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ORIGINAL ARTICLE

Design and evaluation of safety operation VR training system for robotic catheter surgery

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Abstract A number of remote robotic catheter systems have been developed to protect physicians from X-ray exposure in endovascular surgery. However, the teleoperation prevents the physicians sensing the force directly which may easily result in healthy vessels injured. To realize the safe operation, a tissue protection-based VR training system has been developed in this paper to prevent collateral damage by collision. The integrated VR simulator cannot only remind the novice possible collisions by visual signs, but also cooperate with the newly designed tissue protection mechanism to remit collision trauma beforehand. Such mechanism exploits the diameter variable pulley in order to implement the safe interaction between catheter and vasculature. To testify the effectiveness of the tissue protection in training system, we invited four non-medical students to participate the successive 5 days training session. The evaluation results show that the average impingement distance (representing tissue damage) to vascular wall has been reduced to 0.6 mm, and the collision frequency is greatly decreased which implies the realization of relative safe catheterization.

Keywords Virtual reality-based training system · Collision trauma · Tissue protection · Robotic catheter operation · Minimally endovascular surgery

1 Introduction

With the rapid development of medical technologies [1], the catheterization endovascular surgery challenges the people's impression of conventional surgery. Due to small incision and few complications, the endovascular surgery benefits the patients a lot. In the catheterization, a slender and flexible catheter is permitted to thread into vasculature. To control and locate the catheter, the surgery is conducted under the X-ray 2D fluoroscopy for image guidance [2], but the long radiation exposure puts the physician's health into risk. With such consideration, a range of teleoperating catheter robotic systems have been developed no matter by the commercial manufacturers [3] or university [4–7]. The robotic catheter teleoperation systems separate the patient and surgeons apart in space. Surgeons manipulate the physician console on master side, and the catheter manipulator of slave side will thread the catheter into the patient based on surgeon's instructions. In telesurgery, as the surgeons cannot feel the catheter insertion resistance directly, the haptic force providers have been developed to assist the surgeons for catheterization [8]. However, even with the help of haptic force feedback or other image guidance, the surgeons must equip with dexterous technical skills and abundant

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experience. In other words, the catheterization training system is highly demanded. In the past, the traditional training methods were by mentors or using the animals (or phantoms) for exercise but the experience gained by mentors was unstructured. Moreover, there are ethical issues and anatomical difference between human and animal. Currently, one promising way to address the above issues is by virtual reality (VR)-based training system, which allows repeatable practices [9, 10]. The VR simulator is able to build up the vasculature [11, 12] and catheter [13] models and displays the visual images of surgical area at the same time.

The VR simulator developed by our lab was based on patient's CT files, which was capable to display the vascular deformation with its mechanical properties [14]. Once the VR simulator combined with master side physical console, the virtual environment could exhibit the catheter's motions in vasculature when a novice operated on master console. To help the novice immense into training process, the haptic force provider [15] was integrated on the master side physician console. Besides, our lab newly realized that both visual and tactile sensations combined VR training system [16] aimed to enhance the novice's eye-hand coordination shown in Fig. 1. It adopted the collision detection algorithms in VR simulator, and the VR was able to release different visual signs to instruct the novices for safe catheterization. Apart from the visualization, the haptic force exerting on catheter was provided by magnetorheological (MR) fluids. From the evaluation results of training procession in [16], even with the help of image and haptic force, the collision trauma is still a big problem, which may bring in collateral damage. To investigate the tissue protection, researchers [17, 18] have summarized the primary determinant of contact force, which is collision force in catheter endovascular surgery. Particularly for cardiac ablation therapy, the catheter tip contact force has been proven to be the lesion assessment in references [19, 20]. Dr. Khoshnam et al. [21] presented a model-based force control system to obtain the catheter distal contact force. To confine such force within prescribed range, Gelman et al. introduced an autonomously catheter contact-force controller in [22] for ablation. However, up to now, few studies have mentioned how to protect the vascular wall from hurting in catheterization. As the fragile vessels (especial cerebral vessels) are vulnerable to collision by catheter tip, the novices have little experience to respond fast enough to manipulate the catheter. Motivated by such consideration, in this paper, the newly developed VR training system devotes to alleviate the collision trauma to blood vessel so as to improve the skills of safe catheterization.

According to the Hertz non-adhesive elastic contact law, the collision force is greatly influenced by the catheter moving speed. In other words, it is possible to remit the collision trauma by decelerating the catheter moving velocity before collision happens. By such inspiration, we introduced a speed adjustable mechanism (SAM) and integrated it into VR-based catheter training system for tissue protection. The VR simulator did not only render the surgical view of virtual catheter and vasculature but also could estimate the collision and display different signs to remind novice. Once the collision was detected beforehand, such important information would be shared with SAM, which was used to decelerate the catheter threading speed and reduce the trauma by collision. In summary, the newly developed safe operation VR training system contributes to raise the awareness of tissue protection in case of piercing the vascular wall. To verify the performance of such training system, we recruited four non-medical students to join in the training exercise and prove the feasible of remitting collision trauma.

2 Method

2.1 Overview of the safe operation VR training system

Our developed safe operation training system is devoted to remitting the collision trauma. It consists of two primary components: mechanical platform and VR simulator, shown in Fig. 2.

In the mechanical platform, the physician console was designed based on surgeon's habit of catheter operation and could realize the translation and rotation of catheter motions. In the training process, catheter motions were detected by two encoders in order to synchronize the virtual catheter position in VR simulator. Such data were transmitted to VR side in real-time by Socket 1 (using TCP/IP). Once received the latest data, the VR simulator would update the virtual catheter's position in the 3D vascular lumen. Meanwhile in the directive notification module (DNM) of VR simulator, the parallel collision detection process was running in loop at every updated time step, which used Gilber-Johnson-Keerthi (GJK) distance algorithm [23] to estimate the collision and calculated the minimal distance between catheter tip and vascular wall. Based on trainee's pre-determined catheter working safe boundary, the DNM partitioned the vascular lumen into three virtual access corridors and named them safe area, warning area, and dangerous area, respectively. Only when the distance between catheter tip and vascular wall was larger than safe boundary, the catheter was claimed to work in the safe area which allowed catheter moving quickly and freely. Once the distance was smaller than safe boundary but collision was not detected, the catheter was supposed to be in the warning area which might easily result in collision. When collision happened, the catheter moved into dangerous area and any mal-

**Fig. 1** The visual and force sensations combined VR training system [16]
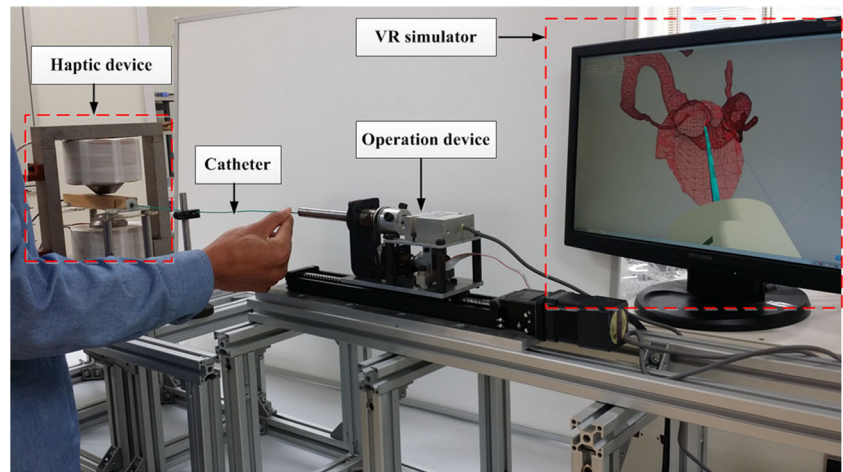
operation would lead to piercing the fragile vessel. Above three areas were rendered by different signs for VR visualization interface.

Since it was possible to protect tissue by slowing down the catheter moving speed before collision, we decided to introduce the SAM in hardware to cooperate with DNM in VR simulator. Once the DNM detected that the catheter inserted into warning or dangerous area, such important information would be feedback to hardware so as to trigger the deceleration function of the SAM automatously. Such working mode was called urgent state which was used to avoid potential collision beforehand or remit the

collision injury to vessels. Besides, when the catheter moved freely in safe area of vessel, the SAM could switch into normal state. In such state, the SAM could transmit the same rotation speed of power supply which served to drive the catheter translation.

In a word, to make a novice aware of safe interaction between catheter and vessels, the novice's manipulation of catheter would be synchronized in VR simulator, and at the same time, the DNM judged such manipulation by visual signs. According to the visual instructions, the SAM facilitated the novice to response collision simultaneously by switching into urgent state. To satisfy the

Fig. 2 The conceptual diagram of the safe operation VR training system
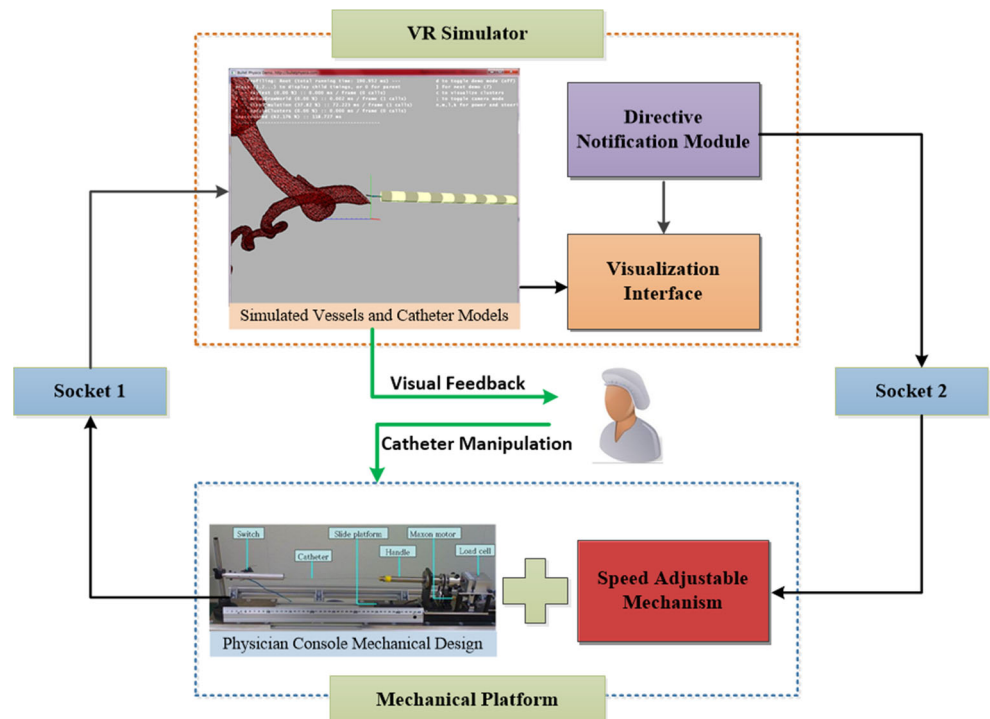
above two functions, the newly SAM assembled on the physician console was shown in Fig. 3. Step motor 1 was the power supply for catheter translation by V-shape belt to drive the ball screw sliding. The information about collision detection in DNM was sent back to physical console by socket 2. We adopted the diameter variable pulley to realize the continuous speed transmission of SAM.

2.2 The structure of speed adjustable mechanism (SAM)

The objective of SAM in hardware was not only to equally transmit the catheter translation power supply (motor 1) but also changed its angular velocity in emergency. To realize such requirements, we adopted a pair of variable diameter pulleys and V-shape belt in SAM. The working principle was displayed in Fig. 4. The SAM consisted of driving and driven two parts. In driving part, the motor 1 was responsible for providing the rotation power, while the motor 2 in driven part was capable of changing the space between two sheaves so as to realize diameter variable pulley. The sheave was exhibited in Fig. 5 which was fabricated by a 3D printer using PLS material. When the two sheaves of driven part moved closer to enlarge the pitch diameter, the sheave (P1) of the driving part would compress the spring because the belt length was constant. Consequently, the output angular speed of driven part could be decelerated. On the contrary, when the motor 2 pulled the movable sheave to the balance position so that the pitch diameters of driven part were equal to that of driving part, the SAM outputted the same rotation speed of power supply (motor 1). The SAM output shaft was linked with a

ball screw slide which served catheter translation in manipulation device shown in Fig. 3. In this way, the SAM could regulate the catheter moving speed and meet the demand of safe interaction between catheter tip and blood vessels.

2.3 The SAM calibration

Firstly, in order to determine the maximal speed ratio of SAM, we carried out the theoretical analysis of SAM by AMESim (12.0 Version). In the software, a continuous variable transmission model was used to simulate the SAM which was configured with the same parameters of fabricated sheaves. Two pulleys were linked by V-shape belt of 635 mm in perimeter. The center distance between driving and driven two parts was 200 mm. According to the diameter variable sheave manufacture parameter, the minimum radial positions of driving and driven parts were calculated to be 30.0 mm and 37.4 mm, respectively. As a result, the theoretical speed ratio was supposed to be 1.48 in maximum.

Next, we conducted the calibration of the SAM which aimed to find the balance position (the pitch diameters of driven part were equal to that of driving part) and relationship between speed ratio and space distance in driven part. In calibration experiment, a micro encoder (MTL, MES020-2000P, Japan) was connected with the output of the SAM shaft like Fig. 6 shown. The detected data would be sampled by 16-bits AD board (CONTEC, AD16-16U, Japan). The motor in driving part was rotated at 0.1 rps speed while the movable sheave in driven part moved every 1 mm for 10 s to find the balance position.

Fig. 3 The newly assembled catheter manipulation device
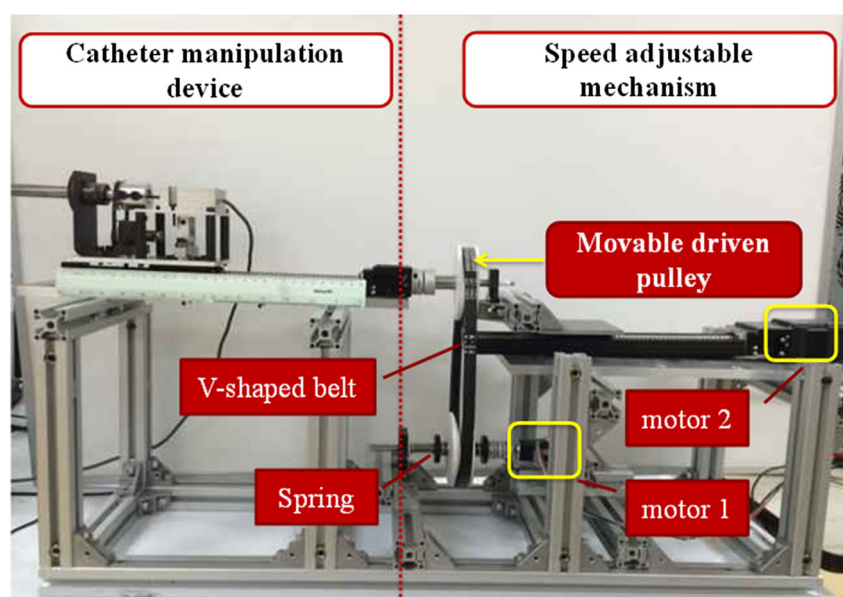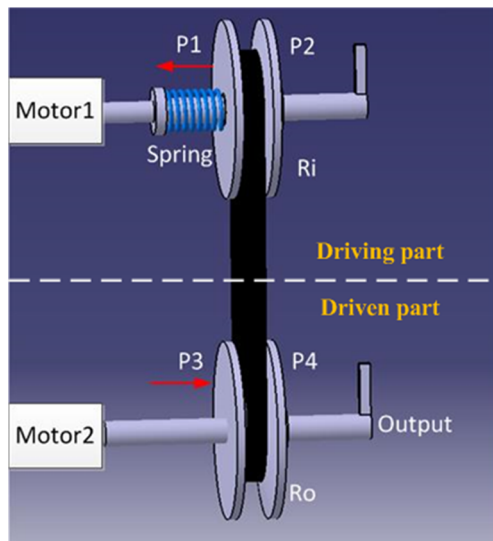
Fig. 4 The working principle of SAM

Consequently, when the movable sheave was apart from the other sheave for 5 mm, the driven part shaft outputted the equal speed with driving part motor.

Finally, to investigate the relationship between speed ratio and space distance in driven part, the movable sheave would move from balance position to the closest position of the other sheave in driven part every 1 mm step for 10 s interval. Above experiment was repeated ten times, and Fig. 7 showed the results of a given instance. The blue line represented the average of sampled rotation speed every 10 s. Figure 8 revealed the final calibration results. The maximal speed ratio reached 1.39 when two sheaves in driven part were closely attached. Furthermore, it was obvious that the rotation speed of driven part output equaled to that of driving part at 5 mm space distance.
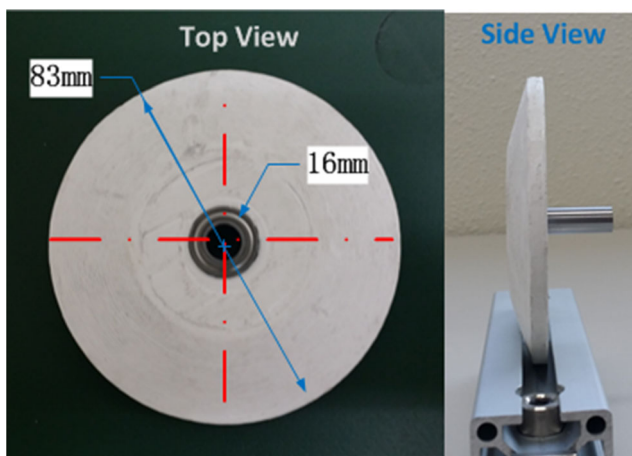
Fig. 5 The top and side views of a single sheave

2.4 The working flow of the overall training system

To reduce the possibility of tissue perforation, above achieved calibration results were served as reference to activate the SAM working. Before the training starts, movable sheaves of SAM were initialized at balance position. As Fig. 9 showed, the novice operated the catheter on physician console and the catheter's motions were transmitted to VR simulator so as to synchronize the virtual catheter's position in vasculature. Parallel running process DNM was able to identify catheter tip in the proximity of vascular wall (warning area) and predict collision (dangerous area) to providing the visual signs for novice. If the catheter tip was threaded into warning area, the SAM was triggered to push the movable sheave to point D1 in Fig. 9 where the catheter speed was reduced 80% of motor 1 output. Such action was as same as brake mechanism aiming to prevent piecing the vascular wall. Unfortunately, if the collision was detected by DNM in VR simulator, the movable sheave moved to point D2 immediately in order to remit the possible impingement of collision. When the SAM worked at D2, it can reach the biggest speed ratio 1.39. The deceleration function of SAM helped novice with fast response to deal with collision situations. As we adopted the diameter variable pulley, the speed change was continuous and seamless. On the contrary, when the DNM displayed the catheter moving in the safe area, the SAM would always work on balance point (B) as Fig. 9 shows.

In a word, the three kinds of catheter working areas in VR simulator asked for the SAM to switch into different working states. In the following section, we would prove the effectiveness of the SAM to alleviate the collision trauma and improve the safety of tool-tissue interaction.

3 Results

3.1 Experimental setup

In the mechanical platform, the drivers of motor 1 (PK513PA-H50S, Oriental Motor CO. LTD) and motor 2 (ASM46AA, Oriental Motor CO. LTD) were connected with conversion terminal (CCB-SMC2, CONETEC) so as to be easily regulated by motion control board (SMC-4DF-PCI, CONTEC). The motion control board was plugged on PC by physical connector PCI bus. Both of the catheter operation and SAM working were implemented on the PC (Intel 2.67GHz Processor and 3GB RAM).

The blood vessel and virtual catheter were simulated in VR by 64-bit server with four processors (Intel 3.07GHz) and 16 GB RAM. The geometrical model of vasculature was formulated

Fig. 6 The SAM calibration setup
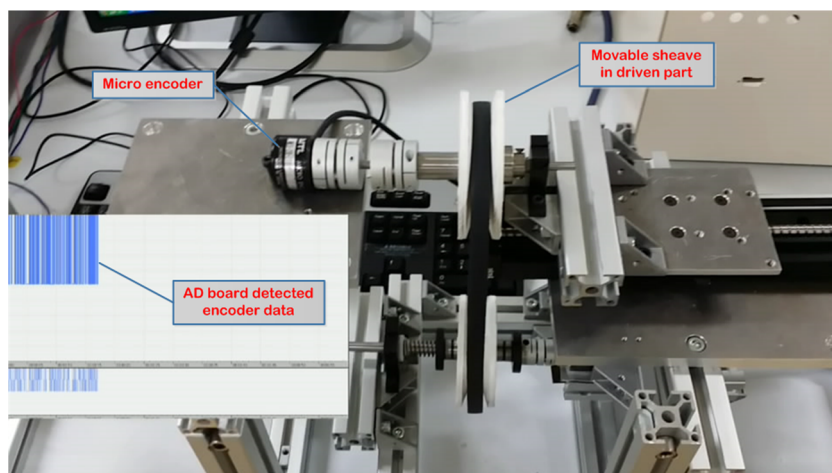
based on specific patient's CT files of the brain which were processed by OpenGL from the DICOM header. Then the cerebral vessels were imported into physical engine Bullet for dynamic deformation rendering. In software Bullet, the catheter was made of 1 mm diameter and 5 mm long cylinders with angle-restrict joints. At the same time, the DNM was realized in VR simulator, and the safe boundary was pre-determined to 2.5 mm by user according to his/her demands. Due to the fact that the nodes consisting of vascular surface were enclosed by 1 mm edge boxers, the warning area was beyond 1 mm but less than safe boundary. To evaluate the injury to vascular wall, the expanding polytope algorithm (EPA) was used to calculate the penetration depth. Besides, the communications between mechanical platform and VR simulator (Socket 1 and Socket 2) were implemented by TCP/IP protocol.

To verify the effectiveness of our developed training system, we recruited four non-medical students (right handed) to join in the experiment. Before the training starts, they were required to familiarize with catheter manipulation and VR simulator for about 30 min. After that, one branch of the cerebral vessel was picked up for training. Because of it with bifurcations and curving turns, it required the volunteers with skills of catheter operation so as to avoid collision or remit the trauma. For comparison, we asked the subjects to conduct the VR-based training system in other two modes. In the mode 1, the VR simulator was able to display the catheter motion according to mechanical platform but it had no visual reminders by DNM. In mode 2, the VR simulator equipped with DNM but no SAM. The newly developed training system in this paper was named as mode 2 with SAM for annotation.

3.2 Experimental results

For performance evaluation, the following two important metrics were taken into consideration: (1) average impingement distance and (2) average percent of catheter tip staying in danger area. The average impingement distance represented the penetration depth of tissue in collision which weighed the tissue injury and its integrity. The second metric denoted the safe operation between catheter tip and tissue in surgery. In the
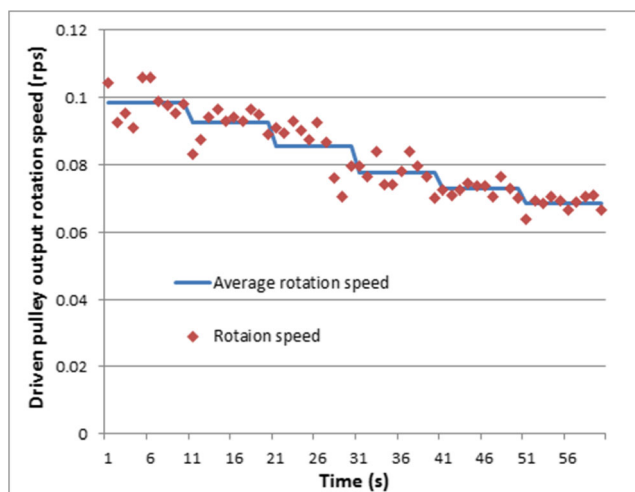
Fig. 7 The results of a given instance
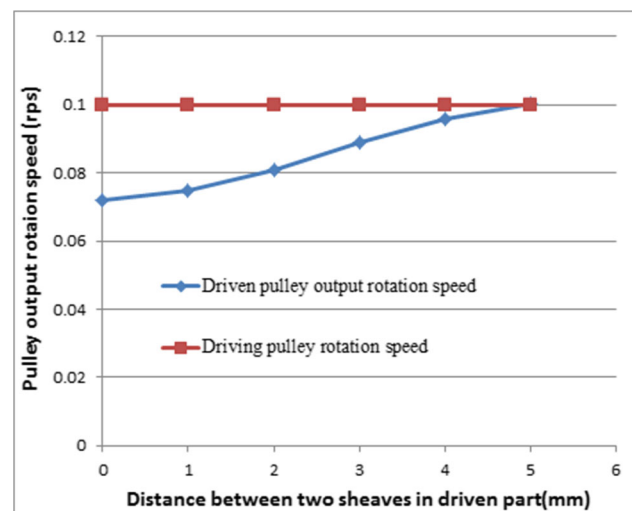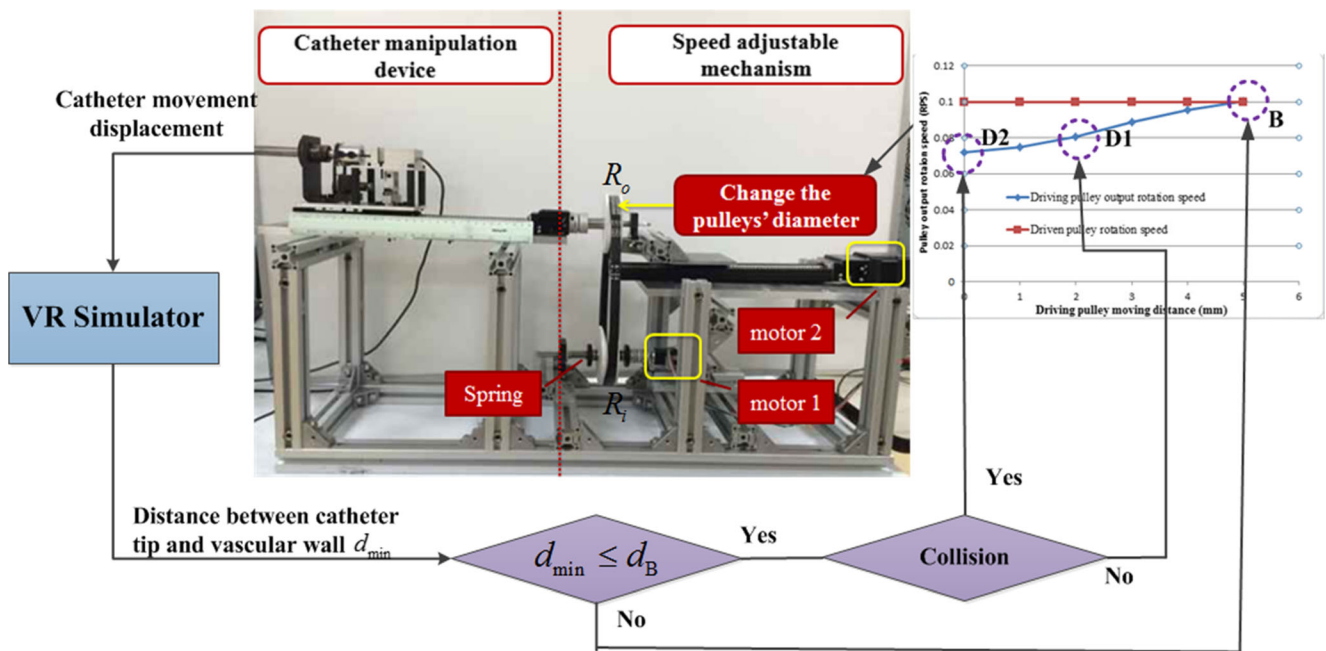

Fig. 8 The calibration results

Fig. 9 The training system working sketch

training exercise, each subject was asked to thread the catheter to the appointed position five times for statistics. The results were a mean value in the figures.

Based on the results shown in Fig. 10, the SAM equipped VR training system (Mode 2 with SAM) has made great contribution to remit the collision trauma for all participating subjects compared with mode 1 and mode 2. The maximal average impingement was below 0.6 mm achieved by subject 1, and the maximal reduction compared with mode 1 is 0.16 mm by subject 3. Such great improvement indicated the SAM played important role in tissue integrity protection. Especially for the cerebrovascular surgery, the lumen was very narrow and vascular wall was extremely fragile. We should pay high attention for the safe operation between catheter and vasculature. On the contrary, even with the visual reminders by DNM in VR simulator, average impingement did not greatly reduce than that of mode 2 with SAM. Therefore, Fig. 10 sufficiently proved the effectiveness of the SAM equipped VR training system which aimed to protect the tissue integrity.

Figure 11 summarized the performance of safe operation by each subject under the three training modes. With the existence of visual signs in VR simulator, the mode 2 greatly reduces the percent of catheter tip residence duration in danger area compared with mode 1. However, such advancement could not ensure the metric under 10% which represented the collision frequency. But once the SAM integrated into mode 2, the three subjects achieved the metric under 10% except subject 2. Especially the subject 1 outperformed best (the percent was only 7.96%), which implied that the SAM avoided many collisions. Above results told that the combination of the SAM and the DNM in training system played an

important role in performance improvement. Once the catheter tip entered into the warning area, the DNM would inform the SAM to activate the brake function for the first time which leaded to collision avoidance. If the collision really happened, the second time deceleration of catheter moving speed would be triggered so as to remit vascular injury. The above two figures verified that the SAM equipped VR training system was able to prevent the tissue penetration greatly.

As the skills learning often took time, the four recruited subjects were invited to participate in successive 5 days training session which was carried out under the same experimental setup. Figure 12 displayed the average impingement distance by four subjects in 5 days. Generally, there was no obvious difference between penetration in mode 1 and mode 2. In comparison, when the mode 2
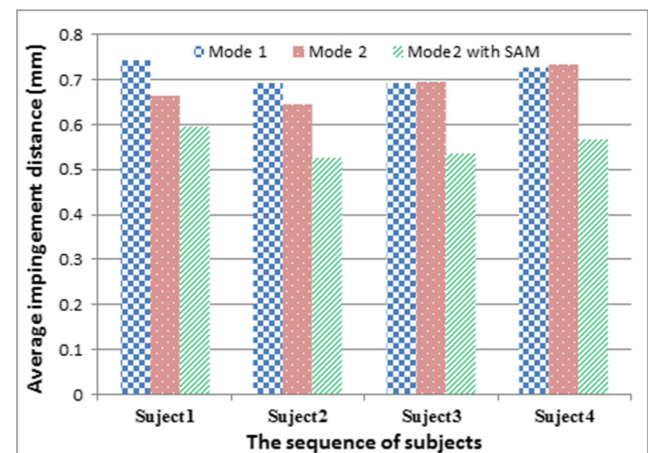

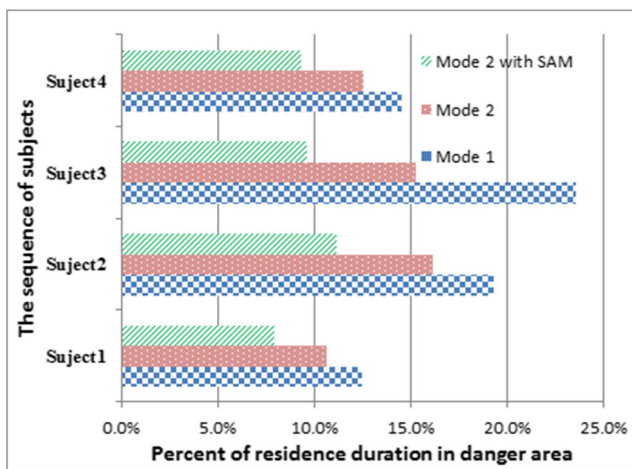**Fig. 10** The average impingement distance

Fig. 11 The percent of catheter tip residence duration in danger

combined with SAM, the average impingement distance had been notably decreased especially the subject 3. On the last training day, the metric was as small as 0.49 mm. Furthermore, the line of each subject under mode 2 with SAM was relatively smooth and steady, which demonstrated the skill acquisition was stable.

Finally, we calculated the percent of catheter tip staying duration in safe area which displayed in Fig. 13. Such metric evaluated the technical skills of safe catheterization. No matter the mode 2 or mode 2 with SAM, the figures revealed that the percent of catheter tip residence duration in safe area of each subject exceeded 50% on the last day. Compared with mode 1, such progress was mainly contributed by visual reminders provided by DNM in VR simulator. Moreover, the metrics corresponding to mode 2 with SAM were over 60% and the maximum was 69.5% by subject 4. The results explained that the SAM equipped VR training system was not only able to remit the collision trauma but also enhance the safe operation of catheterization. The deceleration function of SAM assisted the trainee to amend the catheter threading path timely in warning area. Also, compared with mode 1, the curves of mode 2 and mode 2 with SAM were comparatively smooth and upward tendency. Therefore, the skills gained in these two modes were fast and stable.

4 Discussion

For improving the catheter manipulation skills in tele-surgery, the visualization and haptic force equipped training systems had been developed to help novices immense into practice. In our previous study [16], we devoted to exploring the VR simulator and force sensation combined training mode. To help novices realizing comparatively safe catheter operation, the DNM used collision detection algorithm results to judge whether the catheter threading in safe area of vascular lumen or not. According to the DNM, the catheter tip working area
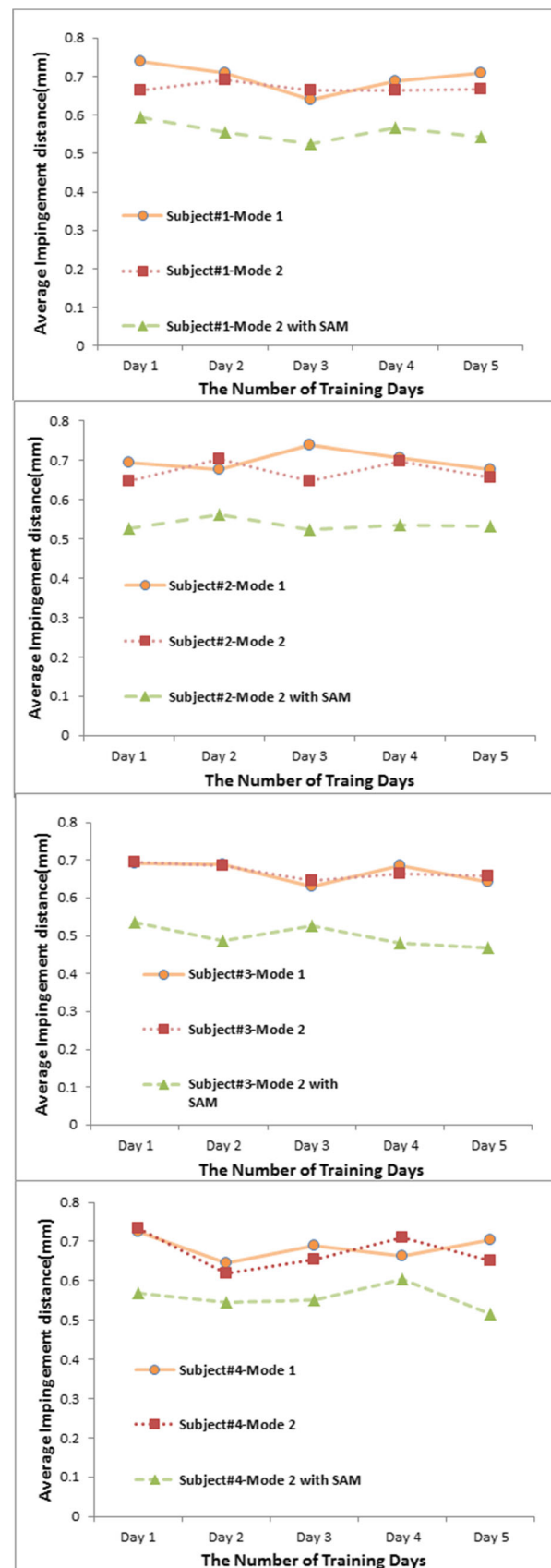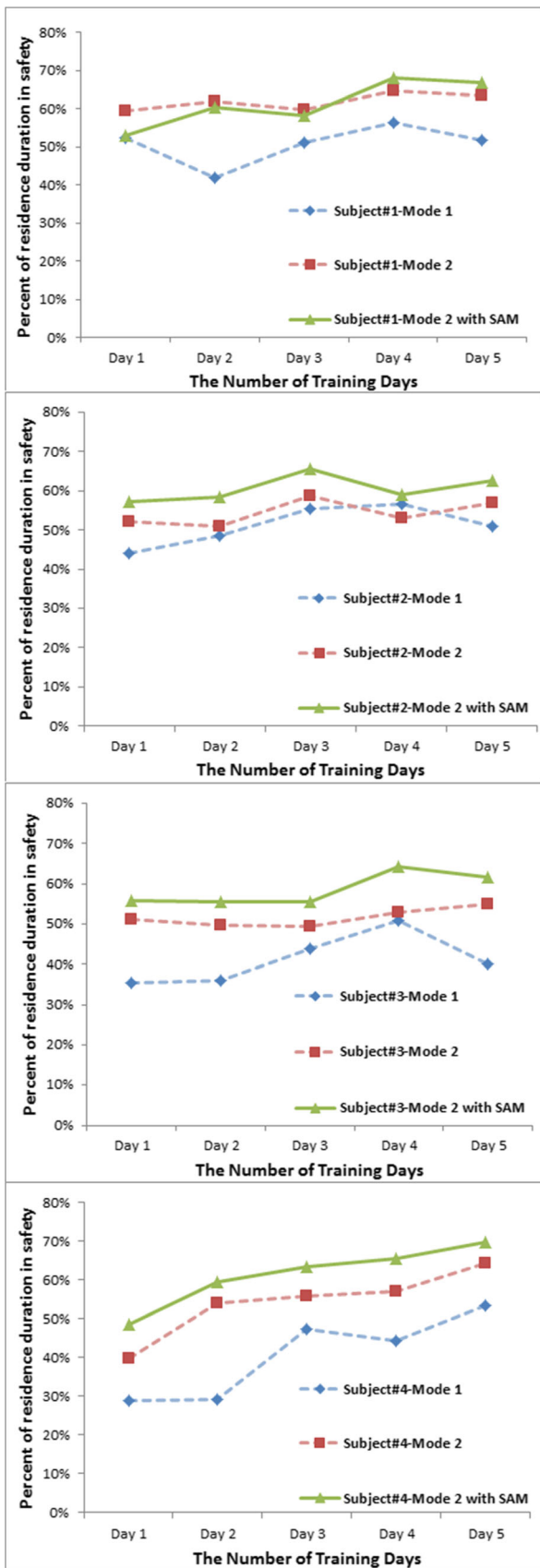

Fig. 12 The average impingement in 5 days training>

Fig. 13 The percent of catheter tip residence duration in safe area in 5 days training

was divided into virtual corridors, which were rendered into different signs to remind novices operating carefully. The safe sign facilitated the novices threading catheter freely and quickly. Once the warning or dangerous signs were released by DNM, the haptic device would cooperate with visual hints to apply resist force on catheter. Both efforts on visualization and tactile sensation reminded the novices to be alert enough so as to avoid potential collisions. The evaluation results showed that the visual and tactile sensations benefitted novices a lot especially in collision avoidance but they failed to remit collision trauma by catheter tip. Particularly, through the observations of volunteers training session, we found that subjects were panicking when collision happened. They could not respond fast enough to deal with such situations. Such findings motivated our team to do the research about tissue protection. The newly fabricated SAM cooperated with both VR simulator and catheter operation device, which could slow down the catheter threading speed in two levels. Equally, the experimental results proved the reduction in impingement which weighed the tissue injury and integrity. Additionally, from the training session results, we concluded that such training system was able to improve safe interactions between catheter and vessels. In the future, we will integrate the SAM into master side of robotic tele-operation system.

5 Conclusions

Tissue protection is one of the important issues in the VR-based training system. Except for providing visual and tactile sensations in the training exercise, it is essential to predict the collision between catheter tip and vascular wall in advance and effectively alleviate the collision injury by novice. Therefore, we developed a collision trauma remitted VR training system for safe operation of catheterization. Such newly realized training system took advantage of DNM in VR simulator which could predict the collision and identify the catheter tip in the proximity of vascular wall. The DNM did not only display visual signs for novice but also feedback the warning or dangerous information to catheter operation device. The catheter operation device integrated our newly developed speed adjustable mechanism which could decelerate the catheter moving speed seamlessly by diameter variable pulleys. The SAM would be triggered when the DNM detected the catheter threading into warning area. The speed ratio of SAM would switch to maximum when the collision was predicted by DNM. By this newly developed system, four subjects were invited to join in the training session for 5 days which aimed to improve the safe operation of catheterization. The experimental results showed that the impingement distance was reduced to 0.6 mm and the percent of catheter tip in safe area grew up to at least 50%. The performance was obviously more outstanding than that of visual and tactile

sensations equipped VR training system. The above system evaluation results sufficiently proved that our developed collision trauma remitted VR training system was capable of tissue integrity protection and safe catheterization. Moreover, the skills gained by our training system were comparatively fast and stable.

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