the rotation movement.

4 Conclusions

This paper proposed a VR-based robotic catheterization training system to train interns to improve operation skills and raise operation experience, which can enhance the safety of operation. We used the mass-spring method and topological structure based on regular tetrahedron to realize collision detection and physical modeling. We have established the dynamics equation of the moving particles in the physical model. We analyzed the elasticity distribution of the vascular wall, and the spring coefficient is identified by analytical results. We established a relationship equation between collision force and soft issue deformation to realize the force feedback and visual feedback. We developed the novel master manipulator (haptic device), which is based on MRF to realize force feedback during training. We have established a feedback force calculation model for the training system, it can realize the contact force transmission to the operator through damper design. We have analyzed kinematics of the catheter in two degrees of freedom, and analyzed the insertion and rotation traceability for catheter between the catheter model in the virtual environment and the real catheter operated by neurosurgeon. The experimental results indicated that the developed VR-based robotic catheter training system can realize accurate operability. Then we have verified the force feedback function of the system. The experimental results indicated the stability of the system can meet our design requirement. We can use the VR system to train the novice. In the future, the developed novel VR-based robotic catheter training system will be used to train interns.

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