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	The realized training system aims to construct a comprehensive training environment which combines visualization and force sensation together.

A virtual-reality simulator and force sensation combined catheter operation training system and its preliminary evaluation

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Abstract

Background The endovascular surgery benefits the patients because of its superior in short convalescence and small damage to healthy tissue. However, such advantages require the operator equipped with dexterous skills of catheter manipulation without resulting in collateral damage. To achieve this goal, the training system is high demanded.

Methods A training system integrated cooperation of VR simulator and haptic device is developed within this context. The VR simulator is capable of providing the visual cues which assist the novice for safe catheterization. In addition, haptic device cooperates with VR simulator to apply sensation at the same time. The training system was tested by non-medical subjects and they were asked to experience a successively five days training session.

Results The performance is evaluated from the safety criterions and task completion time. The results demonstrate that the operation safety is improved 15.94% and task completion time is cut 18.80 seconds for maximum. Moreover, according to subjects' reflection they are more confident in operation.

Conclusions The realized training system constructs a comprehensive training environment which combines visualization and force sensation together.

Keywords virtual-reality simulator, collision detection, haptic force device, training system

INTRODUCTION

Endovascular surgery has been the focus of many recent studies due to its advantages like small incisions, less blood loss, quicker recovery over the traditional surgeries. Even some commercial companies like Hansen Medical and Catheter Robotics Inc. have developed catheter robotic systems such as Sensi (Hansen Medical) [1][2] and Amigo (Catheter Robotics Inc.) [3] to assist surgeons. But the high costs of purchase and maintenance limit commercial products use widely. Therefore, a number of investigators have put their efforts on catheter robotic system development. Arai et al. [4] at Nagoya University used the linear stepping mechanism inspired by mechanical pencil to move the catheter step by step. Yogesh et al. [5] developed the remote catheter navigation system which allowed surgeons operating real catheter. Furthermore, our lab designed master-slave catheterization system [6][7] is displayed in Fig.1. The tele-operated system design protected surgeons from fluoroscopic X-ray exposure during catheter guide intervention and the design of catheter manipulator was to imitate surgeon's hand inserting catheter procedure.

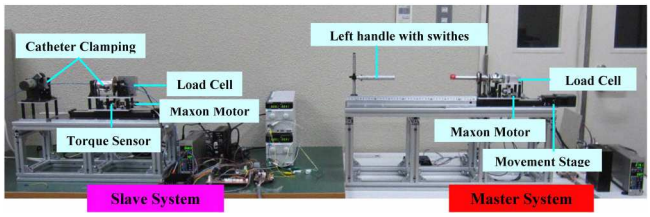

Fig. 1 Master-slave Catheterization System [7]

However, manipulating catheter safety and position catheter tip in target usually require physicians equipped with technical skills and considerable experience which are difficult to gain in short period. Thus, the catheterization training system is highly demanded.

Traditionally, the conventional way to continue training is by mentored method and with the extra excises on animals or anatomic phantoms. But the experience gained by mentor is unstructured and lacks performance feedback. Also there's the anatomical difference between animals and human and some other ethical issues. With such considerations, the virtual-reality based training system is a promising way to assist novice surgeons at no-risk environment for repeatable practices [8]. Moreover, the evidence from Yale [9] and Grandtcharov [10] showed that VR-trained participants made significantly fewer intraoperative errors than the standard-trained participants.

One of famous training systems was produced by Mentice AB called Vascular Interventional System Trainer (VIST) [11], which consisted of cardiovascular simulation system, the haptic interface device and the instructional system. Another example was ANGIO Mentor [12] which was multidisciplinary endovascular simulator and provided hands-on practice. Zhou et al. [13] proposed virtual training platform for cardiovascular interventional surgery which equipped force feedback to deliver realistic simulation to trainees.

Apart from these complete systems, some researchers focused on building up the VR system, such as graphic rendering, model behavior of vascular (tissue) or instruments. The virtual-reality simulator began with 3D volumetric model construction. Through the acquired image data, the vascular geometric model was generated [14][15]. To strengthen the realistic visualization, vascular deformation was essential. The mass-spring model was a common method in real-simulator [16] because of its superiority in computation. Compared with mass-spring model, another widely used method was finite element [17]. To take advantage of both methods, [18][19] proposed to use mass-spring model for simulation but the spring coefficient was determined by finite element method to improve precision. Except for tissue model construction, the catheter and guidewire modeling was studied by Tang et al.[20] who used elastic rod model for guidewire simulation. But this method was only suit for slender body. [21] presented a hybrid modeling approach which used nonlinear elastic Cosserat rods for guidewire shaft and generalized bending model for flexible tip.

Although a lot of efforts have been made in each aspect of VR simulator, there're some defects need be modified. Specifically, the previous VR simulator aimed to replicate the realistic environment such as build up the vessel and catheter models and describe their behaviors. But few researchers have explored how to use the VR simulator assisting the novice to thread catheter safely. Such as provide any visual hints for inexperience surgeons in advance of potential collisions. Besides, little study has investigated the impact of VR and haptic coordination in training system. With above considerations, firstly the directive notification module integrated VR simulator is developed in this paper which is specialized for training system. It can create view from the intra-operative perspective as well as delivering the real-time visual indications when catheter moving. Through such way, the visual instructions in VR are capable to assist the trainees' manipulation of catheter and keep catheter from piercing vessel. Apart from the graphic environment, the magnetorheological (MR) fluid is adopted in to provide the haptic force on trainee's hand. The force sensation is related with visual indications in VR so that it may use to practice hand-eye coordination. To testify the performance of the training system, a preliminary evaluation has been carried out. Meanwhile, a training session is designed for recruited subjects in order to demonstrate that our developed training system is refined to enhance the proficiency level.

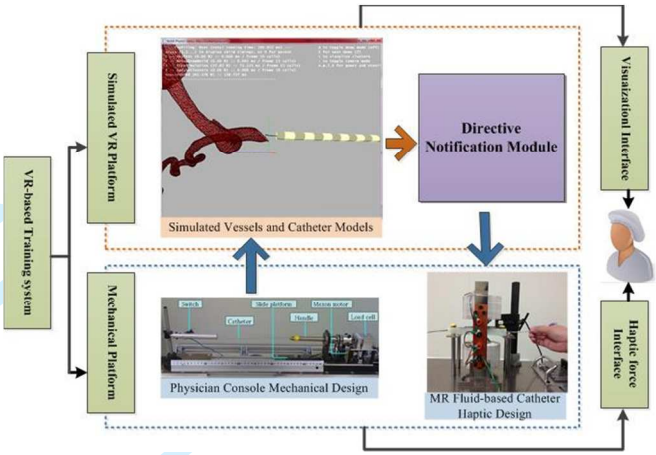

Fig. 2 The framework of VR-based training system

MATERIALS AND METHODS

Our developed training system is made of manipulation mechanical platform and simulated VR platform. In the mechanical platform, the physician console part provides two degrees of catheter motion (translation and rotation), which is designed according to physician's habit of inserting catheter. The catheter movement will be transmitted to VR and drive the virtual catheter motions.

In the VR platform, the vascular geometrical model and physical model have been done by our previous works [22][23]. The virtual catheter can thread in vascular lumen freely. Through transmitted data from the physician console's side, the virtual catheter will update its position. During the catheter inserting procedure, the new developed directive notification module (DNM) will work to provide visual signs for trainees. Meanwhile, it will inform the haptic device to generate the force based on visual signs. This training procedure which utilizes VR simulator and haptic force provider aims to foster the hand-eye coordination and realize safe surgery.

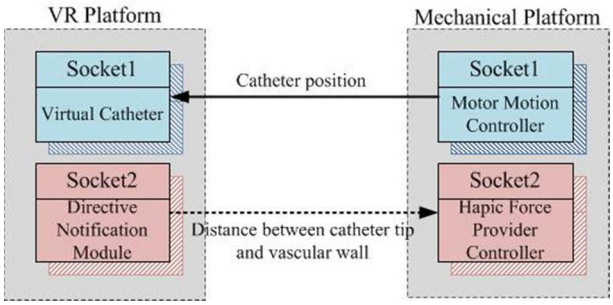

Fig. 3 The diagram of communication

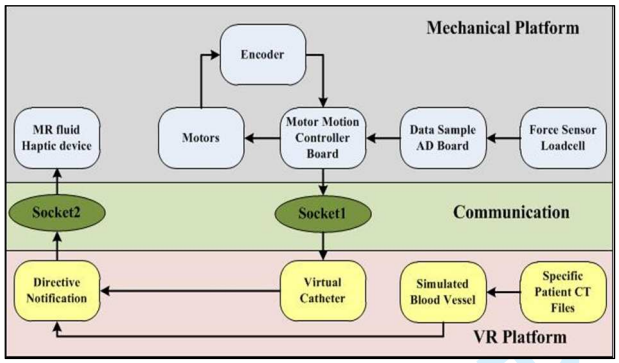

Fig. 4 The detail block diagram of VR-based training system

As the mechanical platform and VR simulator need to communication, we decided to use the socket to transmit data between applications shown in Fig.3. Both the computers responsible for VR simulation and the one supporting the mechanical platform are connected by local area network, it is possible to ignore the time delay because of prompt data updating.

MECHANICAL PLATFORM

A. Physician Console

On the basis of surgeons' experience, the friction between the vascular wall and catheter surface is impossible to avoid when operator insert or extract catheter in vessel. Therefore, the physician console is not only able to facilitate the surgeon manipulating the catheter but also provide the friction resistance in catheter moving. To accomplish such objectives, the implementation is shown in Fig.4.

Assume the trainee moving the catheter forward. The trainee's hand exerted pulling force on catheter and such force is measured by load cell. After that, AD board samples the force which prepares to drive translation slide by motor. But this signal has to be processed by filter because the trainee's hand is possible to tremble during manipulation. Butterworth filter is adopted to process the signal. To guarantee motor moving smoothly, median filter algorithm is used to eliminate the unexpected value resulting from trainee's mistake. Next the processed force signal will be employed to control the motor. The admittance control method, which dynamically determines the motor's output velocity based on input force, is used to regulate the interaction. A spring-mass-damper system is modelled to maintain a dynamic relationship between force and velocity. However, a dynamic extension of stiffness is loosely considered because the mechanical admittance is treated as a dynamic generalization of compliance. Thus based on admittance control, the dynamic relationship is derived as

$$v_{n+1} = \frac{\Delta t}{m} F_n + (1 - \frac{c}{m}\Delta t) v_n \quad (1)$$

In Eq.(1), the parameters v, m, F_n are motor speed, device weight, and processed sample force respectively. Δt is motor acceleration or deceleration time and c is impedance set by user. The catheter's moving speed is determined by novice's applied force F_n and Eq.1. But from the perspective of surgery safety, we set the threshold of motor's output speed so as to restrict the catheter's maximal moving speed. At the same time, the motor's position is detected by encoder and transmitted to VR simulator by socket 1 to drive the virtual catheter make corresponding movement.

B. MR fluid-based Haptic Device

To make the trainee immerse in the VR-based training system, the haptic force device is indispensable since it provides realistic kinesthetic sense to operator. The objective of haptic device in our developed training system is to facilitate the trainee experiencing variable force corresponding to different visual signs delivered by directive notification module in VR. With the development of smart fluid, many haptic devices exploited magnetorheological (MR) fluids or electrorheological (ER) fluids [24]. As reported in [25][26], in rheological state the particles will be arranged in chain-like structure and the haptic sensation is generated by regulating the magnetic field.

In our team designed haptic device, two coils are vertically fixed by supporter to generate the magnetic field and the MR fluids are sealed in slender rectangular container. The catheter moves through the fluids freely as shown in Fig.5. The current amplifier is used to supply the magnetic generator which changes the magnetic intensity. Yin et. al[27] conducted the haptic force calibration experiments to find the relationship between the haptic force and current. By DNM delivered data, the haptic force is regulated closely related to the distance between catheter tip and vascular wall. To be brief, the smaller the distance is the bigger force the device will supply.

VR PLATFORM

As the visual assistance for training system, the VR is capable to simulate the scenario where the virtual catheter moves in the vessels according to physician console side's commands. At the same time, the image information related directive notification module (DNM) is integrated into VR platform. On one hand, the DNM aims to enhance the perception of catheter tip acting area and inform the trainee maneuvering catheter in relatively safe space. On the other hand, the DNM is able to develop the hand-eye coordinate by cooperating with MR fluids based haptic device. The VR platform workflow is displayed in Fig.6. The visualization thread is circulated and contributes to exhibit the latest motion of catheter and vessel.

The DNM is running parallel with visualization thread. The collision detection algorithm Gilbert-Johnson-Keerthi distance (GJK) [28] is implemented in DNM to judge whether there's collision between the catheter tip and

vascular inner wall at every updated time step. If collision happens, the Expanding Polytope Algorithm (EPA) [29] is used to find the penetration depth and vector between two convex shapes. Once the penetration depth and vector are achieved, the minimum distance between the catheter tip and vascular wall $d_{\min}$ can be calculated.

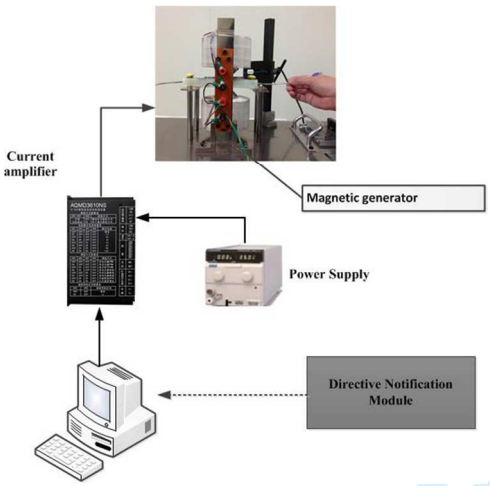

Fig. 5 The detail block diagram of haptic device

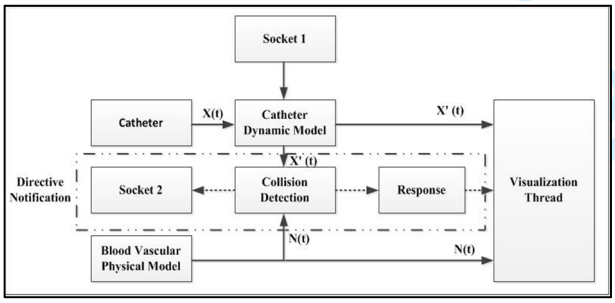

Fig. 6 The schematic of VR platform

On the one hand, the DNM acquired results will be used to exhibit the visual signs for trainee in order to realize the safe robotic maneuvering. Specifically, the novice can pre-determine the safety boundary B_{safety} where the catheter can move freely and quickly. Also the safety boundary can be set into different values considering that the blood vessels in different part of body having different radii. According to the minimal distance, the catheter comes into warning area if $d_{\min}$ is smaller than the safety distance threshold. In this area, the trainee should be alert enough to operate the catheter because the any small miss may result in the collision. If the GJK algorithm finds the collision happens then the catheter enters into the dangerous area. The trainee should be careful in case piercing the vessels. Through this boundary partition, the catheter working area is divided into virtual dynamic access corridors. Meanwhile the different signs are rendered by visualization thread. Particularly, the vector connecting the closest point is labeled in visualization which is an auxiliary reference for trainee to change the manipulation. All above efforts are achieved by directive notification module (DNM) which devotes to make trainee comply with the safety operation criteria by sight.

On the other hand, the collision detection acquired results will be feedback to haptic device which is capable to supply force based on the catheterization situation. Specifically, when the catheter moves in safety area in VR simulator, no force will be provided by haptic device. But when the catheter is moving into the warning area, the trainee can feel the sensation and the applied force will grow in the inverse proportion to the minimal distance between catheter tip and collision point. That means as the catheter tip approaches vascular wall, the sensation will become stronger. Until the collision happens and catheter enters into danger area, the haptic device imposes the maximal resistance on the catheter. The working flow of DNM is shown in Fig.7.

In a word, our designed training system aims to cultivate the novice's ability to avoid dangerous situations both from the visualization and sensation. When the collision is about to happen, the visualization thread releases warning sign and the haptic force applied on catheter. Both efforts from VR system and haptic device prevent the serious damage to vessels.

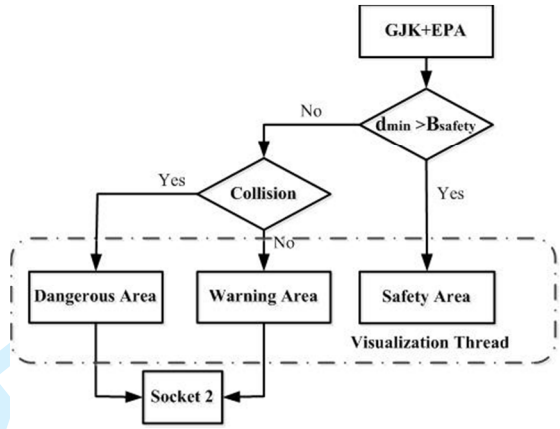

Fig. 7 The flow chart of directive notification module

RESULTS

A. Experimental Setup

As it is shown in Fig.8, one recruited subject was conducting the preliminary evaluation experiment by our developed training system. In the mechanical platform exhibited in Fig.9, the step motor (ASM46AA, Oriental Motor Corp.) and its closed loop driver (ASD13A-A, Oriental Motor Corp.) used in physician console were connected with conversion terminal (CCB-SMC2, CONTEC) which was capable of easily and appropriately connecting a high-speed line driver output motion control board (SMC-4DF-PCI, CONTEC). The motion control board was embedded on PC by physically connector PCI bus and motor control was implemented on this standard PC (Intel 2.67GHz Processor and 3GB RAM). The force measurement was by apparatus load-cell (TU-UJ, TEAC, Japan) and strain amplifier (SA-570ST; TEAC, Japan). The power rate was 5 N with 0.0002N in resolution. The load-cell measurement data were sample by 16 bit AD board (PCI-3165; Interface, Japan) for motor control use. The MR-fluids haptic device used current amplifier (AQMD3610NS; Chengdu AIKONG Electronics, China) to adjust the current supplying for magnetic generator and current amplifier shared the same PC with physician console. The connection between PC and

amplifier was the port-powered RS-232 to RS485 converters (TCC-80; MOXA).

The VR simulator was executed on 64 bit server with four processors (Intel 3.07GHz) and 16GB RAM. The individual images were processed by openGL from the DICOM header of the MRI images to generate the cerebral-vessel structure. And then these volume data were imported to Bullet. The virtual catheter was simulated by a chain of 1 mm diameter and 5mm long cylinders with the angular limited joints. In the DNM, the safety range was set exceeding 2.5mm and warning range was beyond 1mm but less than 2.5mm. As the nodes on vascular surface were enclosed by 1mm edge boxes, the collision was detected less than 1mm. The VR simulator server and PC on mechanical platform were communicated by TCP/IP. In the experiment, one branch of cerebral-vessel with bifurcations and curving turns was picked up for exercise.

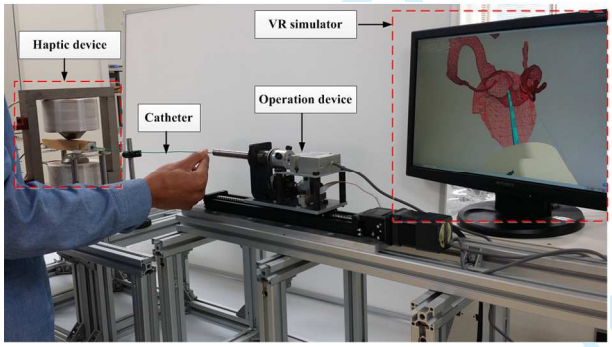

Fig. 8 The training system set-up used in subjects' practice session.

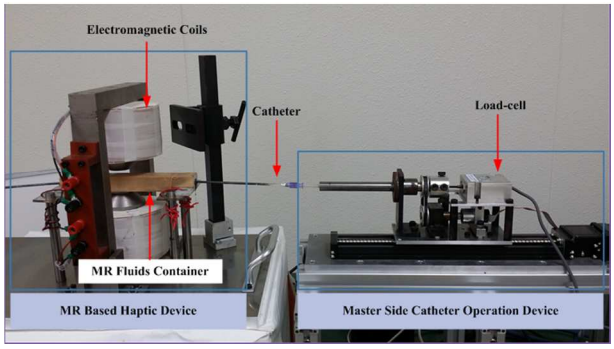

Fig. 9 The mechanical platform

B. *The preliminary evaluation task*

To assist preliminary performance evaluation, four non-medical students (right handed) were invited to join in the excises. Before the training, the subjects were asked to familiarize with the operation of system for about 20 minute and after that they were required to insert the catheter into the appointed location. Each subject repeated the task 5 times for statistical use and there was 5 minute rest between each task. To demonstrate our developed training system facilitating the eye-hand coordination of trainee, the subjects participated in the same task under two different modes. In the mode 1, the VR simulator only displayed the virtual vessel and catheter without providing any visual cues for trainee. According to physician console, the rendered catheter was able to move in the VR system without haptic force. The mode 2 was our proposed training system.

In the experiment, the minimal distance between the catheter tip and vascular wall was stored in files for later statistical analysis. Moreover, the catheter tip's positions were record during the procedure. Besides, six important evaluation metrics were taken into consideration: 1-3) the percentages of catheter tip residence duration in safe area, warning area and danger area. 4) The average of distance in warning area. 5) The average impingement distance in danger area. 6) The task completion time. After the recruited subjects experienced two different modes, they were invited to join in the successive five days practice session. In these periods, subjects were asked to complete the same task under mode 1 and model 2. Each kind of training excises was undergone for five times one day.

C. *Results*

Through the log files, the results were presented as mean value (Mean) and standard deviation (SD) for per trainee. The Fig.10 displays the percentages of catheter tip spent the time at safe area for four subjects on the first training day. It's obvious that the percentages under mode 2 are higher than those of mode 1 and the safe percentages reached 50% with the exception of subject#4. The maximal growth rate is up to 15.94% achieved by the third subject and even the fourth subject has got 10.75% growth rate after one day training session. The dramatic improvement in safety navigation indicates that DNM providing vital visual clues combine with haptic sensation facilitating trainees to avoid the potential collisions.

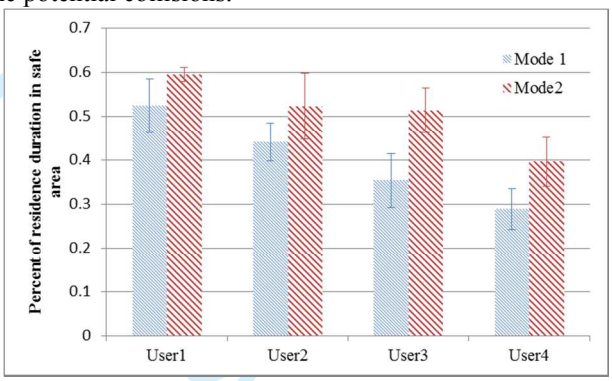

Fig. 10 The percentage of catheter tip residence duration in safe area corresponding to 4 subjects

Table 1 summarized the percentages of catheter tip residence duration in warning and danger areas. The exhibited data reveal that percentages of the catheter tip entering in warning area are greatly reduced maximum to 13.2% by user 4. Such decrease makes big contributions to improve the safety catheterization. But the reductions are not conspicuous on the metrics about percentage of catheter tip residence duration in danger area as well as warning distance. The primary cause is that even though the dangerous sign is released in mode 2 some contacts are hard to avoid because of the vascular tortuosity. Due to visual clues and force sensation, the subjects will handle the catheter with low speed and more cautiously which explains that there's slight decline (maximum 0.08cm by user 1) in impingement.

The task completion time of two modes are compared in

Fig.11. The results show the consistent reduction for all participants in two modes. The maximum reaches 18.8 seconds and minimum is 4.2 seconds. The DNM provided visual marks ensure the catheter passing through the safe area with comparative fast speed. On the contrary, if no any visual hints by DNM the consciousness of each subject may prolong the task completion time.

Apart from VR provided visual field, the haptic device provided resistance also benefits the training performance in dramatic percentages reduction of warning area. Therefore, the combination of tactile sense and visual information helps the subjects to master eye-hand coordination and deal with the probable happening danger situations.

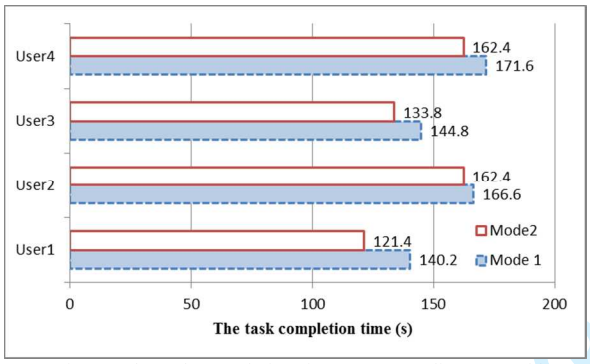

Fig. 11 The task completion time corresponding to 4 subjects

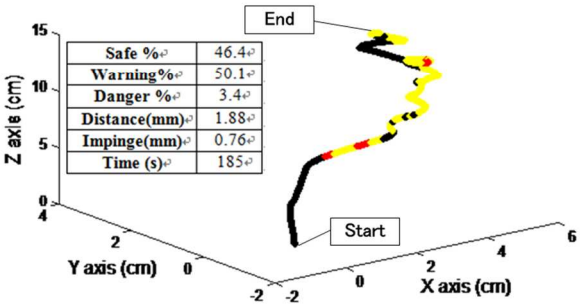

Fig. 12 The Catheter Tip Trajectory in Mode 1

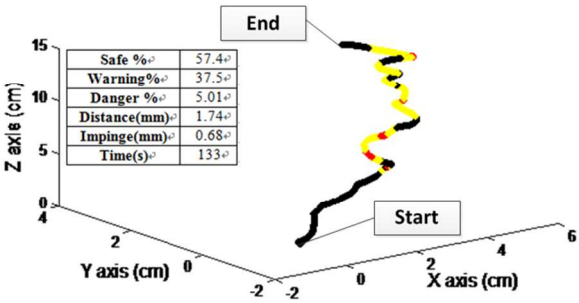

Fig. 13 The Catheter Tip Trajectory in Mode 2

Considering from the individual subject, figure 12 and 13 display the catheter tip trajectories in mode 1 and 2. These data were generated by the subject#1 when he first operated the training system on the first day. The black, yellow and red dots signify the catheter tip tracks in safe, warning and danger areas respectively. The lateral form lists the specific performance metrics of subject#1. Apparently, the percentage of catheter tip in safe area grows 11.0% from mode 1 to mode2. Just as the two figures exhibited, the warning segments of mode 1 are less than that of mode 2 because parts of the track are mended under the mode 2. The visual and haptic guidance benefits slightly the reductions in metrics of distance in warning area and impingement as well. The outstanding progress is made by task completion time which decreases for 52 seconds.

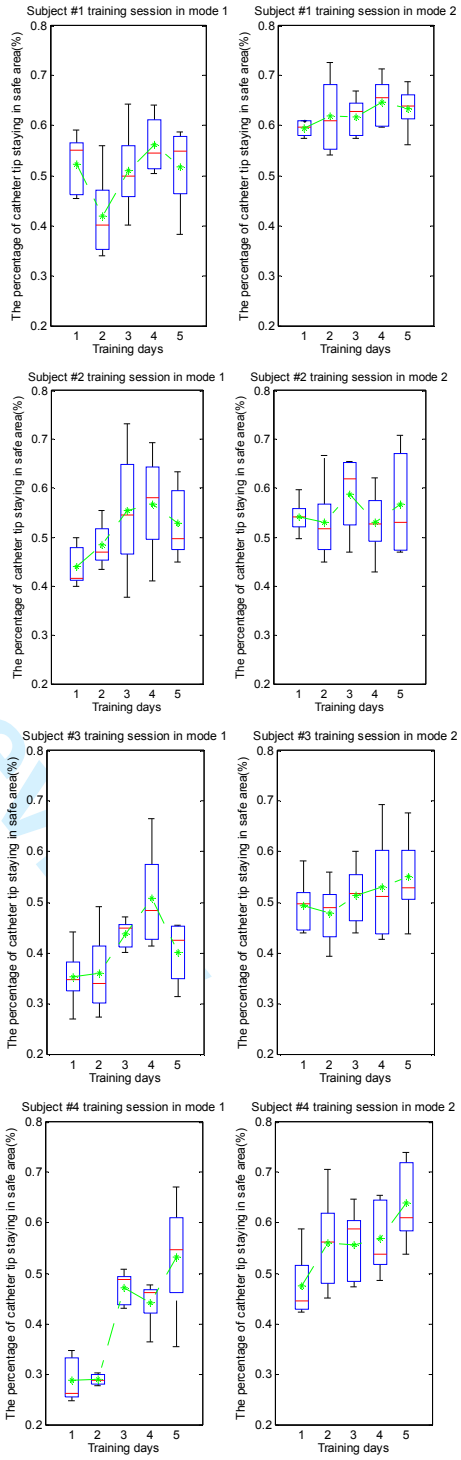

Fig.14 The skill improvement comparisons of four subjects in five days training session

To ensure there is a great difference between the two modes in terms of the percentage of catheter tip residence duration in safe area, the analysis of variance (ANOVA) has been carried out on each subject. The calculated results show that there is a significant difference ($p<0.05$) between two modes.

Figure 14 box plot organized four subjects' percentages of catheter tip staying in safe area in continuous five days training trails. Apparently, the time of catheter tip staying in safe area in mode 2 is longer than that of mode 1. Besides, the relatively smooth growth rate in right row indicates the subjects' skills achieved in mode 2 are more stable.

The Table 2 presented the final performance of four subjects. Compared with initial training results, the notable reduction of task completion time is achieved by the training session and especially the SD in mode 2 is comparatively smaller than that in mode 1. Smaller task completion time variances indicate that the trainee's catheter operation skills are relatively stable in mode 2. Similarly, the same trend can also be found in metrics like the percentage of catheter tip in warning area and the impinge distance. These two metrics decreases imply the operation safety is enhanced.

DISCUSSION

To provide both visual information and force sensation for inexperience surgeons in practice, this paper developed a VR-based training system shown in Fig.2. On the one hand, the VR simulator renders the operation in the surgeon's view and furthermore the newly added DNM can inform the trainee using specific visual signs. These signs are released based on the real-time updated distances between the catheter tip and vascular wall. Moreover, the intra-vascular lumens are divided into three spaces according to user's requirements. The safe area allows catheter passing through quickly and the warning area alerts trainee to slow down the catheter moving speed. When the collision happens, the catheter enters into danger area. Based on evaluation results shown in Fig.11, the signs in safe area ensure the trainee to accelerate the catheter moving speed resulting in the task completion time reduction. Meanwhile the visual cues in warning area and danger area help the trainee avoid the possible collisions referring to Table 2. On the other hand, the haptic force device cooperates with DNM providing the tactile sensation to trainees when the catheter enters in the warning or dangerous areas. As the catheter tip approaches the vascular wall closer, the bigger haptic force will be exerted on the catheter. Applied resistance on the trainee's hand combined with the visual information benefits the subjects' technical skills improvement. Such progress totally agrees with the results reported in [30]

To weigh whether our developed training system is suitable for learning skills, 4 subjects are invited to participate the successive five days training session. The ultimate results show that our designed training system helps trainee achieve better performances than virtual VR training system. But it is better that the technical skills proficiency level is measured by experts and such grading work will be discussed in the future.

CONCLUSION

In this paper, a VR-based training system is realized which not only provides visualization but also haptic force for trainee. The visualization in VR simulator displays the virtual catheter moving procedure in the vessels as well as various visual signs. Such signs assure security in safe area and remind the possible collisions in warning area. Meanwhile to foster the hand-eye coordination, the haptic force device will apply resistance on catheter when it moving into warning or danger areas. To do the preliminary evaluation, we have analyzed six metrics to weigh the surgery safety and task completion time. From the catheter safe navigation, the maximal growth rate about the percent of catheter tip residence duration in safe area reaches 15.94% which results from the percent reductions of the warning and dangerous areas. The average task completion time decrease 18.8 seconds in maximum from mode 1 to mode 2. Above results demonstrate that our developed training system is able to enhance safety and cut down the time dramatically.

ACKNOWLEDGEMENT

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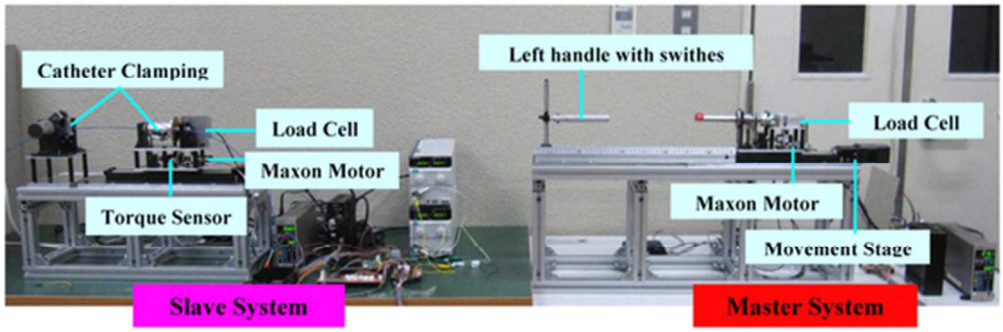
Table 1 Summary of four subjects' performance on the first training day

Subject#		#1		#2		#3		#4	
Mode		1	2	1	2	1	2	1	2
Warning area %	Mean	40.5	29.8	36.6	31.6	41.1	33.4	56.6	43.4
	SD	9.1	4.7	7.1	4.4	9.9	3.8	5.4	10.4
Danger area %	Mean	9.1	10.6	19.3	16.4	23.6	15.3	14.5	16.9
	SD	4.2	3.3	3.6	3.8	10.7	5.5	6.7	7.4
Warning distance (mm)	Mean	1.84	1.77	1.77	1.69	1.75	1.65	1.73	1.71
	SD	0.06	0.09	0.06	0.08	0.12	0.13	0.08	0.12
Impinge Distance (mm)	Mean	0.74	0.66	0.69	0.64	0.69	0.68	0.73	0.72
	SD	0.04	0.03	0.04	0.06	0.06	0.11	0.09	0.05

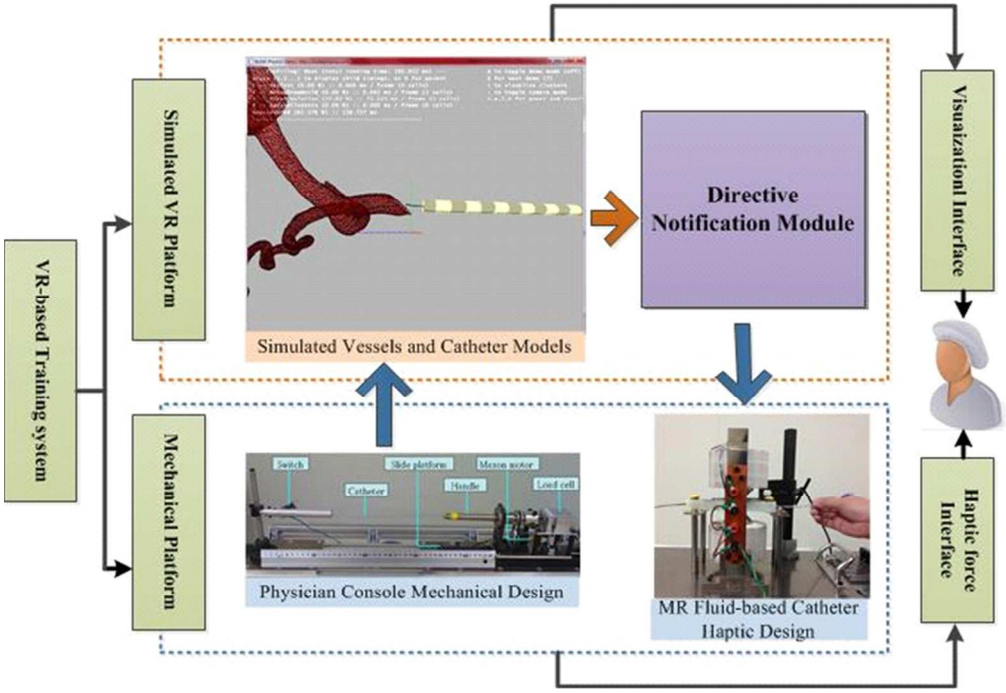
Table 2 The final achieved results of four subjects

The Fifth Day		Task completion time (s)		Percent of residence duration in safe area (%)		Percent of residence duration in warning area (%)		Percent of residence duration in danger area (%)		Average distance in warning area (mm)		Average impingement in danger area (mm)	
Mode 1	Subject#	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
	1	84.2	12.5	51.8	8.4	35.8	7.8	12.5	2.1	1.64	0.10	0.71	0.05
	2	155.4	10.2	50.9	9.7	42.0	10.4	7.0	1.3	1.71	0.08	0.68	0.10
	3	67.4	4.8	40.1	6.2	41.4	4.0	18.4	6.3	1.65	0.15	0.64	0.05
	4	111	16.5	53.2	11.8	36.2	9.3	10.6	4.9	1.70	0.12	0.71	0.04
Mode 2	Subject#	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
	1	92.4	4.6	63.5	4.6	28.3	4.5	8.1	2.4	1.74	0.07	0.67	0.04
	2	110.4	4.9	56.8	11.0	35.4	13.1	7.7	3.1	1.73	0.08	0.65	0.06
	3	105.4	9.1	55.0	8.7	39.5	7.4	5.5	2.4	1.81	0.09	0.66	0.11
	4	113.8	13.3	64.5	8.4	28.5	9.7	7.4	2.6	1.76	0.04	0.65	0.04



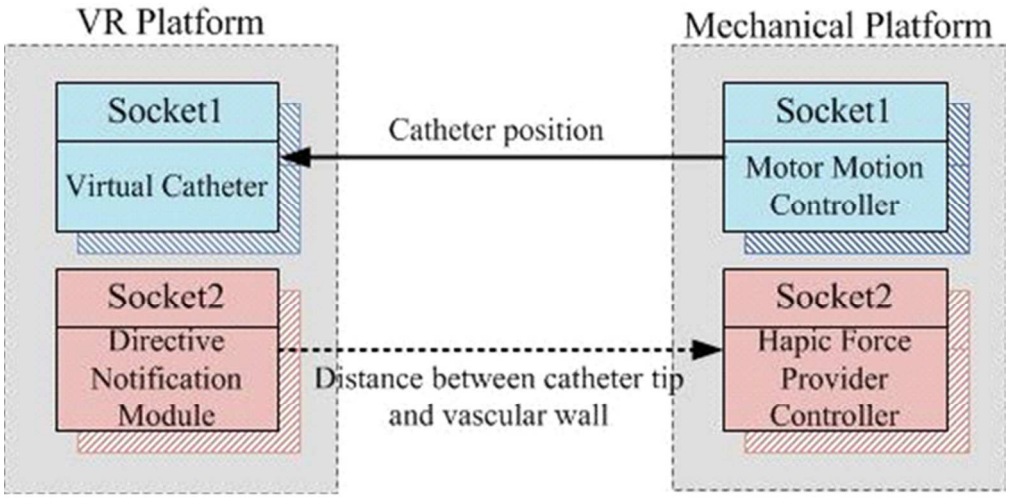
Master-slave Catheterization System

49x16mm (300 x 300 DPI)



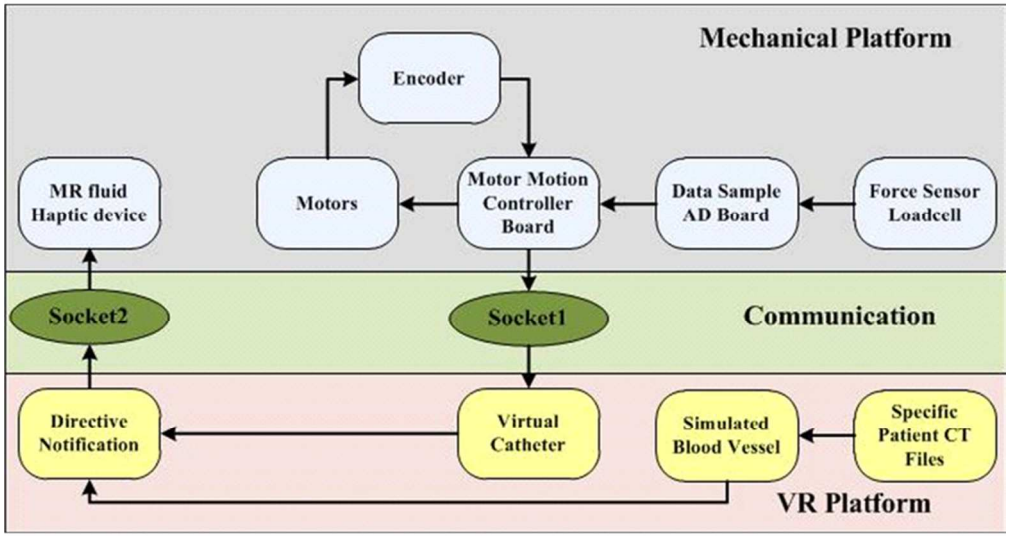
The framework of VR-based training system

101x70mm (300 x 300 DPI)



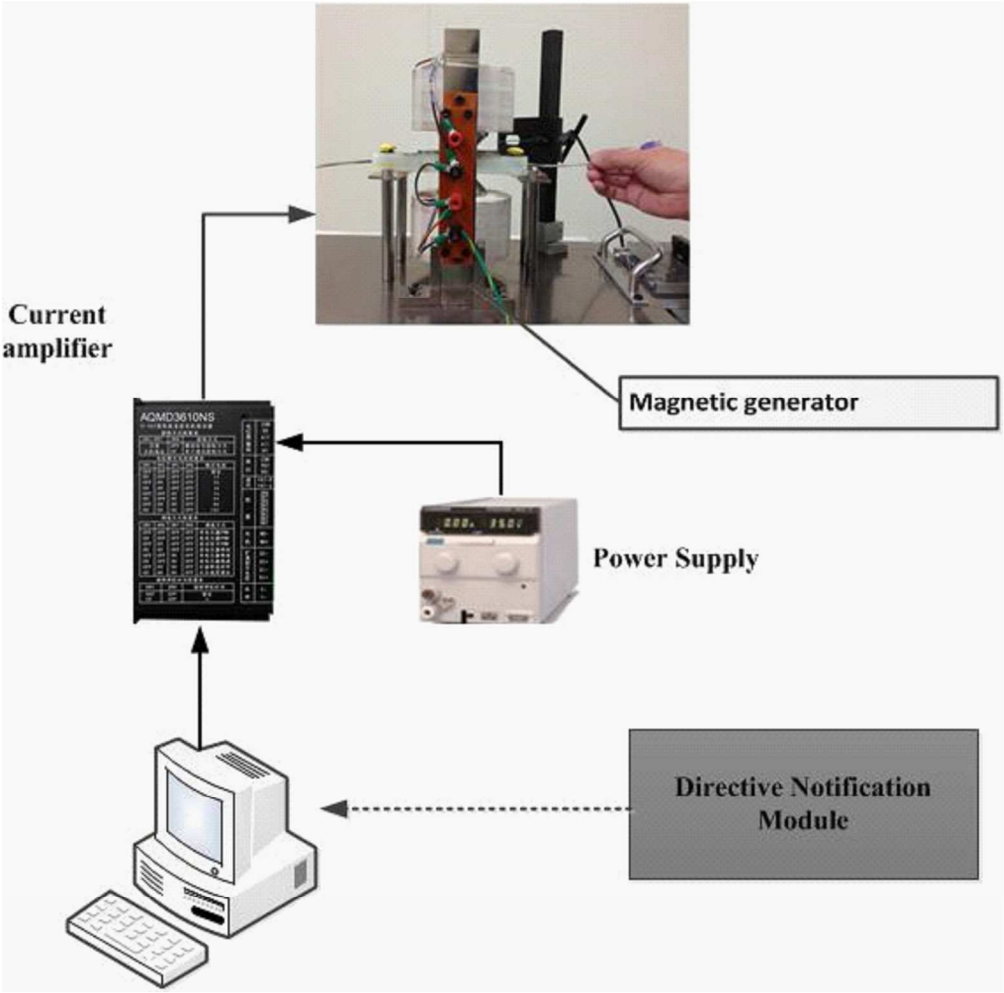
The diagram of communication

67x33mm (300 x 300 DPI)



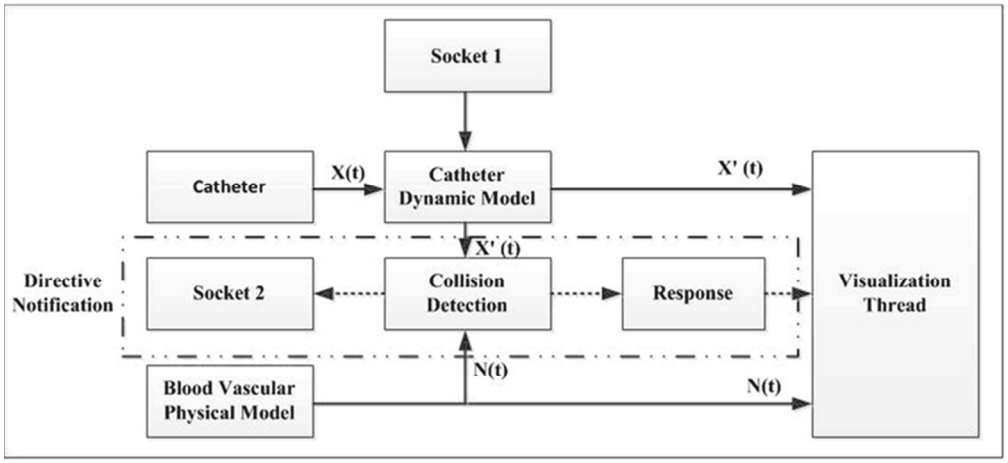
The detail block diagram of VR-based training system

77x41mm (300 x 300 DPI)



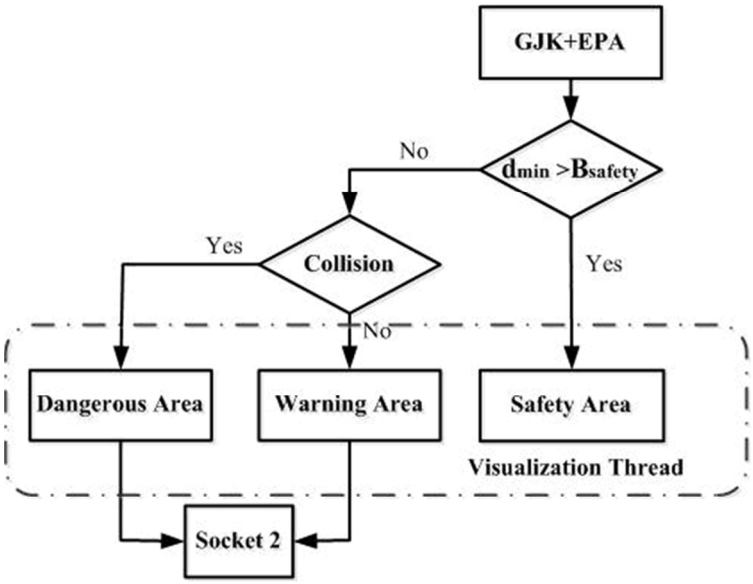
The detail block diagram of haptic device

146x145mm (600 x 600 DPI)



The schematic of VR platform

69x33mm (300 x 300 DPI)



The flow chart of directive notification module

107x65mm (300 x 300 DPI)

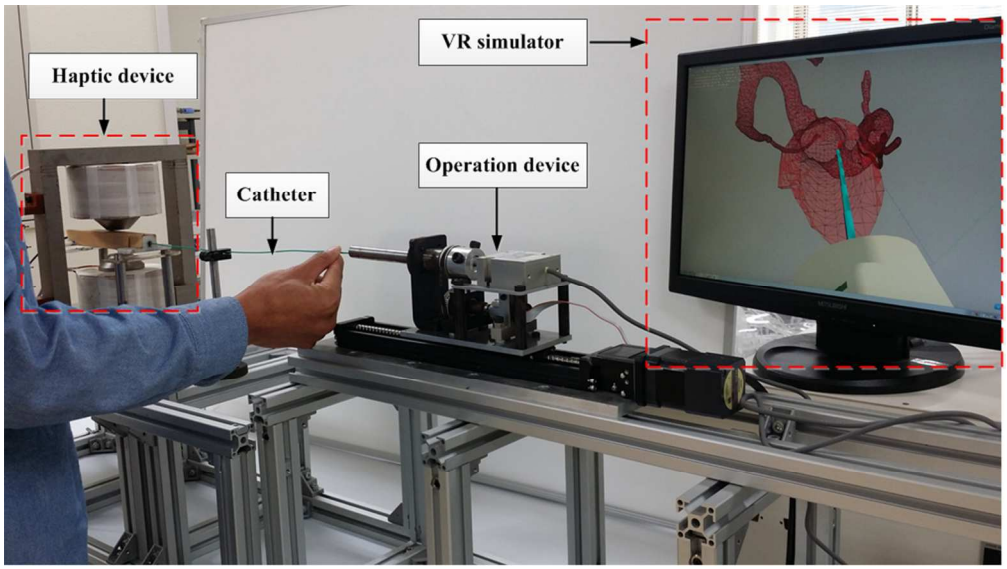


Fig. 8 The training system set-up used in subjects' practice session

267x150mm (96 x 96 DPI)

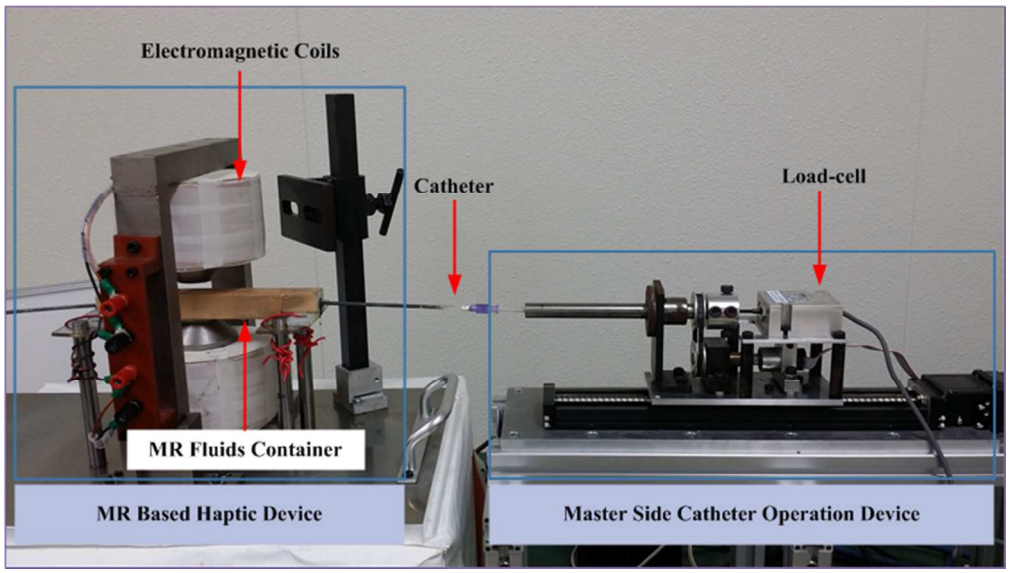
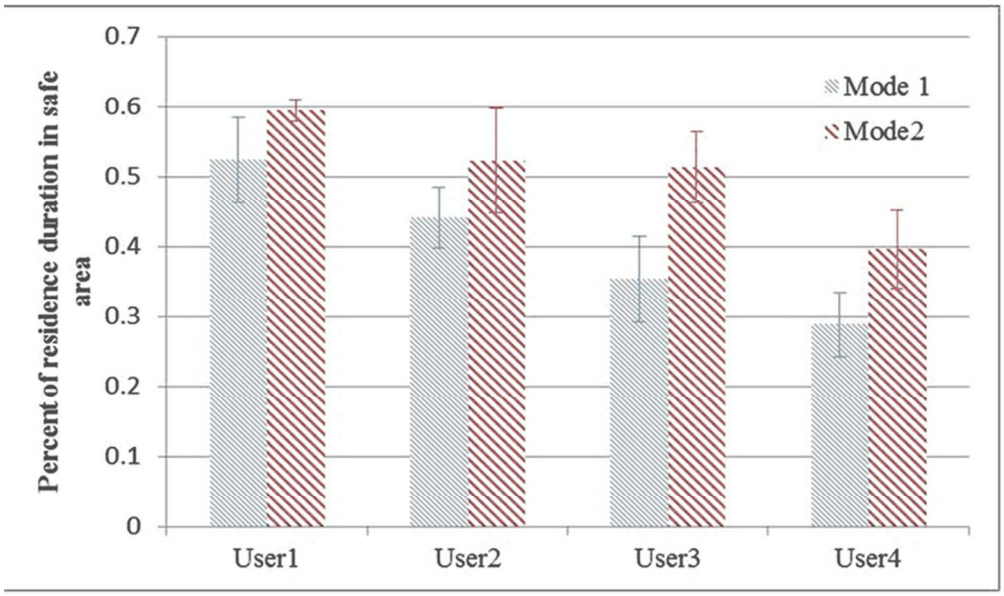


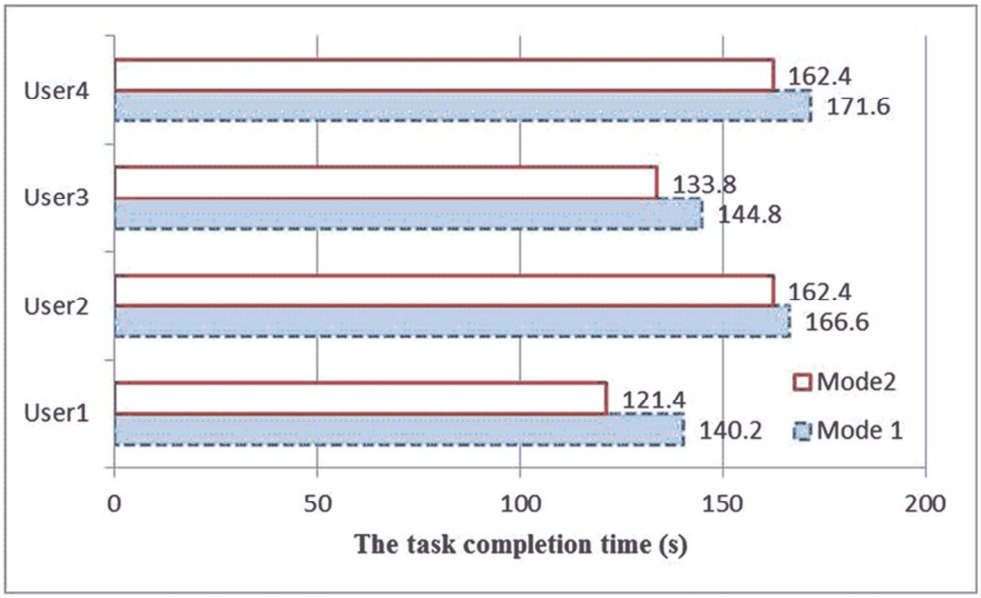
Fig. 9 The mechanical platform

200x112mm (96 x 96 DPI)



The percentage of catheter tip residence duration in safe area corresponding to 4 subjects

71x41mm (300 x 300 DPI)



The task completion time corresponding to 4 subjects

71x42mm (300 x 300 DPI)

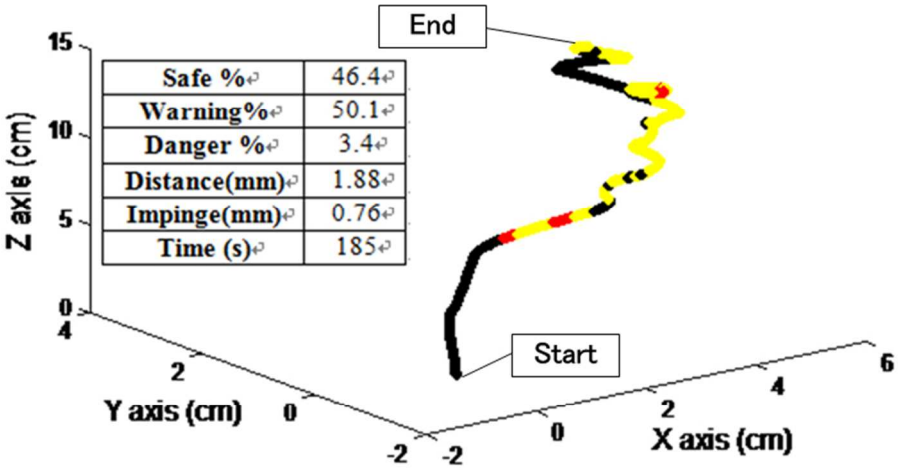


Fig. 12 The Catheter Tip Trajectory in Mode 1

215x127mm (96 x 96 DPI)

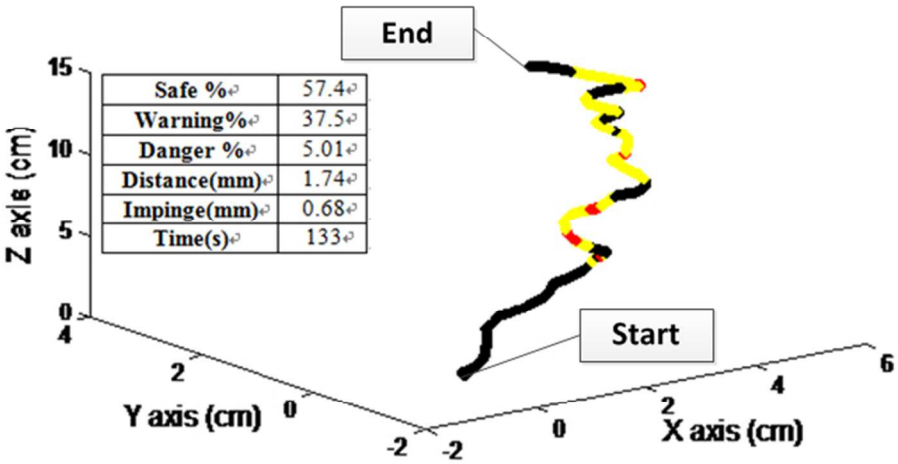


Fig. 13 The Catheter Tip Trajectory in Mode 2

188x103mm (96 x 96 DPI)

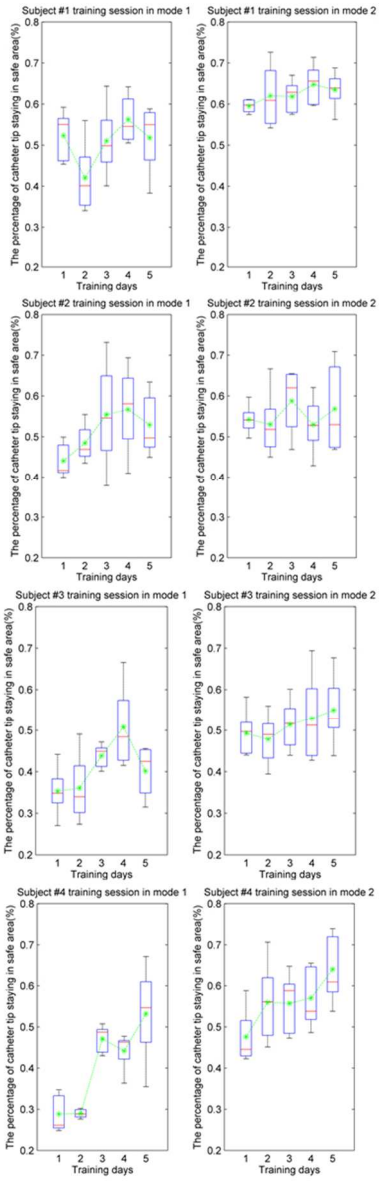


Fig.14 The skill improvement comparisons of four subjects in five days training session

115x321mm (96 x 96 DPI)