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ORIGINAL ARTICLES

A novel virtual reality simulation training system with haptic feedback for improving lateral ventricle puncture skill

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Abstract
The lateral ventricle puncture is an important step of external ventricular drain. It is one of the most basic but challenging skills that must be mastered by physicians. For improving the lateral ventricle puncture skill, a novel virtual reality simulation training system equipped with haptic feedback was developed in this paper. A series of experiments and questionnaires were conducted to evaluate the fidelity of simulated haptic force and the effectiveness of this system. Both the forces generated by the haptic device during the virtual puncture and that generated during puncturing on a pig brain were obtained and compared. The results indicate that these two forces have the similar varying tendency under different puncturing conditions. In addition, two groups of neurosurgical interns named A (trained without this system) and B (trained with this system) were selected to verify the effectiveness of this system. The operation metrics, including operative dictation, operation time, positioning of Kocher's point, times of repeated punctures, and the punctured position on lateral ventricle, were assessed by the chief physician for both groups. The results show that group B achieved higher scores than group A in all operation metrics except only operative dictation ($P=0.001$). This indicates that the proposed virtual training system is an effective aid in training neurosurgery physicians' lateral ventricle puncture skill.

Keywords Lateral ventricle puncture · Virtual reality · Surgery simulation · Training system · Haptic feedback

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1 Introduction

The lateral ventricle is a vital organ located deep in the brain. Caused by injury or disease, excessive cerebrospinal fluid in the lateral ventricle may lead to an increase in intracranial pressure and therefore cause headache, nausea, vomiting, dizziness, and visual disturbances (Osztie et al. 2009). To ease the intracranial pressure, external ventricular drain (EVD) is often used for lateral ventricular drainage (Bender et al. 2019; Bow et al. 2019), which is one of the earliest skills learned by a junior neurosurgery physician. However, it is not easy to successfully complete the operation with bare hands (Huyette et al. 2008), and a failed puncture can lead to ventricle haemorrhages or infection (Cuesta et al. 2017; Zhong et al. 2018). As one of the most essential steps in EVD, deciding the puncture angle, is always a tricky step due to the variety of human brain (Zhong et al. 2018). Nowadays, to master EVD, most neurosurgery trainees are still trained by traditional teaching methods, including multimedia, autopsy, and surgery observation, which are more or less limited in delivering comprehensive understanding of this technique (Henn et al. 2002; Choi et al. 2004; Ryan et al. 2015). Therefore, it is necessary to find a better way for lateral ventricle puncture training.

With the medical education developing, a novel surgery training system by means of virtual reality (VR) technology has been increasingly used for its unique experience of immersion. It can put the surgical procedures and anatomical knowledge into a virtual environment. Virtual reality simulators can provide a highly immersive environment and give trainees extra freedom for operating, thus to reduce the training cycle and improve the trainees' operational skills effectively (Triantafyllou 2014; Morone et al. 2017; Perin et al. 2018; Wynn et al. 2018; Bow et al. 2019; Li et al. 2019). A commercialized virtual reality simulator called ImmersiveTouch has been used to simulate EVD placement or ventriculostomy (Michael et al. 2007; Perin et al. 2018; Rangwala et al. 2018), and there has been an EVD simulator developed on mobile devices, allowing trainees to practice EVD placement in a more flexible manner (Morone et al. 2017).

In this paper, we developed a novel virtual system specialized in training lateral ventricle puncture skill. The function modules are designed to recreated the fundamental steps in an EVD procedure: the CT reading training function aims to improve the students' ability to spatialize the cranial structures from CT scans, thus to better plan the operations; the haptic feedback function provides a realistic experience for trainees, granting them reliable muscle memories before operating on real patients. Moreover, the simulated operations can be stored in a database – the trainees can replay training procedures to find out where to improve and learn from others' courses of actions.

2 Virtual system development

The system establishes an immersive environment with virtual reality technology. In order to provide a more realistic operating environment and enhance the immersion of the trainees' experience, 3DS MAX (Autodesk Inc., America) was used to build virtual models related to the operation, including the operating room, shadowless lights, surgical instruments, etc. The human head models, including the scalp, skull, brain, vessels, and lateral ventricle, were reconstructed using Mimics (Materialise Inc., Belgium), as shown in Fig. 1. ThinkPHP framework was used for the database. The HTC VIVE PRO (HTC Inc., China) controllers and a Geomagic Touch X (SensAble Technologis Inc., America) haptic feedback device were used as tools to interact with the system, as shown in Fig. 2.

This system, based on virtual reality technology and consisted of pre-operative learning module, surgical training module, and data management module, was developed for training the lateral ventricle puncture skills. The trainees can study the spatial structure of the human brain and train the CT reading ability in the pre-operative learning module, and train the puncturing operation in the surgical training module. After each puncturing finishes, the trainees can review operation information from the database, as shown in Fig. 3.

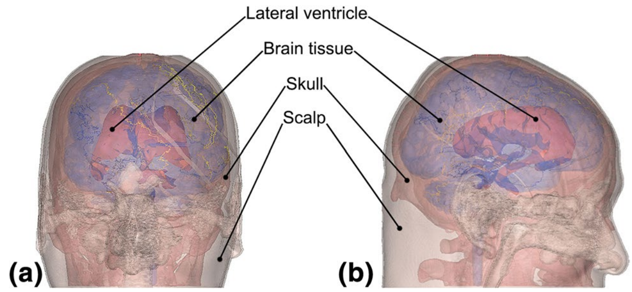

Fig. 1 The reconstructed 3D virtual model of the brain

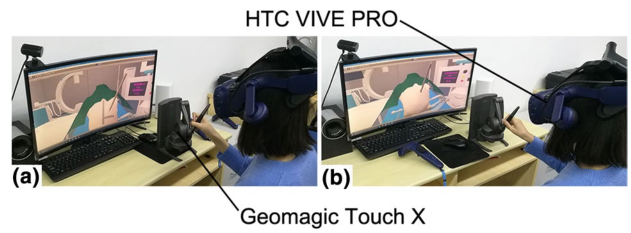

Fig. 2 Interact with the virtual environment by HTC VIVE PRO and Geomagic Touch X: **a** marking Kocher's point, **b** puncturing

2.1 Pre-operative learning module of virtual system

The pre-operative learning module includes two functions: brain anatomy and CT reading training. A head model, including scalp, skull, brain, cerebral artery, and lateral ventricle, was used for brain anatomy observation. In the CT reading training, different lateral ventricle models with corresponding CT images were divided into six groups and numbered, respectively, based on the lateral ventricle ratio. Fronto-occipital horn ratio (Thomale et al. 2018) is used to calculate the lateral ventricle ratio in this paper, as

$$R = \frac{L_f + L_o}{2 * L_b} \quad (1)$$

where R is the lateral ventricle ratio, L_f is the widest length of the forehead, L_o is the widest length of the occipital horn, and L_b is the widest length of the brain tissue, as shown in Fig. 4.

In a CT reading training session, the system displays one CT image and multiple lateral ventricle models: the models can be moved and rotated through the controllers, allowing trainees to observe from different angles. The trainees

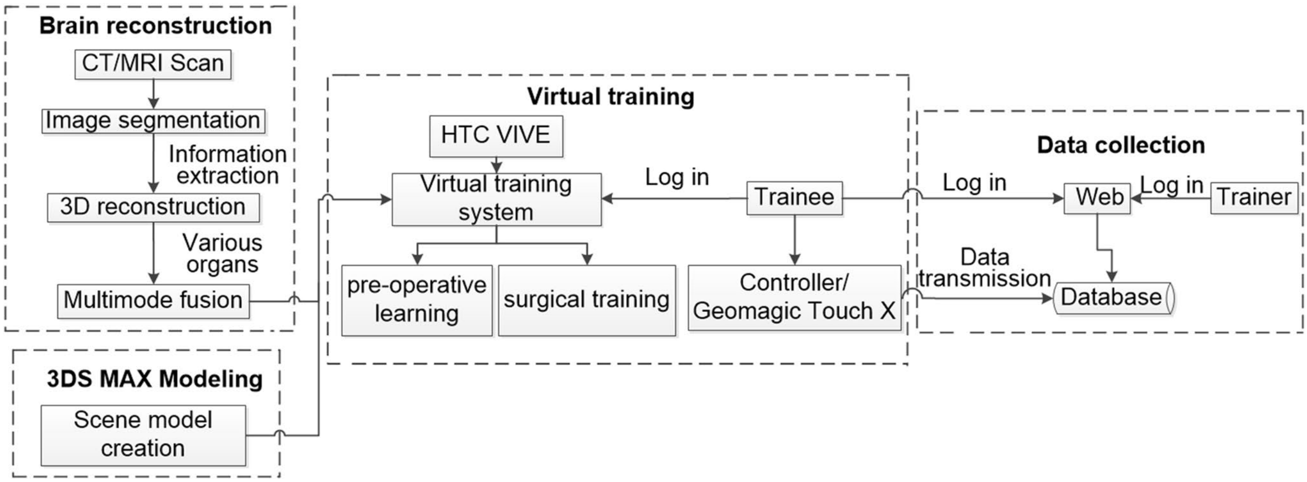

Fig. 3 The schematic diagram of the virtual system

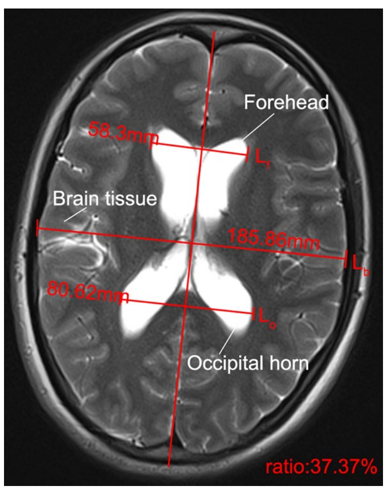

Fig. 4 The lateral ventricle ratio

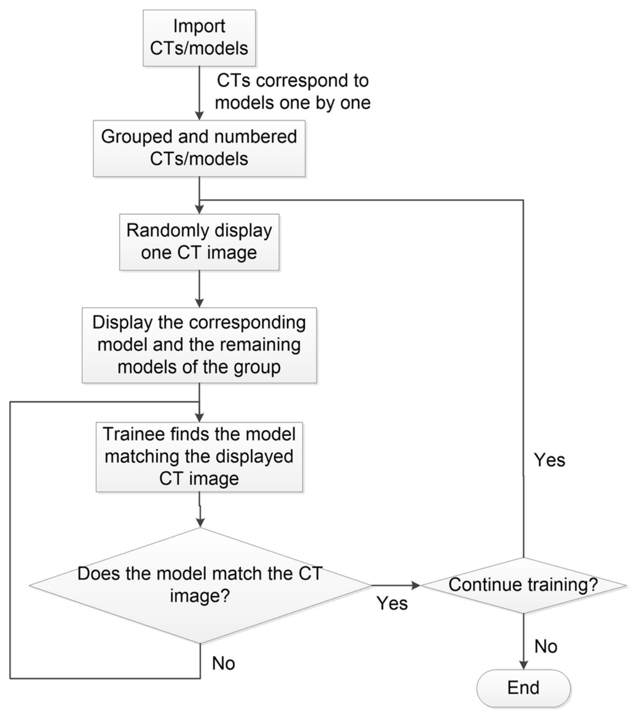

Fig. 5 CT reading training flowchart

are required to find the lateral ventricle model matching the displayed CT image. As shown in Figs. 5 and 6, the menu buttons are used to select functions and training levels. The option buttons are used to choose the correct answer.

After the CT reading training, the trainee can click the "Test" button to verify the training effects. The system displays a group of CTs and lateral ventricle models in a random order for the trainee to make matches. Then, the system calculates the rate of correct match and records it in the database, as shown in Fig. 7.

2.2 Surgical training module of virtual system

This module consists of three parts, as shown in Fig. 8. On the left is the UI interaction area, which allows trainees to select case and operation instruments, or compare operation results with the reference procedure. The reference procedure is represented as a red path of catheter performed by the chief physician in advance, which can be regarded as the optimum approach for the specific case. In the middle of the scene is the operation area, in which placed a head model and surgical instruments for the trainees to simulate the operation. Two essential steps in the operation are retained: selecting the position of Kocher's point and puncturing the lateral ventricle, while other non-essential steps are simplified. On the right side of the scene is the information display area, which displays the position information of Kocher's

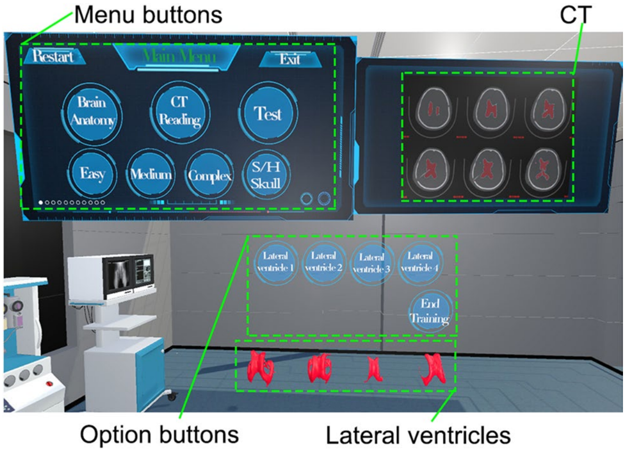

Fig. 6 CT reading training interface

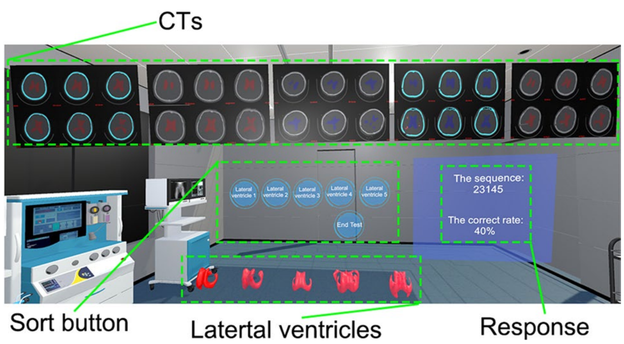

Fig. 7 CT sorting test interface

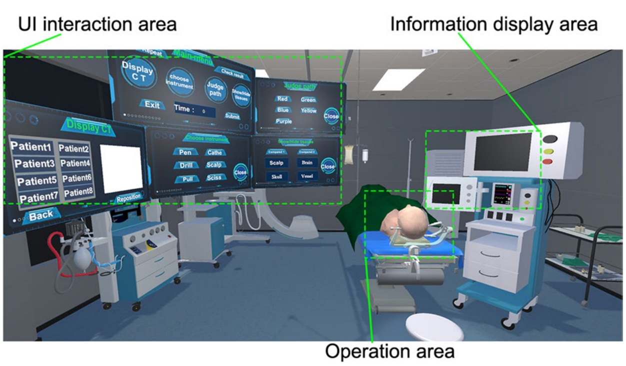

Fig. 8 The surgical training module interface

point, the angle deviation of the puncture, the depth and the final puncture results in real time.

2.2.1 Quantified operation

The current conventional puncture method is to locate the Kocher's point, drill a small hole on the skull at the Kocher's point, and puncture with the depth of about 4–6 cm towards

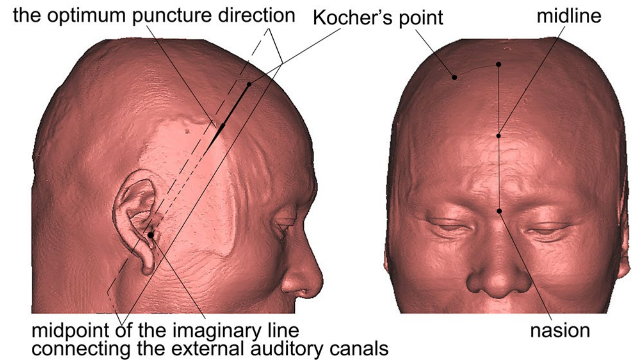

Fig. 9 Ideal puncture direction and the Kocher's point

the midpoint of the imaginary line connecting the external auditory canals (Xu et al. 2019). Usually, the Kocher's point is selected at about 10 cm upward from the nasion and 2–3 cm lateral to the midline of the head, but they could vary with different lateral ventricle's ratios. As shown in Fig. 9a, the parallelogram is the plane where the Kocher's point and external auditory canal connection lies, and the arrow that points to the left is the direction towards the midpoint of the imaginary line connecting the external auditory canals. In the simulation, a trainee can determine the position of Kocher's point by reading CTs and mark it on the scalp using the virtual pen, and then, the animation of drilling procedure is displayed. After that, through the haptic controllers, the trainees can perform the puncturing using the virtual catheter. The procedures are shown in Fig. 10.

The location information of Kocher's point selected by trainees is specified by two arc lengths: the arc length posterior from the nasion, and the arc length lateral to the midline (which starts from the nasion and extends to the top of the head), as shown in Fig. 9b. The deviation angle between the optimum puncture direction and trainees' puncture direction is calculated and recorded, as well as puncture depth, which is the distance between the selected Kocher's point and the final position of catheter tip.

2.2.2 Haptic feedback

In the procedures of selecting the position of Kocher's point and puncturing, Geomagic Touch X is used to provide the necessary haptic feedback, that is, the force of the pen tip touching the scalp and the force of the puncture catheter moving in the brain tissue. The Unity plugin is used to connect Geomagic Touch X.

The haptic force provided by the haptic device is divided into three stages: the first stage is when the catheter touches and punctures through the exterior of brain tissue; the second stage is when the catheter moves in the brain tissue, and the third stage is when the catheter tip punctures through the

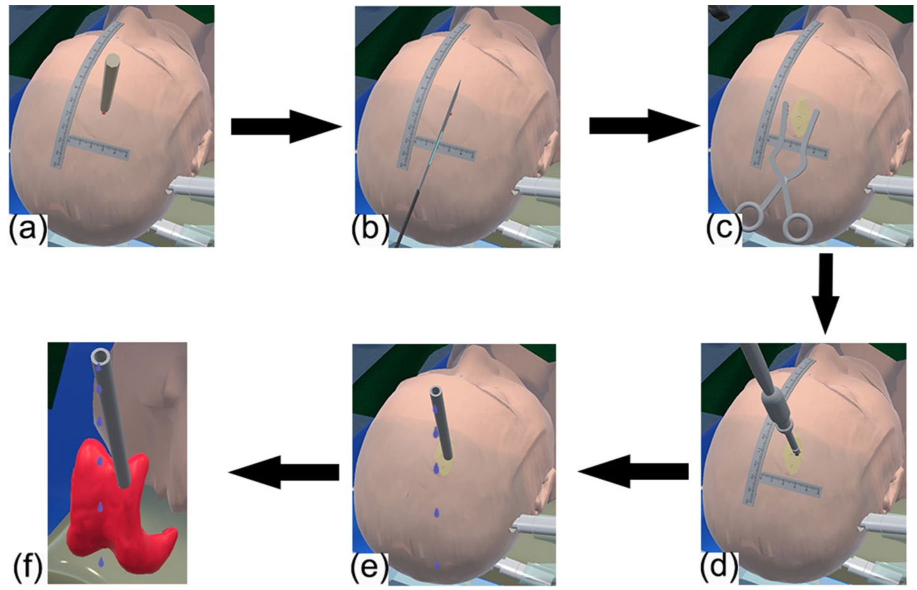

Fig. 10 Lateral ventricle puncture procedure: **a** marking the Kocher's point, **b** cutting the scalp, **c** spreading scalp, **d** drilling a hole in skull, **e** puncturing, **f** hiding other organs to see the puncture position on lateral ventricle

lateral ventricle. Equation (2) is used for calculating the force in the first stage, and Eq. (3) is used for the two latter stages, as

$$F_1 = -\mathrm{k}_{s_1} * (\Delta \mathrm{x}) - \mathrm{k}_{d_1} * V \tag{2}$$

$$\mathrm{F}_2 = -KV - k_{s_2} * (\Delta \mathrm{x}) - \mathrm{k}_{d_2} * V \tag{3}$$

where F_1 is the force when virtual puncture catheter enters the brain tissue, k_{s_1} and k_{d_1} are the spring coefficient and damping coefficient of brain tissue; F_2 is the force when the virtual puncture catheter moves in the brain tissue and breaks through the lateral ventricle, K is the gain of brain tissue, k_{s_2} and k_{d_2} are the spring coefficient and damping coefficient of lateral ventricle, V is the speed of puncture catheter.

2.3 Data management module of virtual system

In order to provide the trainees and trainers with the puncturing information, this study uses Apache as the Web server, and the PHP network scripting language to establish the connection between the database MySQL and the Apache server. Based on the browser/server (B/S) architecture, users can access the server-side web application and view the information through a browser.

Figure 11 shows the framework of database. MySQL was used to create user information tables and puncturing information tables, and the ThinkPHP-SVC framework was used to create front-end and back-end web pages. Before the first training, the trainee needs to register a new account. The logs of simulated operation are stored and linked to the account for further review. When the trainee logs in the system, Unity submits the username and password to the external interface of the background management platform for matching verification. Trainee can enter the system after successful verification, and system submits the training information to database after training. The database records the training information of each training, including the case number, the coordinates of selected Kocher's point,

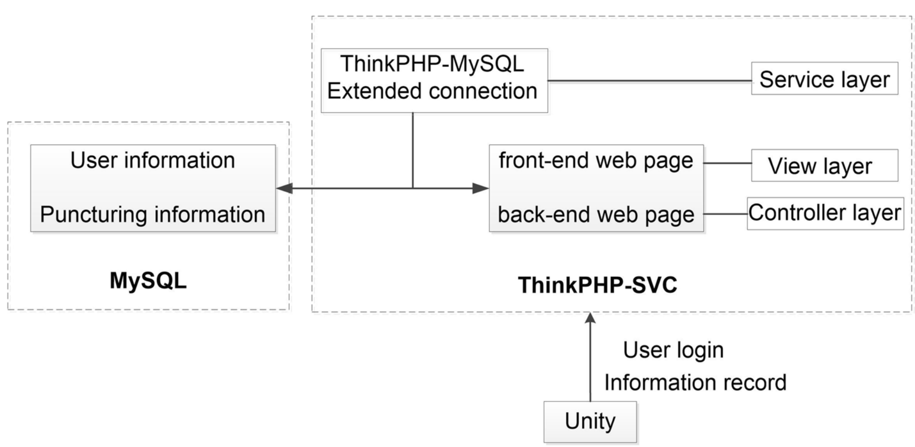

Fig. 11 The framework of database

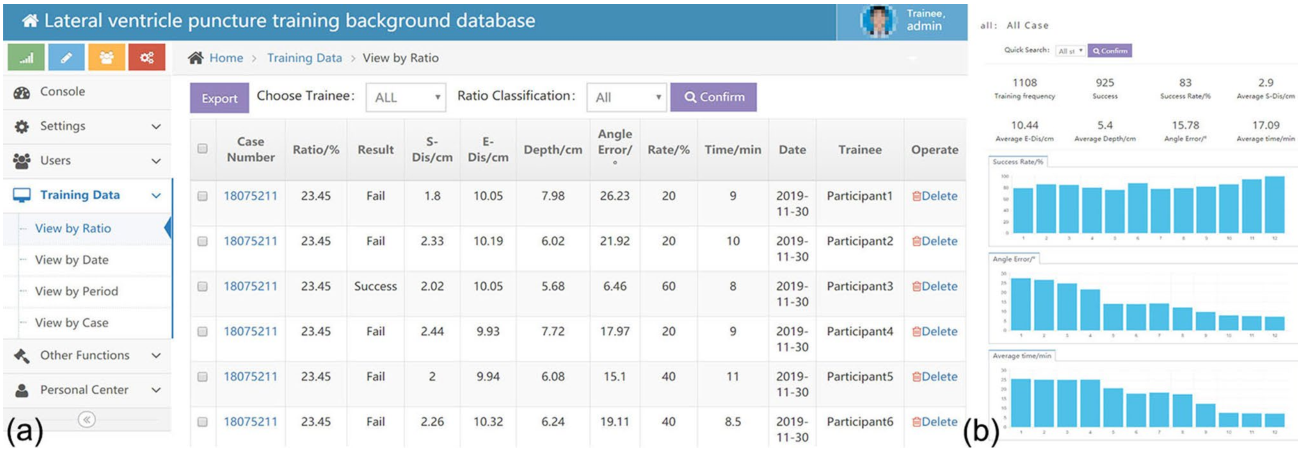

Fig. 12 The user interface of database: **a** puncturing information; **b** information statistics

the puncture depth, the angle deviation, the CT reading test results, the puncture result (success/failure), and the operation time. As shown in Fig. 12a, *S-Dis* is the distance lateral to midline, *E-Dis* is the distance posterior from the nasion, and *Rate* is the CT reading test results. Figure 12b shows the information displayed in bar charts for viewing the training progress.

3 Experimental procedure

3.1 Validation of haptic device

During the puncturing procedure of an EVD operation, neurosurgeons can only rely on their bare hands and experiences, and therefore, it is important to provide trainees with the opportunity to experience the haptic sensation before conducting on real patients. To evaluate the fidelity of the haptic device in the system, the puncturing procedure was conducted on fresh pig brains bought from a local livestock market, and the puncture forces are collected. The force values and force variation tendencies are compared between the collected results and the haptic device.

Figure 13 shows the haptic force was collected in the virtual system, the virtual catheter corresponds to the handle, puncturing the virtual brain in the virtual scene. The spiral frame was used to control the movement of the handle. A digital push–pull gauge was used to gather the force generated by puncturing the pig brains, and the curve was compared with the curve generated by the haptic device during the virtual puncture process, as shown in Fig. 14.

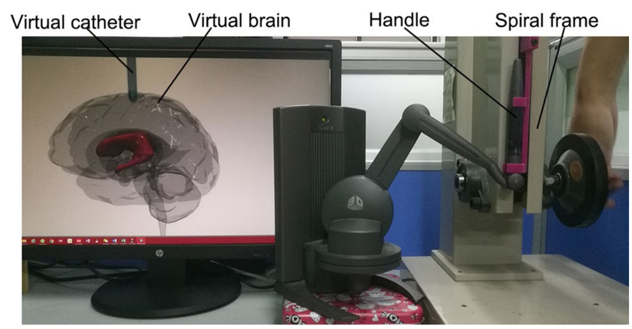

Fig. 13 Gathering the haptic force in the virtual system

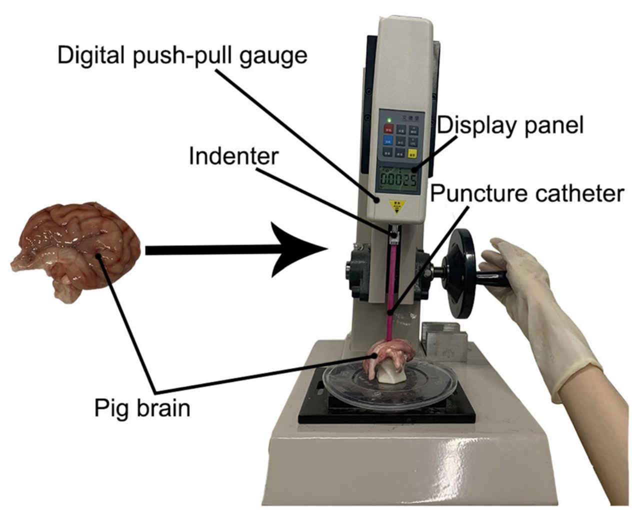

Fig. 14 Gathering the puncturing force generated by puncturing the pig brain

3.2 Validation of system

To verify the effectiveness of the system, 30 neurosurgical interns in Fujian Provincial Hospital were invited. All participants had studied the lateral ventricle in brain anatomy, but had yet received any training on lateral ventricle puncture surgery. The 30 participants were evenly divided into two groups, the control group A and the experimental group B. The control group A were trained by traditional way; the group B were trained by the proposed virtual system, as shown in Fig. 15.

All participants were guided by the same mentor. Group A was guided by the mentor for 30 min a day by traditional way, including textbooks, anatomy atlases, operating room observation, videos, etc. The mentor guided group B through the virtual system on how to perform lateral ventricle puncture. Each trainee in group B was trained 30 min a day by using the virtual system. After one week of training, participants in group A and B are required to operate puncture tests on identical 3D printed brain models from CT reconstruction (Yi et al. 2019). As shown in Figs. 16 and 17, the brain tissue was made of hydrogel, the balloon in the lateral ventricle module can be replaced and filled with water when in use, which can mimic the membrane of lateral ventricle. The chief physician performed the operation on the 3D printed brain model before the test begins, and position of Kocher's point and the punctured position on lateral ventricle recorded from the chief physician's operation were used as the optimum result. The position of Kocher's point was recorded based on the distance posterior from the nasion and the distance lateral to the midline. The punctured position on lateral ventricle was recorded according to the distance between the reference point with the punctured position on the sagittal direction and the coronal direction, as shown in Fig. 18. During the tests, the chief physician scored the performance of the participants, including operative dictation (10 points, scored by the correctness and completeness of dictation.), operation time (10 points, longer operation time means less score), position of Kocher's point (10 points, being closer to the standard position means higher score), times of repeated punctures (10 points, less repeat means higher score) and the punctured position on lateral ventricle (10 points, being closer to the standard position means higher score). The scoring standard is shown in Table 1.

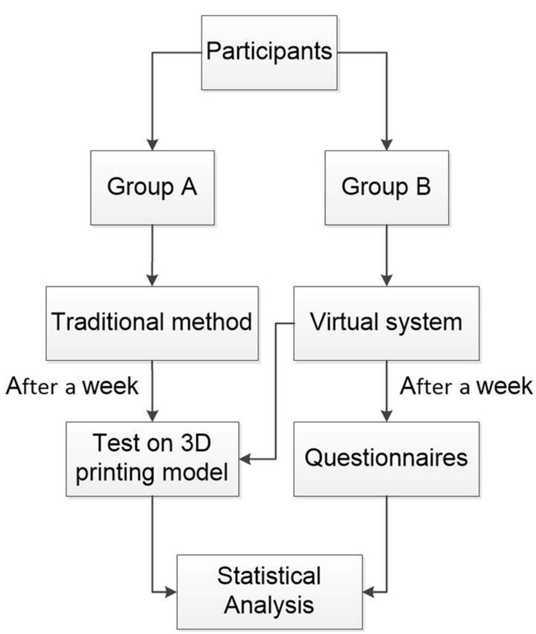

Fig. 15 Experimental flow chart for group A and group B

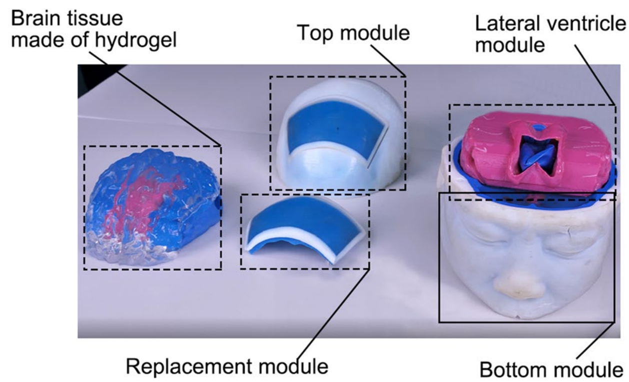

Fig. 16 Model for testing

Operative dictations include aspects on: operation preparations, analysis on locating Kocher's point, analysis on puncturing direction and depth, and potential post-operation complications. If the puncture catheter fails to reach the lateral ventricle, then it needs to be withdrawn and punctured again till the lateral ventricle was reached successfully. The chief physician had no knowledge of the participants' previous groupings. After the test, group B were asked to finish a questionnaire, which was proposed after discussing with the physician. Also, participants were asked to provide suggestions for improvement. The independent sample t-test was used to analyze the 3D printing test results. Statistics were analyzed by Graphpad Prism 7 software. $P < 0.05$ was statistically significant.

4 Results

4.1 Haptic device and pig brain puncture

The values of force generated by puncturing the pig brain and the values of force generated by haptic device were plotted in a graph to observe the trends during the puncture process, as shown in Fig. 19. The two curves are similar in trend. During the process of puncturing the pig brain with the puncture catheter, the puncture force decreased twice, that is, the puncture force curve has two troughs. Similarly, the curve corresponding to the haptic device also appeared two troughs. Because the human hand cannot feel the haptic feedback if the parameter value is too small, we set the parameter value a little bigger. That's why the force

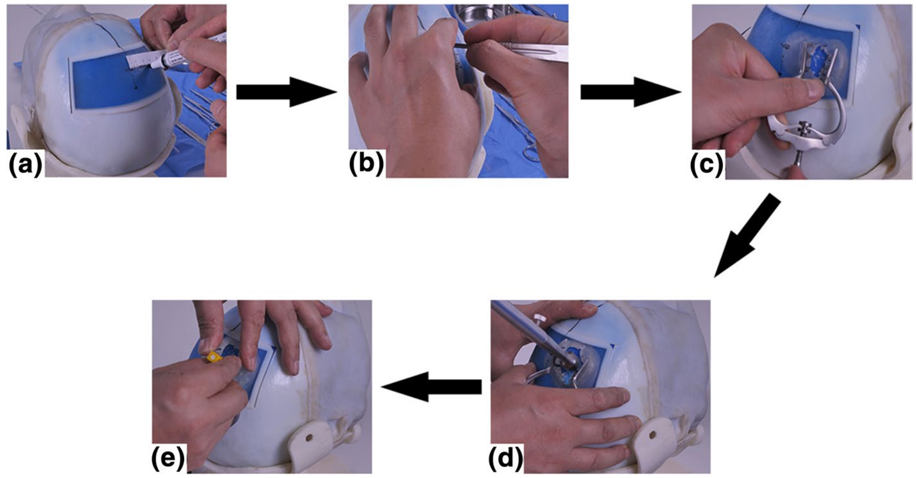

Fig. 17 Operation test process: **a** marking the Kocher's point, **b** cutting the scalp, **c** spreading scalp, **d** drilling a hole in skull, **e** puncturing

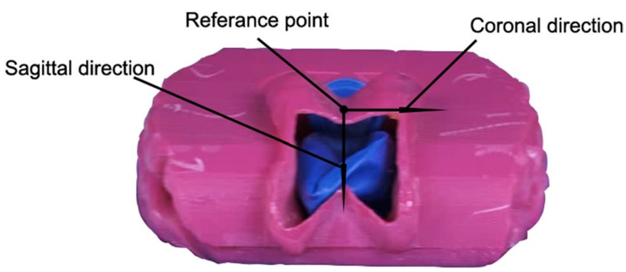

Fig. 18 The sagittal direction and the coronal direction

generated by the haptic device force is a little larger than the force of puncturing the pig brain. Since the forces generated are at "mN" level, the difference in the magnitude of the force reflected in the hand feeling is not very obvious.

4.2 Virtual training system

The research conducted a total of 30 tests based on the 3D printing model. The difference between group A and group B is that group A only relies on traditional methods throughout the training period, while group B only uses virtual system. Both groups spend the same amount of time for training. From the experimental results, the two groups showed significant differences in operative dictation, operation time,

Table 1 The scoring standards

Metric	Standard	Score (point)
Operative dictation	Content complete and accurate	8–10
	Content incomplete but accurate	5–8
	Content incomplete and inaccurate	< 5
Operation time	Operation time is less than 10 min	8–10
	Operation time is during 10–15 min	5–8
	Operation time is during 15–20 min	3–5
	Operation time is more than 20 min	< 3
Position of Kocher's point	Distance is less than 1 mm	8–10
	Distance is during 1–3 mm	5–8
	Distance is during 3–5 mm	3–5
	Distance is less than 5 mm	< 3
Times of repeated punctures	Times is once	10
	Times is twice	7
	Times is three times	5
	Times is more than three times	0–3
The punctured position on lateral ventricle	Distance is less than 1 mm	8–10
	Distance is during 1–3 mm	5–8
	Distance is during 3–5 mm	3–5
	Distance is less than 5 mm	< 3

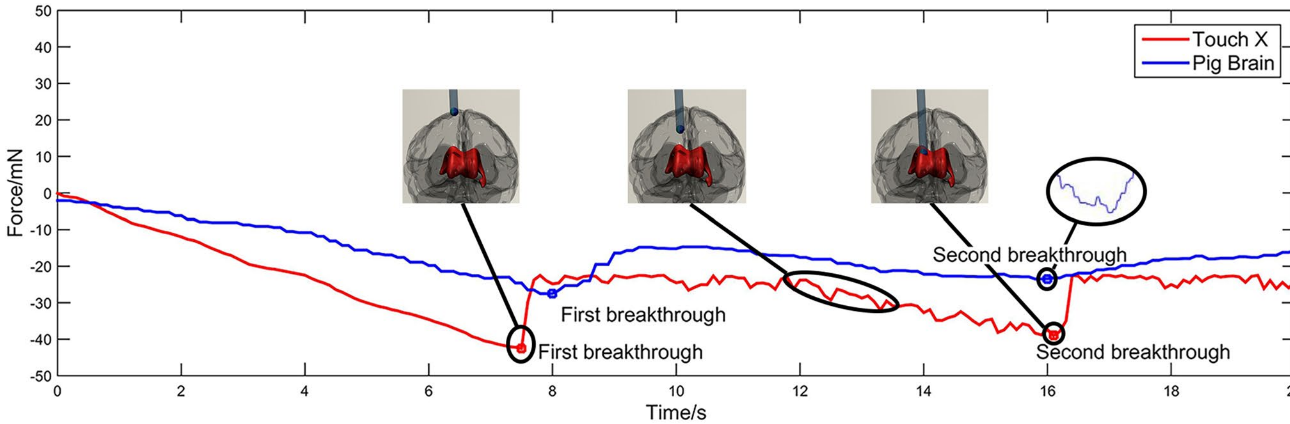

Fig. 19 The curves generated by puncturing on the pig brain and generated by haptic device

Table 2 Score of 5 metrics in group A and group B

Group	Participant	Metric 1	Metric 2	Metric 3	Metric 4	Metric 5	Total score
A	1	7.5	5.5	5.5	7	5.5	31
	2	7	5	5	5	5	27
	3	6	4.5	6	1	6.5	24
	4	5	4.5	5.5	5	5	25
	5	5.5	6	7	1	6.5	26
	6	7.5	5.5	7	1	7	28
	7	7	5.5	5	7	4	28.5
	8	7.5	4.5	5.5	5	5	27.5
	9	5.5	5	5.5	5	5.5	26.5
	10	5	5	5.5	3	5.5	24
	11	6.5	5.5	7	1	6.5	26.5
	12	5.5	5.5	6	1	6	24
	13	8	4.5	5.5	5	5	28
	14	8	5.5	6.5	1	6	27
	15	7.5	5	5.5	5	5	28
Mean ± SEM		6.60 ± 0.28	5.13 ± 0.12	5.87 ± 0.18	3.53 ± 0.60	5.60 ± 0.21	26.73 ± 0.50
Group	Participant	Metric 1	Metric 2	Metric 3	Metric 4	Metric 5	Total score
B	1	5	7.5	6	7	7.5	33
	2	5	7	6.5	7	7.5	33
	3	6	6.5	7	10	7.5	37
	4	5	6.5	5.5	5	5	27
	5	6.5	7	5.5	7	5	31
	6	6	7	7	10	8	38
	7	4.5	5.5	7.5	7	7.5	32
	8	4.5	6.5	7.5	7	7.5	33
	9	5	6.5	5	5	5	26.5
	10	5	7	6.5	7	5	30.5
	11	6	6.5	7	7	7	33.5
	12	6	6.5	6	5	4.5	28
	13	5	6.5	7.5	7	7.5	33.5
	14	6	7	8.5	10	8.5	40
	15	4	6.5	7	7	8	32.5
Mean ± SEM		5.30 ± 0.19	6.67 ± 0.12	6.67 ± 0.24	7.20 ± 0.43	6.73 ± 0.36	32.57 ± 0.98

position of Kocher's point, times of repeated punctures, the puncture position on lateral ventricle, and total score. Among them, group A were significantly better than group B in operative dictation ($P = 0.001$), while group B were significantly better than group A in other metrics ($P < 0.005$), as shown in Table 2 and Fig. 20. The metric 1 is operative dictation, metric 2 is operation time, metric 3 is position of Kocher's point, metric 4 is times of repeated punctures, and metric 5 is the puncture position on lateral ventricle.

The 15 participants from group B answered the questionnaire. As can be seen from Table 3, there are ten questions about the entire system and nine questions about the database.

Questions 1–10 are about the system, using Likert scale, and mean scores and standard errors were recorded. For Questions 11–19, we calculated the proportion of answer "yes" in each question answered by participants. Judging from the questionnaires, though some participants expressed uncertainty about this system in improving puncture skill, the vast majority of participants expressed their approvals. In addition, all participants expressed that during training they checked the database often and accordingly adjusted their puncturing methods, e.g. the puncture depth, the position of Kocher's point, and the puncture angle. Finally, a total of seven participants gave suggestions for improving system. After summarizing, the suggestions can be divided into four points: (1) The virtual scene can be rendered more realistically; (2) The effects of surgical failure can be added, such as intracranial haemorrhage or to show intracranial infection occurs after surgery; (3) The contraindications, indications and other knowledge can be added in the pre-operative learning module; (4) The system can add the mission mode, for example, it can require trainees to puncture to the specific position on the lateral ventricle from Kocher's point.

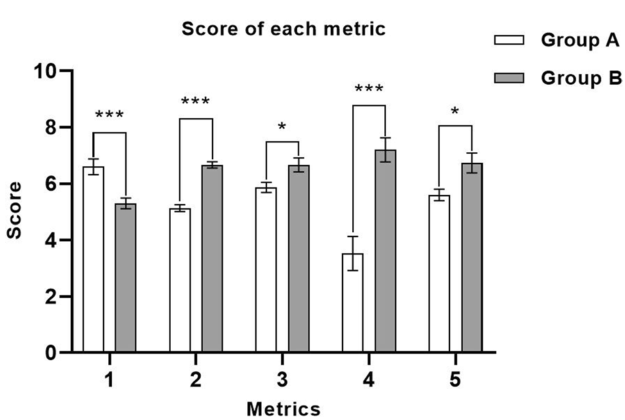

Fig. 20 Score of each metric, metric 1 is operative dictation, metric 2 is operation time, metric 3 is position of Kocher's point, metric 4 is times of repeated punctures, metric 5 is the puncture position on lateral ventricle

5 Discussion

Lateral ventricle puncture surgery is often used for emergency fluid drainage treatment. It seems beyond dispute that the existing surgical methods relied on doctors for blind puncture are difficult to implement (Bender et al. 2019). The use of a virtual reality simulator with haptic force can simulate surgery more realistically (Michael et al. 2007; Grajewski et al. 2013), thereby improving surgical skills through training. The virtual reality training system proposed in this paper is equipped with haptic feedback, with which can provide beginner better training effect (Pinzon et al. 2016). The training effect can be better if the haptic feedback is more real (Singapogu et al. 2014). In this system, the puncture force was divided into three stages: the puncture catheter entered the brain tissue from the outside, the puncture catheter moved in the brain tissue, and the puncture catheter entered the lateral ventricle. The feedback forces were calculated accordingly at different stages for better fidelity. During the first stage, the puncture catheter obtains the resistance occurred from the upper membrane of brain tissue. After the first breakthrough, the puncture catheter obtains the resistance from the brain tissue. Like the first breakthrough, the second breakthrough occurred when the puncture catheter touched the lateral ventricle. The haptic feedback in the system simulated three stage of the puncture force in order to help the trainees to perceive the different organs during the puncturing process, thus to feel the haptic sensation and improve their puncturing skills efficiently.

There are five metrics used to evaluate the performance of participants: operative dictation, operation time, position of Kocher's point, times of repeated puncture, and the puncture position on lateral ventricle. Among them, the operative dictations were used to evaluate participants' familiarities with the theory related to lateral ventricle puncture. Time consumption was used to evaluate the proficiency of the participants in the surgery: the shorter operation time, the more familiar with the operation is (Rosser et al. 1998). The position of Kocher's point, times of repeated puncture, and the puncture position on lateral ventricle were used to evaluate the accuracy of the participant's puncturing.

Compared with group B, the participants in group A learned more about the theory of lateral ventricle surgery from books, so they were better in operative dictation. Group B is significantly better than group A in other metrics because they have a better grasp of surgery operation and anatomy about lateral ventricle (Alfalah et al. 2019) than group A. The virtual training system proposed in this paper provides trainees with a more realistic way of operation training through the surgical training module. Through the surgical training module, the trainee can

Table 3 Questionnaire about system and database

Number	Question	Result
1	I think the virtual system is highly immersive	3.93 ± 0.15
2	I think the virtual system is easy to use	4.6 ± 0.16
3	I think the haptic device improved the authenticity of the operation	4.73 ± 0.12
4	I think I can grasp the puncturing depth better now	4.73 ± 0.15
5	I think I have mastered the operation procedure very well	5
6	I think the CT reading function can improve my ability	4.67 ± 0.16
7	I think I can select the position of Kocher's point easily now	4.93 ± 0.07
8	I think I can judge the puncture direction better now	4.67 ± 0.16
9	I think the database provided references during the training	4.8 ± 0.14
10	I think the system improves my puncture skill	4.67 ± 0.18
11	I used to check the database often during training(Yes/No)	100%
12	I used to adjusted the position of the Kocher's point based on the database records (Yes/No)	33.33%
13	(Continue to question 12) The success rate of puncturing after adjustment get higher (Yes/No)	60%
14	I used to adjusted the puncturing depth based on the database records (Yes/No)	40%
15	(Continue to question 14) The success rate of puncturing after adjustment get higher (Yes/No)	83.33%
16	I used to adjusted the puncturing direction based on the database records (Yes/No)	60%
17	(Continue to question 16) The success rate of puncturing after adjustment get higher (Yes/No)	77.78%
18	I have found the reason why I failed often based on the database(Yes/No)	86.67%
19	(Continue to question 18) According to the reasons, I made adjustments and the success rate gets higher (Yes/No)	92.31%
20	Suggestions	(1) The virtual scene can be rendered more realistically; (2) The effect of surgical failure can be added, such as intracranial haemorrhage or to show intracranial infection occurs after surgery; (3) The contraindications, indications and other knowledge can be added in the pre-operative learning module; (4) Task mode can be added, like requires trainee to puncture to the specific position

repeat the simulation training of the operation to improve the operation proficiency. In addition, the system trains the trainee's 2D to 3D transformation and matching ability through the pre-operative learning module, so that the surgical planning ability can be further improved.

There are many 3D reconstruction software for CT reconstruction assisting surgical planning, such as 3D-Slicer and Mimics. However, the reconstruction work is time consuming, therefore not particularly suitable in emergencies where neurosurgeons are required to plan puncturing procedure based on only 2D scanning. In other words, it is important for neurosurgeons to build the "3D models" according to CT or MRI in their mind (Ferroli et al. 2013).

The results of the experiments affirm the role of the virtual puncture system in improving puncture skills, and it can be considered that the database plays a certain role in it based on the results of the questionnaires. It is necessary to provide information feedback to trainees during training (Zahiri et al. 2018). The positive attitude of the participants towards the database was also demonstrated through a questionnaire survey and demonstrated the effectiveness of the database from the other aspects. The system records the virtual surgical training information of the trainees through the database. Trainees and trainers can log in to the database to review previous practices, summarize failure patterns, and make better plans for future training based on each trainee's performances. What's more, the system developers can optimize the training module by analyzing the trainees' failure information.

Although the systems developed with ImmersiveTouch (Michael et al. 2007; Perin et al. 2018; Rangwala et al. 2018) provide fully simulation of the puncturing process and scoring the puncturing results, they are costly and only provide the final score to each simulated operation. On one hand, due to the high costs, it is difficult to be widely adopted in the field of medical education. The lack of simulation parameters in details, on the other hands, prevents trainers and trainees from analyzing their performances extensively.

6 Conclusion

A novel virtual simulation training system for lateral ventricle puncture surgery was developed in this paper. According to the verified experiments and questionnaires, it can be concluded that this system is beneficial for trainees to improve their puncturing skills. Based on the experimental results and questionnaires, the training system has the advantage of providing trainees with a safe, immersive, and repeatable operating environment to practice their puncturing skills. However, it is not as good as traditional teaching methods in helping trainees acquire basic theoretical knowledge; therefore, integrating the two aspects organically is the future direction.

Authors' contributions WL contributed to software, writing—original draft; ZZ was involved in writing—review and editing, conceptualization; BH contributed to supervision, project administration; YL was involved in funding acquisition, resources; WH contributed to validation, formal analysis; ZLwas involved in validation, investigation.

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