IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 13, 2020, accepted March 16, 2020, date of publication March 20, 2020, date of current version April 1, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2982219

A Tactile Sensation Assisted VR Catheterization Training System for Operator's Cognitive Skills Enhancement

YU WANG[1], **FAN YANG**[1], **YAXIN LI**[1], **TAO YANG**[2], **CHENG REN**[1,3], **AND ZHIHANG SHI**[1]

[1]School of Electrical Engineering and Information, Southwest Petroleum University, Chengdu 610500, China
[2]General Hospital of Western Theater Command, Chengdu 610083, China
[3]Laboratory of Mathematics of Atlantic Brittany, University of South Brittany, 56000 Vannes, France

Corresponding author: Yaxin Li (liyaxin@swpu.edu.cn)

This work was supported by the National Science Foundation of China under Grant 61907036.

ABSTRACT In the clinical vascular interventional surgery, experienced surgeons usually rely on visual feedback to reason tool-tissue interaction, because haptic forces are easily contaminated by frictions between the catheter and the introducer sheath, which brings difficulty in collision force perceptions. Thus, cognitive skills are highly demanded for novice surgeons to thoroughly interpret the relative positions between tool and tissue in images and make appropriate decisions about further catheter motions in case of collisions. In this paper, an operator's cognitive skills training system has been introduced, which exploits the tactile sensation to reinforce the visualized spatial positions between catheter tip and vascular wall in the VR simulator. In cooperation with the collision alert module (CAM) in the VR simulator, the newly developed catheter manipulator can provide tactile sensations for novices when catheter tip is threaded beyond safety boundary, so that the VR exhibited tool-tissue interaction can be deliberately intensified. For demonstrating such tactile sensations adequate to strengthen visions, the system model has been established to facilitate the analysis in the perspective of operator's kinesthetic perception. A series of experiments have been conducted at last and the results reveal that the catheter manipulator can not only realize the accurate catheter motions but also provide the enough tactile sensations for novices. Moreover, statistical data prove that subjects under cognitive trainings have developed the ability to interpret the relative spatial positions between catheter tip and vascular wall. Such findings support that the operator's cognitive skills can be enhanced by the tactile reinforcement of VR visualized tool-tissue interaction.

INDEX TERMS Catheterization training system, cognitive skills, tactile sensation, VR simulator, collision detection.

I. INTRODUCTION

The vascular interventional surgery (VIS) is emerging as an alternative to treat cardiovascular and cerebrovascular diseases since it outperforms open surgery in aspects of small incisions, less pain and short recovery time. By taking advantage of a long flexible catheter, experienced interventionalists are capable of steering catheter to the target of interest with the help of image guidance. However, such overwhelming superiority of VIS is obtained at the cost of narrow sight scope and indirect access to the anatomy [1]. In this situation, interventionalists are required to manipulate catheter through fragile vascular systems under the presence of physiological motion [2]. The limited maneuverability of catheter imposes high demands on operator's technical skills. Meanwhile, the fluoroscopic image guided catheterization approach puts interventionalists' health into risk due to long time radiation exposure. Thus, several commercial corporations have developed master-slave based catheter manipulation systems [3]. The most well-known commercial products of catheter robotic systems are called Magellan^{TM} and Sensei X2 developed by Hansen Medical (USA). Hundreds of clinical practices have been performed by these systems globally [4], [5]. Both systems mainly consist of a catheter robotic arm at patient table and a remote physician console which keeps interventionalists away from radiation source.

The associate editor coordinating the review of this manuscript and approving it for publication was Shafiqul Islam.

However, the high costs of purchase and maintenance limit their widespread adoptions. Amigo^{TM} is another commercial robotic catheter introduced by Catheter Robotics Inc. and it has already received FDA approval. To date, several clinical reports have been presented by employment of Amigo^{TM} in ablation [6] and mapping trials in heart [7]. Even if it is comparatively inexpensive as far as commercial remote catheter manipulations, the handle design at the master side doesn't take interventional radiologists' operation habits into account.

By contrast, researchers in universities have done fundamental studies extensively. With analysis of human motion for safe endovascular surgery, Srimathveeravalli *et al.* designed and fabricated a system for endovascular teleoperated access which were capable of manipulating guidewire and catheter simultaneously [8]. To improve the manipulation capacities of clinicians, a novel automatic catheter with electromagnetic image guidance was developed in [9]. However, the studies mentioned above haven't provided any insights into ergonomic design for master manipulations. Been bio-inspired, Feng *et al.* came up with a dual-finger robotic hand which imitated movements of surgeons' two-finger to deliver guidewire and balloon/stent catheter in the percutaneous coronary interventions [10]. Besides, as accurate force/torque information was very important for robotic catheterization system, a wearable device was designed to measure the force and torque in multi-region contacts between catheter and vessel. The device collected data were crucial knowledge of haptic-based master interface because interventionalists relied on haptic feedback to perceive the tool-tissue interaction and respond in coordinated and dynamic manner to protect fragile vessels. Therefore, a growing number of researchers focused on methods of how to generate haptic sensation. Sankaran *et al.* provided the haptic feedback in real-time by motor which drove the catheter translational motions on the surgeon conventional gesture augmented endovascular robotic system [11]. Referred to [12], Payne *et al.* aimed to achieve axial force feedback by over-tube to resist insertion whilst kept the natural ergonomic skills of catheterization. Researchers in Kagawa University proposed to exploit the smart-materials called Magnetorheological (MR) fluids to realize haptic sensation [13], [14]. Apart from that, they paid more attention to promoting surgeon's safety operation consciousness by means of haptic sensation, since excessive force exerted on vasculature was possible to result in complications like inflammation, thrombosis, perforation and haemorrhage [15]. Following up their recent studies, Zhang *et al.* integrated such MR-fluid haptic interface into the master side of catheter robotic system to protect blood vessels [16]. Guo *et al.* proposed to employ MR-fluids based haptic interface to discriminate the "pseudo-collision" and "real collision" between catheter tip and vascular wall, which could help interventionalists gain an optimal operation strategy in catheterization [17]. Moreover, in order to remind operators to avoid collisions in advance, researchers introduced a safety operation early warning system combined with feedback force generated by magnetic field [18]. But in clinical practices, the haptic force felt by surgeon is usually contaminated by the friction between the catheter and the introducer sheath, which means it's hard to sense the contact force by collision alone.

Based on above discussions, more attention should be paid to improving the catheter manipulation skills in order to reduce the risk of tissue damage or even vessel rupture. In addition, the tortuous vascular anatomy brings difficulty and challenge to catheter navigation, which has great impact on the success of endovascular procedure under some circumstances [19]. Consequently, there has been a growing interest in development of the catheterization training systems. Recent advances in VR based training systems assisted by haptic/tactile-feedback, have been treated as promising ways to acquire dexterous catheter manipulation skills. Research towards the development of immersive VR simulators has inspired studies to formulate physical models of both vessels [20], [21] and catheter [22], [23]. With the consideration of tissue-protection, Wang *et al.* made contributions to avoiding possible collisions between catheter tip and vascular wall by both visual and haptic cues [24]. Besides, our previous work was mainly concentrated on remitting collision trauma beforehand by development of a safety operation VR training system integrated with unique tissue protection mechanism [25].

However, most available studies, which claim to address the safety operation issues in catheter robotic systems or training simulators, adopt passive methods such as designed algorithms or mechanical devices to prevent possible collisions or alleviate vascular trauma. Up to now, few studies have mentioned that safety operation concerns to the operator-tool interaction, which is not only related to technical skills but also has close relationship with cognitive skills of operators. Especially with the advent of minimally invasive surgery, cognitive skills including reasoning and decision making in surgery are of increasing relevance and importance [26].

Thus, except for training technical skills, cognitive competency is highly demanded for novice surgeons to thoroughly interpret the level of tool-tissue intervention in image and judge the further catheter motions in the absence of haptic feedback. Inspired by such thought, this paper is contributed to developing a VR based cognitive skills training system with the assistance of tactile sensation. The system aims to enhance the operator's cognitions by deliberately tactile reinforcement of the VR visualized tool-tissue interaction. When dealing with collision issues, the novices can use cognitive skills to strengthen their safety awareness. To verify the feasibility of such training system, volunteers were recruited to join in the five-day training session and they were asked to challenge a new task with no haptic clues. The remainder of this paper is organized as follows. The VR based cognitive skills training system is introduced in Section II. In Section III, we present system modeling and analyze tactile sensation in perspective of operator's kinesthetic perception.

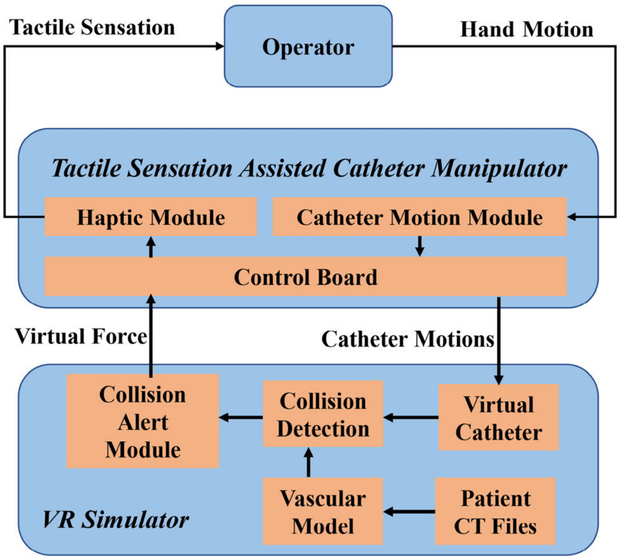


FIGURE 1. The block diagram of the operator's cognitive skills training system.

Section IV contains a series of experiments and results. Finally, we discuss the relevant results and summarize the paper in Section V and Section VI respectively.

II. SYSTEM DESIGN

Currently, even though there exist a number of haptic-interface based catheter robotic systems, interventionalists overwhelmingly depend on visual feedback to interpret the relative spatial positions between tool and tissue since the feedback haptic forces are easily contaminated by the frictions of the catheter and the introducer sheath. This situation explains why cognitive skills training is essential to novice surgeons. In this paper, a novel training system has been introduced to instruct novices and enhance their cognitive skills by the tactile reinforcement of VR exhibited tool-tissue interaction. The developed operator's cognitive skills training system, as shown in Fig.1, mainly consists of two parts: the tactile sensation assisted catheter manipulator and the collision alert module (CAM) equipped VR simulator.

A. OVERVIEW OF THE OPERATOR's COGNITIVE SKILLS TRAINING SYSTEM

Operator, as the center of VR based cognitive training system, proceeds the catheterization practice on the mechanical platform called the tactile sensation assisted catheter manipulator. The operator's hand motions are captured and converted into catheter movements, which are transmitted to VR simulator and used for driving the virtual catheter moving. The VR simulator can not only render the virtual catheter's behavior in the reconstructed vascular model, but also run the collision detection algorithm in parallel to predict the relative interaction level of tool-tissue. According to the detected results, when collision is about to happen the designed collision alert module (CAM) will generate a virtual guidance force to evaluate the displayed relative distance between catheter tip and vascular wall. Meanwhile, such virtual force will be sent back to the haptic module of the catheter manipulator to produce tactile sensations. In this way, novice surgeons' cognitive skills can be enhanced by the tactile reinforcement of the VR visualized tool-tissue interaction. The overall system is showed in Fig. 2.

B. THE CATHETER MANIPULATOR

The limited maneuverability of catheter inside vessel requires the manipulator equipped with two degrees of freedom: translation and rotation. Usually, catheter is advanced or retracted in vessel to realize translational motion. When necessary, the catheter can be twisted by operator to realize rotational motion.

With the consideration of surgeon's natural gestures and conventional skills, the newly developed catheter manipulator utilizes a lightweight operation handle to imitate the holding posture of surgeon's hand. Two hollow shafts are assembled outside both ends of the handle with the key-groove structure, which only allows the handle moving back and forward inside hollow shaft along axial direction. When surgeon prepares to twist the handle, a couple of bearings outside hollow shafts make the handle to rotate freely. In this way, the catheter rotational motion is realized and a rotary encoder coaxially connected to shaft can measure the rotational angle. When surgeon pushes the handle to move forward, as shown in Fig.2 enlarged view, the hall sensor placed inside the shaft will be activated due to a tiny magnet attached to the end of handle and it can sense the hand moving displacement x_h. By the hall sensor detected displacement, the surgeon applying force on the handle, which is produced by the spring inside the hollow shaft, can be calculated easily and used to drive the step motor. To realize catheter translational motion, a ball-screw actuator is coupled with the step motor and it can drive the slider of ball-screw actuator moving back and forth. The displacement of moving slider x_c is just equal to that of the catheter translational motion. Above work, including capturing the operator's hand motions and converting them into translation or rotation respectively, is realized by catheter motion module. For safety consideration, two snubbers are fixed along the ends of ball-screw actuator in case the slider goes beyond the range of ball-screw actuator. Furthermore, in order to deliberately reinforce the spatial positions between tool-tissue interaction, the tactile sensation along the axial direction is rendered in haptic module when collision is about to happen. The spring embedded in hollow shaft serves to provide haptic force by means of the translational displacement difference of operator's hand and slider. The detail about the tactile sensations will be introduce in the last part of this section and its analysis has been conducted in the Section III.B.

C. THE VR SIMULATOR

As a visual guidance, the VR simulator is responsible for offering the repeatable and safe training environment for novice surgeons. In this paper, a patient-specific VR simulator is prepared to practice. The CT and MRI based image data are firstly processed to construct the 3D geometrical

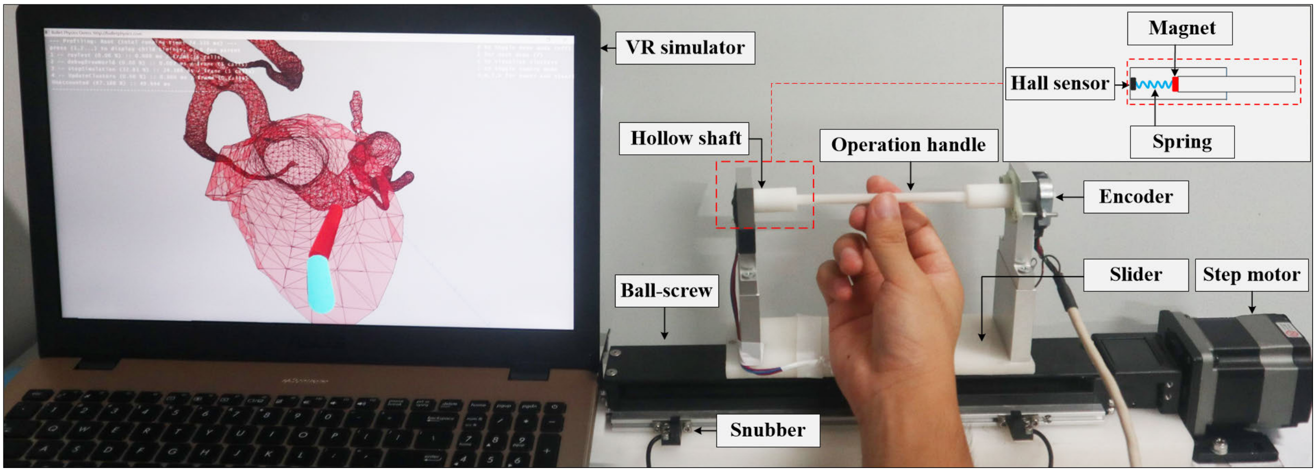


FIGURE 2. **The overall system design of the operator's cognitive skills training system.**

model of cerebral-vessels [27]. Then this vascular model is imported into physical engine called Bullet and the mass-spring-model is adopted to render the vascular physical deformation. To simulate the virtual catheter in real-time, a chain of 1mm diameter and 5mm long cylinders with limited angle joints are built in Bullet. By the construction of both vascular and catheter physical models, the catheterization training tasks can be performed in the VR simulator where the virtual catheter is navigated in vessel according to the motions transmitted from the catheter manipulator. This VR based catheter training system has shown great potential in improvement of novices' technical skills and surgical proficiency.

However, interventionalists don't only rely on psychomotor skills to proceed the VIS. The cognitive skills, especially the appropriate interpretation of tool-tissue interaction by visualization, can help surgeons avoid possible collisions, which may result in vessel damage or complicating the procedure or even worse leading to fatalities. With the objective of training operator's cognitive skills, a collision alert module (CAM) is realized in the VR simulator and it pre-defines a parameter called safety boundary B_{safe} based on experts' knowledge and catheterization training scenario. The parameter B_{safe} denotes the minimal safe distance between the catheter tip and vascular wall and it divides the lumen of vessel into two operation spaces, namely safe area and dangerous area. To evaluate the interaction level of tool-tissue, the combination of collision algorithms GJK (Gilbert-Johnson-Keerthi) and EPA (Expanding Polytope Algorithm) are run in parallel so that they facilitate the CAM to obtain the minimal distance D_{min} between catheter tip and vascular wall in real-time.

According to the rules made in the CAM, as long as the minimal distance D_{min} is larger than the safety boundary B_{safe}, novices may operate the catheter freely and quickly to traverse in vessel since the catheter tip is located in the safe area. But once the minimal distance D_{min} is smaller than B_{safe}, which indicates the catheter tip is threaded beyond the safety boundary into the dangerous area of vascular lumen, at this moment it's necessary to hone the novice surgeons' cognitive skills so that they can make decisions about further operations based on the VR displayed tool-tissue interaction. The CAM introduces a virtual guidance force F_{vg} to weigh the relative interaction level of tool-tissue. The force implies how close the catheter tip approaches the vascular wall by the virtual spring model, which is written by

$$F_{vg} = K_{vg}\left(B_{safe} - D_{min}\right), \quad D_{min} \leq B_{safe} \tag{1}$$

where K_{vg} is constant of the virtual spring model. When the catheter tip is detected in dangerous space, such force will be calculated and sent back to the catheter manipulator for generating the tactile sensation.

D. THE TACTILE REINFORCEMENT STRATEGY

Though the cooperation of catheter manipulator and VR simulator, the tactile reinforcement strategy will be adopted to enhance operator's cognitive skills. Specifically, as long as the catheter tip is threaded from safe area into dangerous area, the virtual guidance force will be generated by the CAM in the VR simulator and transmitted to the catheter manipulator. Just as (1) indicates that the virtual guidance force increases when the catheter tip comes closer to the vascular wall. To strengthen the cognition of such visualized distance in VR simulator, much stronger sensation is imposed on the operator's hand by the catheter manipulator. As shown in Fig.2, the spring embedded in the hollow shaft is responsible for providing haptic forces by the displacement differences of operator's hand and slider on the ball-screw actuator, which can be expressed as

$$F_h = \frac{K}{s}\left(\dot{x}_h - \dot{x}_c\right) \tag{2}$$

where spring coefficient is K and s represents the Laplace transformation variable. Since x_h denotes the operator's hand translational displacement, based on (2) the tactile sensation is determined by x_c, which not only represents the slider moving displacement but also is transmitted to VR simulator to control the virtual catheter translation. In this case,

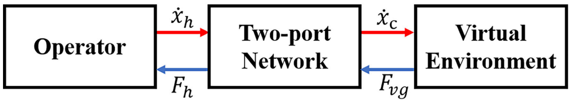


FIGURE 3. The system block diagram of two-port network.

the movement of slider is achieved by equation below

$$\dot{x}_c = \frac{K}{s} Z_m^{-1}\dot{x}_h - sgn \cdot Z_m^{-1} F_{vg} \tag{3}$$

$$sgn = \begin{cases} 1, & D_{min} \leq B_{safe} \\ 0, & D_{min} > B_{safe} \end{cases} \tag{4}$$

where $Z_m = Ms + B + K/s$ is introduced for convenience and M and B are the inertia and velocity control gain of the catheter manipulator respectively. When the operator is able to keep the catheter tip working in the safe area of vascular lumen, as seen in (3) and (4), no virtual guidance force will be generated in the CAM. The slider of ball-screw actuator simply needs to move following the operator's hand translational motion. Through the tactile reinforcement of VR visualized tool-tissue interaction, the novices' cognitions will be improved gradually and at last they can make decisions about further catheter motions independently.

III. SYSTEM MODELING AND ANALYSIS

The catheter manipulator can be regarded as the connection between the operator and the virtual environment, which not only transfers the operator's motions to VR simulator but also creates a feedback path to convey kinesthetic cues to operator. Thus, as displayed in Fig.3, such catheter manipulator can be modeled as a two-port network [28], [29] due to the existence of bi-directional channels between the operator and the virtual environment. To capture the motions and haptic information exchanges, the relationship between two terminals of the two-port network is characterized and the kinesthetic perception provided by the catheter manipulator is investigated as well in this section.

A. SYSTEM MODELING

According to the generalized system block diagram in Fig.3, operator's hand motions $\dot{x}_h$ are the input of network and converted into catheter movements $\dot{x}_c$ output to the VR simulator for synchronization of virtual catheters' behaviors. At the same time, the VR generated virtual guidance force F_{vg} is sent back to the network for rendering the haptic force F_h to stimulate novices. In order to describe the information exchanges between the operator and the virtual environment, a hybrid matrix $\boldsymbol{H}$ is defined as follows according to study [30]

$$\begin{bmatrix} F_h \\ -\dot{x}_c \end{bmatrix} = H \begin{bmatrix} \dot{x}_h \\ F_{vg} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} \dot{x}_h \\ F_{vg} \end{bmatrix} \tag{5}$$

where each sub-component in matrix $\boldsymbol{H}$ is a frequency dependent function and the negation sign of $\dot{x}_c$ is necessary to keep the consistency of the network formalism. By the combination of (2) and (3), the haptic force applied on operator's hand can be solved as

$$F_h = \left(\frac{K}{s} - \frac{K^2}{s^2} Z_m^{-1}\right)\dot{x}_h + \frac{K}{s} Z_m^{-1} F_{vg} \tag{6}$$

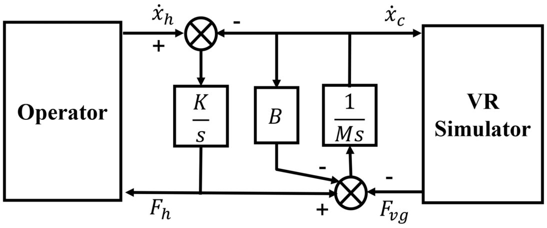


FIGURE 4. The control architecture of the two-port network.

When the catheter is threaded beyond the safety boundary equation (6) implies that much stronger tactile sensation will be imposed on operator's hand with the catheter tip approaching closer to the vascular wall. Through the integration of (3) and (6), the specific expressions of sub-components in matrix $\boldsymbol{H}$ can be derived by

$$\begin{bmatrix} F_h \\ -\dot{x}_c \end{bmatrix} = \begin{bmatrix} \frac{K}{s} - \frac{K^2}{s^2} Z_m^{-1} & \frac{K}{s} Z_m^{-1} \\ -\frac{K}{s} Z_m^{-1} & Z_m^{-1} \end{bmatrix} \begin{bmatrix} \dot{x}_h \\ F_{vg} \end{bmatrix} \tag{7}$$

According to the derived hybrid matrix, the control architecture of the two-port network is established as illustrated in Fig.4. It is obvious that the network is linear, and its stability is relative to the derived hybrid matrix $\boldsymbol{H}$. Referring to [29], [31], when the operator and the VR simulator are assumed to be passive terminations, the Llewellyn's stability criteria provide both necessary and sufficient conditions for absolute stability of the two-port network in terms of the hybrid matrix $\boldsymbol{H}$ sub-components below

$$\begin{cases} Re\,(h11) \geq 0 \\ Re\,(h_{22}) \geq 0 \\ 2Re\,(h_{11})\,Re\,(h_{22}) \geq |h_{12}h_{21}| + Re\,(h_{12}h_{21}) \end{cases} \tag{8}$$

where symbol Re denotes the real residue of sub-component in $\boldsymbol{H}$. Based on the derived hybrid matrix in (7), it totally satisfies the Llewellyn's stability criteria for all frequencies ω regardless of the positive M and B.

B. THE OPERATOR'S KINESTHETIC PERCEPTION

As the tactile sensation is exploited to reinforce the VR visualized tool-tissue interaction in this paper, it's necessary to explore the operator's kinesthetic perception. Based on previous study in [31], there are two kinds of perception thresholds to describe the detection and discrimination in terms of a kinesthetic stimulus, which are absolute limen (AL) and difference limen (DL) respectively. AL weighs the smallest stimulus to produce a sensation, while DL is termed as the smallest amount of stimulus change required to generate in the sensation discrimination.

When the operator manipulates the catheter working in the safe area of vascular lumen, the impedance provided by the catheter manipulator to operator is expressed as

$$Z_{to}^{S} = \frac{K}{s} - \left(\frac{K}{s}\right)^{2} Z_{m}^{-1} \tag{9}$$

where the superscript of Z_{to}^{S} represents the occasion when the virtual catheter tip is detected in the safe area of vessel. Once the operator steers the catheter running into the dangerous area, the CAM generated virtual force will result in the sudden sensation change so as to strengthen the visualized tool-tissue distance in the VR. At this moment, the impedance transmitted to operator yields equation

$$Z_{to}^{D} = \frac{K}{s} - \left(\frac{K}{s}\right)^{2} Z_{m}^{-1} + \left(\frac{K}{s}\right)^{2} Z_{\mathrm{m}}^{-1} \frac{Z_{e}}{Z_{e} + Z_{m}} \tag{10}$$

where Z_e represents the impedance of VR environment and the superscript of Z_{to}^{D} stands for the situation when the catheter tip is detected in the dangerous area of vessel. In essence, the impedance transmitted to operator is the kinesthetic feeling the catheter manipulator can provide. Based on above analysis, when the virtual catheter tip traverses from the safe area to the dangerous area, the smallest amount of sensation change can be defined by using the parameter DL as follows

$$\mathrm{DL} = Z_{to}^{D} - Z_{to}^{S} = \left(\frac{K}{s}\right)^{2} Z_{m}^{-1} \frac{Z_{e}}{Z_{e} + Z_{m}} \tag{11}$$

According to the known Weber's Law, there exists a linear relationship between the perception discrimination threshold DL and the initial stimulus φ_0:

$$\mathrm{JND} = \frac{\mathrm{DL}}{\varphi_0} \tag{12}$$

where JND is referred as the just noticeable difference. In our developed catheterization training system, since cognitive skills are enhanced by sudden tactile sensation change when the CAM detects the catheter tip operating beyond the safety boundary, it's evident that the parameters DL and Z_{to}^{S} (treated as initial intensity of stimulus) can be used to express the operator perceived sensation JND as follows:

$$\mathrm{JND} = \left(\frac{K}{s} Z_{m}^{-1} \frac{Z_{e}}{Z_{e} + Z_{m}}\right) \Big/ \left(1 - \frac{K}{s} Z_{m}^{-1}\right) \tag{13}$$

Only when the JND is greater than the perception low limit AL, can sudden tactile sensation change be detected and used to reinforce the visualized tool-tissue interaction.

IV. PERFORMANCE EVALUATION

In this section, a series of experiments were carried out to evaluate the performance of operator's cognitive skills training system. The experimental setup was as follows. In the catheter manipulator, a hall sensor (DRV5056A4, Texas Instruments, USA) and a spring (spring coefficient K = 0.29N/mm) were embedded inside the 3D printed hollow shaft for operators to detect the push or pull force. According to (3) such force could be used to control the catheter translational speed by setting the inertial M and the velocity control gain B to 0.1 kg and 0.23Ns/mm respectively, so that the catheter translational motions followed the operator's hand motions. The step motor (AZM66AC, Oriental Motor, Japan) was chosen to connect with a high-precision ball-screw actuator (LX2602C, MISUMI, Japan) with 300mm length for catheter translation. This step motor was equipped with a driver (AZD-C, Oriental Motor, Japan), which had a built-in encoder to sample the motor's speed. To detect the operator's rotational motion, an incremental capacitive rotary encoder (AMT112S-V, CUIINC, USA) with resolution of 2000 PPR (Pulse Per Revolution) was assembled in the catheter manipulator. To update the virtual catheter motions, both the catheter translational and rotational data were sampled by the control board (Mega 2560, Arduino, Italy) and transmitted to the VR simulator through UART (Universal Asynchronous Receiver/Transmitter). Moreover, the patient-specific vascular physical model and virtual catheter were reconstructed using the open source physical engine Bullet (Version 2.80) to realize the VR simulator. The C++ written VR simulator was compiled in Visual Studio 2008 and implemented on a 64-bit laptop with four CPUs (Core i5-7300HQ, 2.5GHz, Intel) and 8 GB RAM.

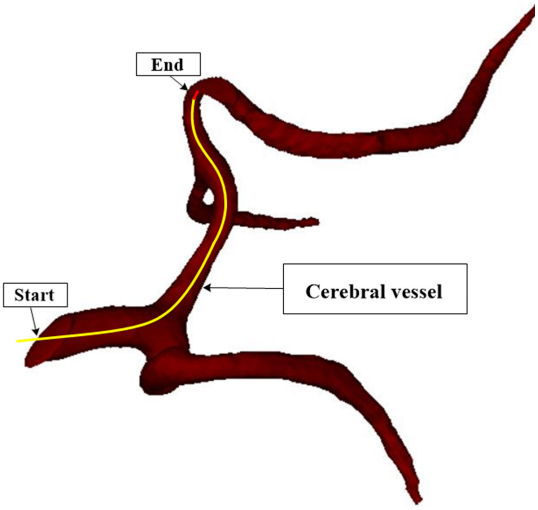


FIGURE 5. The catheterization task practice scenario.

A. PERFORMANCE EVALUATION OF THE CATHETER MANIPULATOR

Before recruiting volunteers and proceeding the training tasks, it's essential to guarantee the accuracy of catheter manipulator. With regard to its mechanical design, the accurate catheter rotational motions are easily realized by the high-precision rotary encoder. But the catheter translational motions need to be assessed because the catheter translational velocities are controlled by the operator's applying forces.

To evaluate the translational accuracy, a non-medical subject with catheterization experience was asked to operate the catheter manipulator and thread the virtual catheter into a branch of specific patient's cerebral vessel as exhibited in Fig. 5. Such segment of cerebral vessel was chosen for training tasks because it had bifurcations and

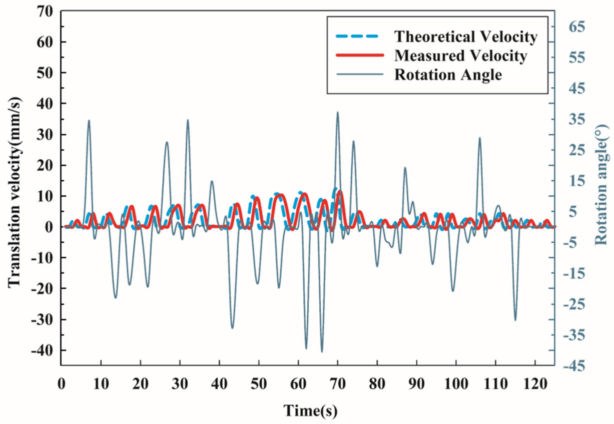


FIGURE 6. **The translational velocities and rotational angles of the catheter manipulator for a catheterization task.**

curving turnings, which required surgeons with skills and experiences to avoid possible collisions. Fig.6 displays the theoretical and measured velocities of catheter translational motions as well as its rotational angles. The theoretical velocities of catheter translational motions are obtained through (3) and (4) without consideration of the virtual guidance force generated in VR simulator. The measured catheter translational velocities are recorded by the step motor's build-in encoder. The comparison results reveal that the catheter manipulator achieves accurate translational velocity control with error of only 0.0708mm/s.

B. VERIFICATION OF THE OPERATOR'S KINESTHETIC PERCEPTION ANALYSIS

According to the analysis of operator's kinesthetic perception, the parameter JND, which represents the just noticeable difference, can be used to describe the operator perceived sensation provided by the catheter manipulator. Once the JND is greater than operators' perception detection low limit AL, operators can feel the sudden tactile sensation changes. But practically it's hard to estimate the low limit of operator's kinesthetic perception due to the individual difference in tactile sensation. Thus, we recruited ten volunteers to participate in the sensation discrimination experiment and tried to find the minimal JND so that all volunteers could perceive sensation successfully.

In the sensation discrimination experiment, all participants (right-handed) had no knowledge of haptics and they were asked to grasp the operation handle of catheter manipulator with thumb and index. When they pushed the handle, the translational motion of catheter manipulator was initialized with different speeds v_0 from 2mm/s to 10mm/s and with increment of 1mm/s, which signified the different initial stimuli. Under each v_0, the translational motion was sudden slowed down with deceleration Δv. Such trials were proceeded to stimulate volunteers and they were asked whether perceived the sensation or not. If volunteers failed to detect the sensation, the stimulus of deceleration Δv would grow until they could detect it successfully. Once volunteers achieved success under each given initial stimulus, the corresponding minimal deceleration was recorded and the minimal JND could be determined. For each volunteer, such process repeated 10 times under every initial stimulus. To help volunteers immerse in the experiment, they wore noise-proof headsets to conduct trials without any visual information.

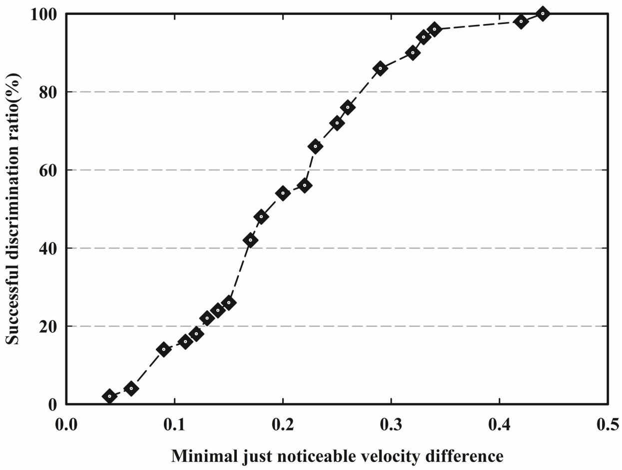


FIGURE 7. **The successful discrimination ratio with its corresponding minimal just noticeable velocity difference.**

Fig.7 depicts the successful discrimination ratio with its corresponding minimal just noticeable velocity difference (MJNVD). The MJNVD is defined as $\Delta v / v_0$ which implicitly represents the minimal JND. Given each MJNVD, the successful discrimination ratio denotes the number of volunteers who perceives sensation successfully among 10 participants. As shown in Fig.7, there exists a growing trend of successful discrimination ratio with the MJNVD rising from 0.04. Not until the MJNVD increases to 0.44, does the successful discrimination ratio reach to 100%, which indicates all participants can detect the tactile sensation. The results are of great importance since they make sure the catheter manipulator can provide sufficient tactile sensations for operators to strength the visions and can be used to set the inertial M and the velocity control gain B as well.

C. THE EFFECT OF TACTILE SENSATIONS IN TRAINING SYSTEM

Since the tactile sensations are adopted as instruction cues to enhance the operator's cognitive skills, a five-day training session was carried out to validate the effect of tactile sensation in skill practices. To ensure generality of the experiment, five non-medical students (right-handed) were chosen under the age group of 20 to 25 years and from the technical background with no knowledge of haptics and VR simulator.

1) EXPERIMENTAL METHOD

In the VR simulator, a cerebral vascular branch was picked up as catheterization training scenario, as shown in Fig.5. Due to the vessel with bifurcations and curving turnings, participants must be equipped with both technical and cognitive skills to operate the catheter reaching the designate site and avoid

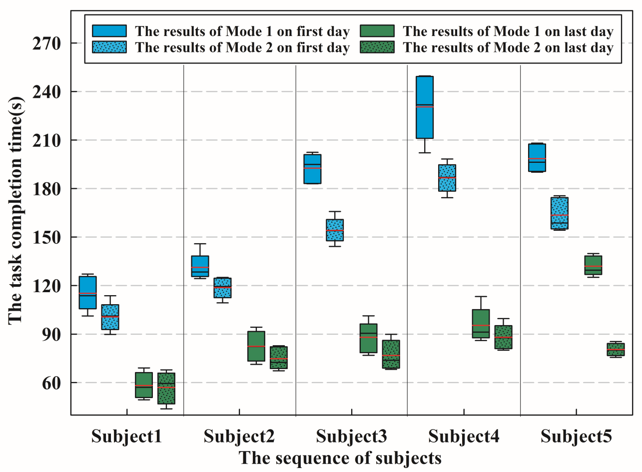


FIGURE 8. The comparison of task completion time on the first day and last day under mode 1 and mode2.

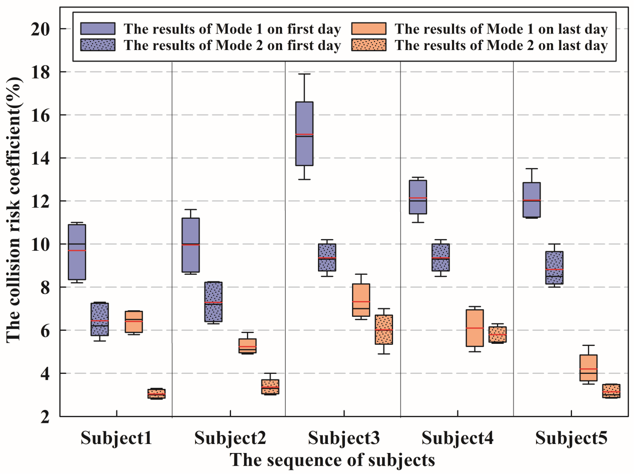


FIGURE 9. The comparison of collision risk coefficient on first day and last day under mode 1 and mode 2.

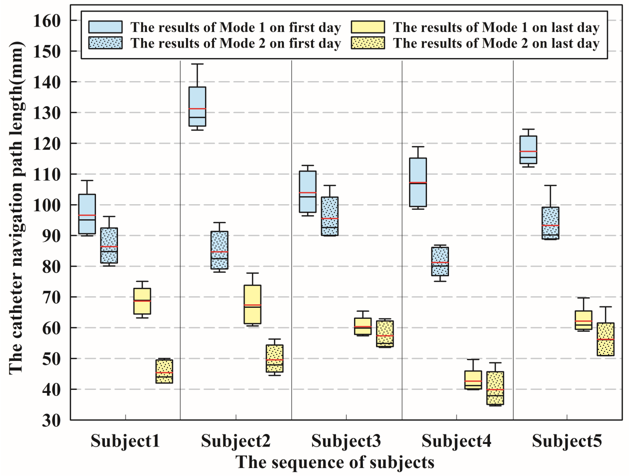


FIGURE 10. The comparison of catheter navigation path length on first day and last day mode 1 and mode 2.

possible collisions at the same time. In the experiment, all subjects were asked to familiarize with the catheter manipulator and the VR environment for about 30 min before training session started. For comparison, all subjects conducted the training tasks under two modes. The mode 1 was a conventional VR based training way. The VR simulator provided only visual feedback for subjects when they threaded catheter in blood vessel. The mode 2 was our developed training method, which employed the tactile reinforcement strategy to generate the sensation for subjects. The safety boundary was pre-defined to 2.5mm by training demands. For each subject, the same training task was conducted under both modes in alternating order and there was 5 min rest between tasks. Everyday all participants repeated practicing five times under two modes respectively for statistical use.

To evaluate the performance of training session, three metrics are defined: 1. The task completion time, which represents the subject consuming time to complete a specific catheterization task; 2. The collision risk coefficient, which represents the percentage of collision duration taking up the task completion time; 3. The catheter navigation path length, which measures the total length of catheter traversing route.

2) EXPERIMENTAL RESULTS

The subjects' five-day training performances have been recorded and listed in Appendix part. In order to show progresses they have made, above defined metrics of each subject on the first and on the last training days were compared in Fig. 8, Fig. 9 and Fig. 10 respectively. The red line in each Whisker box denotes the average value.

Figure 8 shows each subject's task completion time under two modes. It's obvious that all subjects consumed less time to finish the task under mode 2 no matter on the first or the last training days. On the first day, subjects consumed 173.6s on average to complete the task under mode 1. By contrast, the average time reduced to 144.7s with the help of tactile sensation under mode 2. Though five-day training session, it took subjects only 91.2s on average to finish catheterization practice under mode 1, while the average time reduced to merely 75.4s under mode 2. In terms of the task completion time, the data show that subjects training under mode 2 make much progress in aspect of the surgical proficiency with the help of the tactile sensation.

Figure 9 displays the collision risk coefficient of each subject under two modes. The results presented that subjects were comparatively easier to avoid collisions under mode 2. Specifically, on the first day subject 1 achieved the minimal collision risk coefficient of 9.7% on average among five subjects under mode 1, while such metric reduced to 6.3% under mode 2. Due to the existence of tactile reinforcement strategy, the volunteers were reminded by the tactile sensations and avoided some collisions in time. On the last day, there was no one under mode 1 who could achieve such metric less than 4% on average, while three subjects under mode 2 achieved this goal. Above results imply that it is a wise decision to employ the tactile sensation as a supplement of visual feedback to dealing with safety operation issues. Even if it's hard to avoid collisions on some occasions, the generated tactile sensations can be alert cues to operator and some corresponding measures can be taken to remit possible collision trauma.

Figure 10 makes comparison with the catheter navigation path length under two modes. On the first day, four subjects' mean catheter traversing paths were longer than 100mm under mode 1. By contrast, the longest path on average under mode 2 was just 95.5mm by subject 3. The short catheter navigation path means the operator is able to steer the catheter with fewer retractions and locate to the interest site with fewer trials. After five days training, the average path length under mode 1 was reduced to 60.3mm. In comparison, such metric of five subjects on average was shorter than 50mm under mode 2, which implied that tactile sensation was a good way to hone operators' skills.

With the synthetical evaluation of three metrics, it's appropriate to conclude that the tactile sensations have great influences on the training processes.

3) PERFORMANCE EVALUATION OF THE COGNITIVE SKILLS TRAINING METHOD

To verify the novice surgeon's cognitive skills can be enhanced by the tactile reinforcement of VR visualized tool-tissue interaction, we recruited ten non-medical volunteers (right-handed) of age 20 to 25 and divided them into two groups randomly to conduct training under two modes separately. For clarification, all volunteers were from the technical background and had never received any catheterization trainings before. Five subjects in group 1 received five-day training session under mode 1. The rest belonged to group 2 and conducted five-day training session under mode 2. They were required to thread the catheter into the left branch of a segment cerebral vessel and the route of catheterization task was plotted in yellow line shown in Fig.5. After five-day training, all subjects needed to challenge a new catheterization assignment, steering the catheter into the right branch of cerebral vessel with more curved turnings. In the challenge, subjects were asked to complete the task only under the visual guidance of VR simulator without any tactile clues. In other words, they had to rely on the newly obtained cognitive skills in training session to manipulate the catheter in the VR simulator. Each participant proceeded the challenge five times repeatedly.

To evaluate the performance of cognitive skills training method, Table 1 and 2 make a comparison of two groups in the catheterization challenge task by above defined three metrics. There existed a prominent reduction of average catheter navigation path from 101.40mm to 70.86mm, which indicated the subjects trained under mode 2 could thread the catheter to the target of interest with much higher accuracy and fewer trials. Along with the decrease of average catheter navigation path length, the averages of task completion time as well as the collision risk coefficient had been reduced slightly. Moreover, it's easy to find that the differences between maximums and minimums of task completion time, collision risk coefficient and catheter navigation path length in mode 2 were relatively smaller than those in mode 1. Similarly, the contrast between standard deviations of mode 1 and mode 2 was consistent with the above results. These findings provide substantial evidence to prove that skills acquisition under mode 2 was comparatively steady. Overall, it is possible to conclude that the developed tactile reinforcement strategy can deliberately instruct subjects to learn the visual knowledge from the VR simulator. When the subjects are equipped with cognitive skills, they can interpret the spatial distances between the catheter tip and the vascular wall precisely and make decisions wisely and quickly.

TABLE 1. **The results of group 1 in the challenge task.**

Results	Task completion time (s)	Collision risk coefficient (%)	Catheter navigation path length (mm)
Average of Group 1	150.86	7.11	101.40
Standard Deviation of Group 1	30.35	1.63	7.89
Maximum in Group 1	203.00	9.70	114.61
Minimum in Group 1	119.52	5.26	91.09

TABLE 2. **The results of group 2 in the challenge task.**

Results	Task completion time (s)	Collision risk coefficient (%)	Catheter navigation path length (mm)
Average of Group 2	144.41	6.78	70.86
Standard Deviation of Group 2	22.84	1.56	6.23
Maximum in Group 2	178.56	8.59	82.81
Minimum in Group 2	113.76	4.34	65.25

Two subjects were picked up from both groups randomly and their catheter trajectories of challenge tasks were exhibited in Fig. 11 and Fig.12 respectively. Based on the pre-determined safety boundary in mode 2, the segments of catheter navigation path in safe area and dangerous area were colored in black and yellow respectively. The red ones meant the catheter tip had collided with the vascular wall. The percentages of catheter tip resident duration in safe area, dangerous area and collision were listed in Fig.11 and Fig.12. When both subjects proceeded the challenge task without any tactile assistances, apparently the subject trained under mode 2 achieved higher percentage of catheter tip resident duration in safe area of vascular lumen and fewer collisions. Such progress had been made by subjects in group 2 because they were able to fine tune the catheter motions based on the better understandings of the relative position between catheter tip and vascular wall. Through the deliberate tactile reinforcement of visualized tool-tissue interaction, the subjects' cognitive skills have been enhanced and they can depend on visual feedback alone to thoroughly interpret the tool and tissue

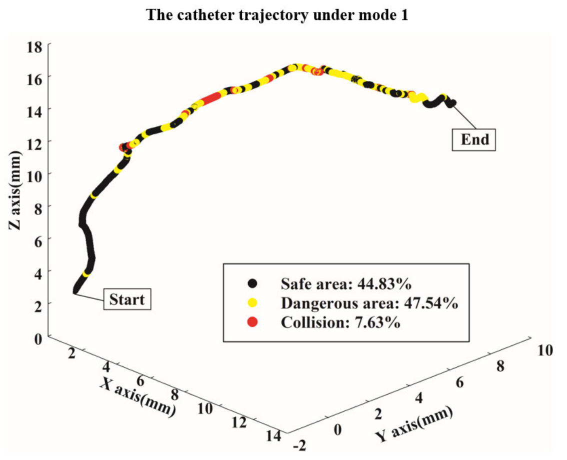


FIGURE 11. **The catheter trajectory navigated by a subject trained under mode 1.**

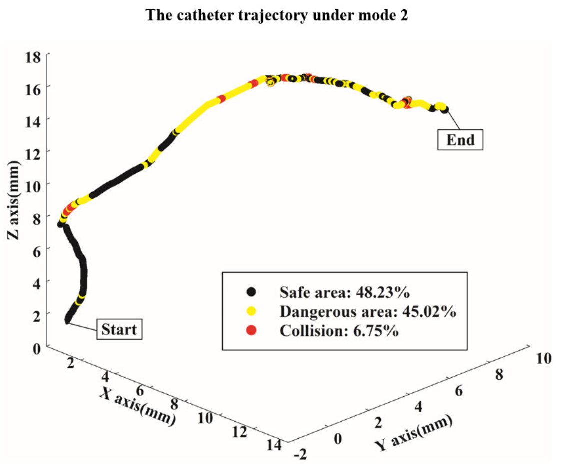


FIGURE 12. **The catheter trajectory navigated by a subject trained under mode 2.**

intervention when the haptic force is contaminated by the friction of catheter and introducer sheath.

V. DISCUSSION

The vascular interventional surgery is proceeded by surgeons under the fluoroscopic image guidance. The limited sight scope brings difficulties in understanding the tortuous anatomy. Surgeons have to depend on haptic feedback to determine the tool-tissue interaction level. However, it's challenging to discriminate the interaction force between the catheter tip and the vascular wall in clinical practice, because the haptic feedback is the combination of contact force, blood viscous drag force and friction force. Therefore, cognitive skills play important roles in catheterization, which aids the novice surgeon to steer the catheter based on the observation of tool-tissue interaction in images.

To enhance the operator's cognitive skills, a tactile sensation assisted VR training system has been developed. Compared with previous investigations, a number of studies have been published on the safety issues of catheter operation [13], [16], [17] but most available literature including our previous work [25] adopts passive solutions to prevent collisions or remit collision trauma to the tissue. Researchers would prefer to concentrate on the haptic guidance methods to improve the novice surgeons' catheter technical skills. But what if novices are in the absence of haptic clues when they navigate the catheter in practice. The solution is laid out in this paper by honing their cognitive skills. Specifically, operators should be qualified to operate the catheter based on their accurate interpretations of relative spatial distances between the catheter and vessels in image. In the perspective of operator-tool interaction, the main contribution of this paper is to resolve above dilemma by development of an operator-centered training system, which exploits the tactile reinforcement strategy to enhance the operators' cognitions

To evaluate the performance of cognitive skills training system, three metrics are defined, which weigh the levels of surgical proficiency, safety and accuracy respectively. These three metrics combined together present the comprehensive performance evaluations. In the training session experiment, above three metrics were compared under two modes between the subjects' first training day and last training day. As shown in Fig.8, Fig.9 and Fig.10, the Whisker boxes were adopted to validate the important role of tactile sensation instead of the reduction rates of three metrics. One probably concerns that the reduction rate of each metric may better indicate the progresses subjects have made through practices, whereas their skills improvements are usually stuck as they get used to the given training system based on our previous study. Thus, the Whisker boxes, which not only describe the subjects' data distributions but also imply their performance stability are better options to assess their cognition achievements.

Furthermore, there possible exists a doubt that the third experiment, which aims to validate the effect of tactile sensation in training system, is a bit unnecessary since the last experiment proves the subjects' cognitions can be enhanced by the tactile reinforcement strategy. But it must be stated clearly that ten subjects participating in the last experiment were trained under two modes separately. After that, they undertook a challenge task without any tactile clues, which meant both individual differences and training modes might affect the experimental results. Thus, the third experiment serving as the supplement of the last one aims to eliminate the individual differences and certify the critical role of tactile sensation in training process. With this guarantee, it's

TABLE 3. **Subject 1: The performance of five-day training session.**

Subject 1	Average task completion time(s)		Average collision risk coefficient (%)		Average catheter navigation path length (mm)	
Mode	**1**	**2**	**1**	**2**	**1**	**2**
Day 1	115.2	100.6	9.7	6.3	96.6	86.4
Day 2	96.2	88.2	8.8	6.3	82.8	62.7
Day 3	70.0	75.4	7.5	4.5	78.0	68.2
Day 4	64.2	54.0	6.3	4.8	81.7	50.8
Day 5	58.2	57.0	6.4	3.0	68.7	45.4

TABLE 4. Subject 2: The performance of five-day training session.

Subject 2	Average task completion time(s)		Average collision risk coefficient (%)		Average catheter navigation path length (mm)	
Mode	**1**	**2**	**1**	**2**	**1**	**2**
Day 1	131.2	118.7	10.0	7.3	100.4	84.7
Day 2	122.7	108.9	6.2	7.7	93.7	83.4
Day 3	96.2	84.7	7.4	6.7	93.8	78.1
Day 4	88.8	77.9	5.8	5.3	91.0	64.0
Day 5	82.4	74.8	5.2	3.4	67.4	49.6

TABLE 5. Subject 3: The performance of five-day training session.

Subject 3	Average task completion time(s)		Average collision risk coefficient (%)		Average catheter navigation path length (mm)	
Mode	**1**	**2**	**1**	**2**	**1**	**2**
Day 1	192.6	154.2	15.1	9.4	103.9	95.5
Day 2	121.9	80.4	9.9	7.8	74.6	62.2
Day 3	97.3	85.2	9.9	5.5	71.2	52.3
Day 4	90.5	83.2	7.6	6.2	68.3	64.1
Day 5	88.0	76.8	7.3	6.0	60.3	57.4

TABLE 6. Subject 4: The performance of five-day training session.

Subject 4	Average task completion time(s)		Average collision risk coefficient (%)		Average catheter navigation path length (mm)	
Mode	**1**	**2**	**1**	**2**	**1**	**2**
Day 1	230.5	186.6	12.1	10.8	107.2	81.3
Day 2	142.8	130.8	10.9	7.1	108.2	76.9
Day 3	122.4	95.0	10.8	6.2	61.1	56.7
Day 4	133.2	82.0	7.5	6.7	57.3	57.4
Day 5	95.4	88.0	6.1	5.8	42.6	39.9

much certain to conclude that the training modes determine the last experimental results regardless of subject individual differences.

VI. CONCLUSION

In the vascular interventional surgery, cognitive skills are highly required for novice surgeons to thoroughly interpret the image data and make decisions about further catheter operations. Therefore, a tactile sensation assisted VR catheterization training system has been developed, which aims to enhance operator's cognitive skills when facing collision issues. Consider that surgeons are sensitive to kinesthetic perceptions, tactile sensations are adopted to intensify the VR visualized tool-tissue interaction when the catheter tip is detected threading beyond the safe area of vascular lumen. Experimental results proved that our developed system can help subjects obtain the cognitions by means of deliberate tactile reinforcement of vision.

APPENDIX

Here are statistics of five subjects' five-day training results.

TABLE 7. Subject 5: The performance of five-day training session.

Subject 5	Average task completion time(s)		Average collision risk coefficient (%)		Average catheter navigation path length (mm)	
Mode	**1**	**2**	**1**	**2**	**1**	**2**
Day 1	198.5	163.5	12.0	8.8	117.4	93.3
Day 2	190.8	151.8	8.5	9.6	95.5	83.9
Day 3	134.4	132.6	7.4	5.3	87.4	70.4
Day 4	135.0	88.2	5.9	4.5	80.8	56.3
Day 5	132.0	80.4	4.2	3.1	62.2	56.2

REFERENCES

[1] P. Lanzer, "Cognitive and decision-making skills in catheter-based cardiovascular interventions," in *Catheter-Based Cardiovascular Interventions*. Springer, 2013, pp. 113–155.

[2] E. V. Poorten *et al.*, "Cognitive autonomous catheters operating in dynamic environments," *J. Med. Robot. Res.*, vol. 1, no. 3, Sep. 2016, Art. no. 1640011.

[3] H. Rafii-Tari, C. J. Payne, and G.-Z. Yang, "Current and emerging robot-assisted endovascular catheterization technologies: A review," *Ann. Biomed. Eng.*, vol. 42, no. 4, pp. 697–715, Apr. 2014.

[4] C. V. Riga, C. D. Bicknell, A. Rolls, N. J. Cheshire, and M. S. Hamady, "Robot-assisted fenestrated endovascular aneurysm repair (FEVAR) using the Magellan system," *J. Vascular Intervent. Radiol.*, vol. 24, no. 2, pp. 191–196, Feb. 2013.

[5] C. Riga, C. Bicknell, N. Cheshire, and M. Hamady, "Initial clinical application of a robotically steerable catheter system in endovascular aneurysm repair," *J. Endovascular Therapy*, vol. 16, no. 2, pp. 149–153, Apr. 2009.

[6] E. M. Khan, W. Frumkin, G. A. Ng, S. Neelagaru, F. M. Abi-Samra, J. Lee, M. Giudici, D. Gohn, R. A. Winkle, J. Sussman, B. P. Knight, A. Berman, and H. Calkins, "First experience with a novel robotic remote catheter system: Amigo mapping trial," *J. Intervent. Cardiac Electrophysiol.*, vol. 37, no. 2, pp. 121–129, Aug. 2013.

[7] T. Datino, A. Arenal, P. M. Ruiz-Hernández, M. Pelliza, J. Hernández-Hernández, E. González-Torrecilla, F. Atienza, P. Ávila, and F. Fernández-Avilés, "Arrhythmia ablation using the amigo robotic remote catheter system versus manual ablation: One year follow-up results," *Int. J. Cardiol.*, vol. 202, pp. 877–878, Jan. 2016.

[8] G. Srimathveeravalli, T. Kesavadas, and X. Li, "Design and fabrication of a robotic mechanism for remote steering and positioning of interventional devices," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 6, no. 2, pp. 160–170, 2010.

[9] H. A. Jaeger, P. Nardelli, C. O'Shea, J. Tugwell, K. A. Khan, T. Power, M. O'Shea, M. P. Kennedy, and P. Cantillon-Murphy, "Automated catheter navigation with electromagnetic image guidance," *IEEE Trans. Biomed. Eng.*, vol. 64, no. 8, pp. 1972–1979, Aug. 2017.

[10] Z.-Q. Feng, G.-B. Bian, X.-L. Xie, Z.-G. Hou, and J.-L. Hao, "Design and evaluation of a bio-inspired robotic hand for percutaneous coronary intervention," in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA)*, May 2015, pp. 5338–5343.

[11] N. K. Sankaran, P. Chembrammel, A. Siddiqui, K. Snyder, and T. Kesavadas, "Design and development of surgeon augmented endovascular robotic system," *IEEE Trans. Biomed. Eng.*, vol. 65, no. 11, pp. 2483–2493, Nov. 2018.

[12] C. J. Payne, H. Rafii-Tari, and G.-Z. Yang, "A force feedback system for endovascular catheterisation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2012, pp. 1298–1304.

[13] X. Yin, S. Guo, N. Xiao, T. Tamiya, H. Hirata, and H. Ishihara, "Safety operation consciousness realization of a MR fluids-based novel haptic interface for teleoperated catheter minimally invasive neurosurgery," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 2, pp. 1043–1054, Apr. 2016.

[14] X. Yin, S. Guo, and Y. Song, "Magnetorheological fluids actuated haptic-based teleoperated catheter operating system," *Micromachines*, vol. 9, no. 9, pp. 465–485, 2018.

[15] J. Bismuth, E. Kashef, N. Cheshire, and A. B. Lumsden, "Feasibility and safety of remote endovascular catheter navigation in a porcine model," *J. Endovascular Therapy*, vol. 18, no. 2, pp. 243–249, Apr. 2011.

[16] L. Zhang, S. Guo, H. Yu, Y. Song, T. Tamiya, H. Hirata, and H. Ishihara, "Design and performance evaluation of collision protection-based safety operation for a haptic robot-assisted catheter operating system," *Biomed. Microdevices*, vol. 20, no. 2, p. 22, Jun. 2018.

[17] S. Guo, Y. Song, X. Yin, L. Zhang, T. Tamiya, H. Hirata, and H. Ishihara, "A novel robot-assisted endovascular catheterization system with haptic force feedback," *IEEE Trans. Robot.*, vol. 35, no. 3, pp. 685–696, Jun. 2019.

[18] J. Guo, X. Jin, and S. Guo, "Study of the operational safety of a vascular interventional surgical robotic system," *Micromachines*, vol. 9, no. 3, pp. 119–136, 2018.

[19] S. Macdonald, R. Lee, R. Williams, and G. Stansby, "Towards safer carotid artery stenting: A scoring system for anatomic suitability," *Stroke*, vol. 40, no. 5, pp. 1698–1703, May 2009.

[20] Y. Wang, S. Guo, and B. Gao, "Vascular elasticity determined mass–spring model for virtual reality simulators," *Int. J. Mechtron. Automat.*, vol. 5, no. 1, pp. 1–10, 2015.

[21] S. Guo, X. Cai, and B. Gao, "A tensor-mass method-based vascular model and its performance evaluation for interventional surgery virtual reality simulator," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 14, no. 6, p. e1946, Dec. 2018.

[22] W. Tang, T. R. Wan, D. A. Gould, T. How, and N. W. John, "A stable and real-time nonlinear elastic approach to simulating guidewire and catheter insertions based on cosserat rod," *IEEE Trans. Biomed. Eng.*, vol. 59, no. 8, pp. 2211–2218, Aug. 2012.

[23] V. K. Venkiteswaran, J. Sikorski, and S. Misra, "Shape and contact force estimation of continuum manipulators using pseudo rigid body models," *Mechanism Mach. Theory*, vol. 139, pp. 34–45, Sep. 2019.

[24] Y. Wang, S. Guo, T. Tamiya, H. Hirata, H. Ishihara, and X. Yin, "A virtual-reality simulator and force sensation combined catheter operation training system and its preliminary evaluation," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 13, no. 3, p. e1769, Sep. 2017.

[25] Y. Wang, S. Guo, Y. Li, T. Tamiya, and Y. Song, "Design and evaluation of safety operation VR training system for robotic catheter surgery," *Med. Biol. Eng. Comput.*, vol. 56, no. 1, pp. 25–35, Jan. 2018.

[26] K. Kahol, M. Vankipuram, and M. L. Smith, "Cognitive simulators for medical education and training," *J. Biomed. Inform.*, vol. 42, no. 4, pp. 593–604, Aug. 2009.

[27] J. Guo, S. Guo, N. Xiao, and B. Gao, "Virtual reality simulators based on a novel robotic catheter operating system for training in minimally invasive surgery," *J. Robot. Mechatron*, vol. 24, no. 4, pp. 649–655, 2012.

[28] G. J. Raju, G. C. Verghese, and T. B. Sheridan, "Design issues in 2-port network models of bilateral remote manipulation," in *Proc. Int. Conf. Robot. Automat.*, 1990, pp. 1316–1321.

[29] R. J. Adams and B. Hannaford, "Stable haptic interaction with virtual environments," *IEEE Trans. Robot. Autom.*, vol. 15, no. 3, pp. 465–474, Jun. 1999.

[30] B. Hannaford, "A design framework for teleoperators with kinesthetic feedback," *IEEE Trans. Robot. Autom.*, vol. 5, no. 4, pp. 426–434, Aug. 1989.

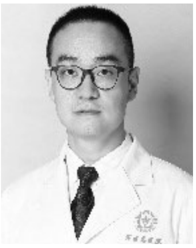
[31] H. I. Son, T. Bhattacharjee, and H. Hashimoto, "Enhancement in operator's perception of soft tissues and its experimental validation for scaled teleoperation systems," *IEEE/ASME Trans. Mechatronics*, vol. 16, no. 6, pp. 1096–1109, Dec. 2011.

[32] G. A. Gescheider, *Psychophysics: The Fundamental*. 1997.

YU WANG received the B.S. degree from Chongqing University, China, in 2010, the M.S. degree from Xi'an Jiaotong University, China, in 2013, and the Ph.D. degree in intelligent mechanical systems from Kagawa University, Japan, in 2016. She is currently an Associate Professor with the School of Electrical Engineering and Information, Southwest Petroleum University, Chengdu, China. Her research interests include robotic endovascular surgery, virtual-reality, smart-material actuators, and underwater robots.

FAN YANG received the B.S. degree from Southwest Petroleum University, China, in 2017, where she is currently pursuing the master's degree. Her research interests include catheterization training systems, haptic sensation interface, and virtual simulation technology.

YAXIN LI received the B.S. degree in automation from Chongqing University, China, in 2010, the M.S. degree in electronics and communication engineering from the University of Electronic Science and Technology of China, in 2013, and the Ph.D. degree in intelligent machine system from Kagawa University, Japan, in 2016. Since 2016, he has been an Associate Professor with the School of Electrical Engineering and Information, Southwest Petroleum University, Chengdu, China. His current research interests include biomimetic underwater robotics, amphibious robotics, and biomedical-related robotics.



TAO YANG received the M.S. and Ph.D. degrees in neuro-oncologic surgery (neurosurgeon) from Army Medical University, Chongqing, China, in 2005 and 2015, respectively. He is currently with the General Hospital of Western Theater Command, China. His main research interests include mechanism and treatment of brain tumor, epilepsy, and traumatic brain injury. He is a member of the China Anti-Cancer Association and the Chinese Medical Association. He and his research team received the first prize of the Sichuan Science and Technology Awards, in 2012 and 2018.

CHENG REN received the B.S. and M.S. degrees in electrical engineering and the Ph.D. degree in communication engineering from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2003, 2006, and 2018, respectively. She is currently studying with the University of South Brittany sponsored by Special Program for Talents Training in Western Region of China Scholarship Council. Her research interests include network optimization, information-centric networking, and software-defined networking.

ZHIHANG SHI received the B.S. degree from Southwest Petroleum University, Chengdu, China, in 2018, where he is currently pursuing the M.S. degree. His research interests include catheter robotic training systems and virtual reality technology.

• • •