Role of Visuohaptic Surgical Training Simulator in Resident Education of Orthopedic Surgery

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■ OBJECTIVE: **We sought to assess the validity of a virtual surgical training system on lumbar pedicle screw placement for residents.**

■ METHODS: **Ten inexperienced residents were randomly assigned to the simulation training (ST) group ($n = 5$) and control group ($n = 5$). The ST group performed the lumbar pedicle screw placement on the virtual surgical training system, and the control group was given an introductory teaching session before the cadaver test. A total of 8 adult fresh cadavers including 5 males and 3 females were collected and randomly allocated to the 2 groups. Each group performed the bilateral L1-L5 pedicle screw instrumentation in the cadaver specimens, respectively. Accuracy was assessed by computed tomography after instrumentation. The screw penetration rates, acceptable rates, and average screw penetration distance of the 2 groups were compared using statistical analysis.**

■ RESULTS: **The screw penetration rate of the ST group (12.5%) was significantly lower than the control group (37.5%, $P < 0.05$). The screw acceptable rates in ST and control groups were 100% and 85%, respectively, with statistical differences between each other ($P < 0.05$). There was also a statistically significant difference of the average screw penetration distance between the ST (1.37 ± 0.62 mm) group and control group (2.42 ± 0.51 mm, $P < 0.05$).**

■ CONCLUSIONS: **The virtual surgery simulation with greater accuracy is superior to the traditional teaching methods in surgical training of pedicle screw placement and can be used as a promising alternative for training of neurosurgical procedures.**

INTRODUCTION

The virtual reality (VR) simulation technology has significantly improved from unrealistic low-fidelity models to current high-fidelity models in recent years and can provide almost unlimited procedures and training to enhance surgical skills.[1] The VR simulation has been widely used in medical training, which enables trainees to acquire knowledge and understanding about surgical techniques by means of interaction within a virtual environment.[2-4] By performing virtual surgery in a safe and controlled setting, medical students are able to make mistakes and learn from them without causing injuries to the patient. Through interacting with a virtual patient, the learning skills can be easily acquired and then applied in clinical practice.

In the field of spine surgery, the fast development of VR simulation technology provides promising potentials for high proficiency of surgical techniques with steep learning curves in the shortest time. The pedicle screw placement as the mostly widely practiced technique in spine surgery has evolved over time and experience. Utmost care needs to be taken during pedicle screw placement to prevent potential damage to neural structures that closely approximate the bony pedicle.[5] Although the intraoperative 3-dimensional (3D) computed tomography (CT)-based navigation system can provide greater accuracy for pedicle

Key words
- Cadaver study
- Lumbar spine
- Pedicle screw placement
- Virtual reality

Abbreviations and Acronyms
CAS: Computer-assisted surgery
CT: Computed tomography
ST: Simulation training
VR: Virtual reality
VSTS: Virtual Surgical Training System

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screw placement, it has disadvantages including increased radiation exposure to the patient and additional preoperative preparation time.[6] These factors have created the need for the development of VR simulators to allow trainees to practice basic skills and receive objective feedback on performance for pedicle screw placement.

The Virtual Surgical Training System (VSTS) is a VR simulator with haptic feedback that aims to recreate the sensation of performing pedicle screw fixation. The aim of this study is to assess the effectiveness of VSTS on pedicle screw placement for surgical training. Firstly, residents were trained to perform simulation training of lumbar pedicle screw fixation on the system. Next, pedicle screws were implanted into the human cadaveric spine specimens. Finally, positions of pedicle screws were evaluated and compared with the control group receiving a traditional teaching method. The results of this study will provide experimental evidence on whether the virtual reality surgical training system can effectively improve the learning effect of lumbar pedicle screw techniques.

MATERIALS AND METHODS

Simulation Training of Lumbar Pedicle Screw Implantation

The study protocol was approved by the ethics committee of our hospital. A total of 10 residents without experience in pedicle screw implantation participated in the study. The experiment was performed in accordance with relevant guidelines and regulations. Informed consent was obtained from all individual participants included in the study, and additional informed consent was obtained from all individual participants for whom identifying information is included in this article. The subjects were randomly assigned to the simulation training (ST) group ($n = 5$) and control group ($n = 5$). The simulation training of lumbar pedicle screw placement was performed on the VSTS for each participant in the ST group (Figure 1). The software of the system uses a series of modules to acquire, process, and render the graphic and haptic data, which are then seamlessly integrated into the hardware platform. The virtual 3D volume of the human lumbar spine was created using the CT scan from patients at our hospital, and the data were presegmented and assembled from a CT DICOM data set.

Figure 1. Virtual surgery training system based on force feedback was used for pedicle screw insertion simulation.

The 5 participants in the ST group were given 30 minutes to practice on bilateral pedicles of L1-L5. Through the force feedback generated by the haptic device, the collision between the virtual drill and the extracted 3D isosurfaces can be detected (Figure 2). The virtual drill is started and stopped by the control button of the operating handle. When the drill is about to complete, the screw can be instantly placed at its final location by pressing the button of the operating handle. Once the operator deviates from the linear trajectory defined according to its orientation, a reactionary force is applied by the haptic device. This is intended to stimulate a firm feeling similar to the tactile sensation experienced during surgery. Once the user wants to change the trajectory, the drill has to be pulled out of the pedicle on the same linear trajectory, and then the drill can be reinserted following a different linear trajectory. The 5 participants in the control group received a teaching session including pedicle screw insertion training using a didactic spine model (40 minutes) and a video demonstration (10 minutes).

Lumbar Pedicle Screw Placement

The collected cadaveric specimens including 5 males and 3 females were randomly allocated to the ST and control groups, respectively. The lumbar fractures, tuberculosis, tumors, and tiny pedicle unsuitable for screw insertion were excluded by preoperative imaging examination on each specimen. In the meantime, the size and transverse angle of pedicles in 2 groups were measured using a CT scan. Three experienced observers were assigned to evaluate the measuring results independently. Comparisons of data between the 2 groups using the independent Student's t-test showed no statistical difference ($P > 0.05$), suggesting that the 2 groups were comparable. After placing the subject in the supine position, posterior median incisions were made in the cadaveric specimens. The soft tissues attached to the lumbar lamina were removed to fully expose the bony anatomic structures (Figure 3). Finally, bilateral pedicle screw fixations were performed on L1-L5 in 2 groups according to the operative procedures well described by Vaccaro AR et al.[7]

Evaluation of Lumbar Pedicle Screw Placement

The lateral and axial CT scans were performed on cadaveric specimens in each group respectively (Figures 4 and 5). Three experienced observers were assigned to evaluate positions of pedicle screws independently. The screw position was evaluated using a simple grading system: grade I: The screw was completely inside the pedicle; grade II: screw penetration of the pedicle wall $\leq$2 mm; grade III: screw penetration of the pedicle wall between 2 and 4 mm; grade IV: screw penetration of the pedicle wall $\geq$4 mm. The unacceptable penetration included the screws with grade III that had a superior, inferior, or medial pedicle breach and screws with grade IV. The other screws were considered to be the acceptable ones.

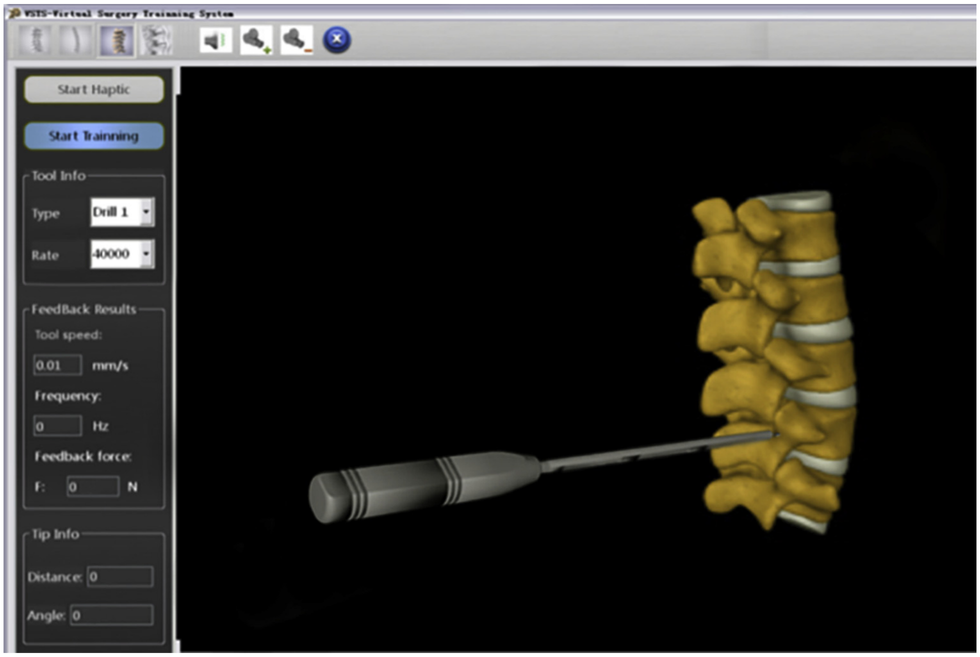

Figure 2. Man-machine interactive interface of the virtual surgical training system and the drilling process with force feedback during pedicle screw insertion simulation.

Statistical Analysis

The chi-square test was used in comparison of screw placement accuracy and acceptable rate of screw position between the 2 groups. The independent Student's t-test was used to investigate whether statistical differences in the average screw penetration distance exist between the 2 groups. All the statistical tests were completed by the Statistical Package for Social Sciences software for Windows (Ver. 17.0; SPSS Inc., Chicago, Illinois, USA), and the difference was considered to be statistically significant at the $P < 0.05$ level.

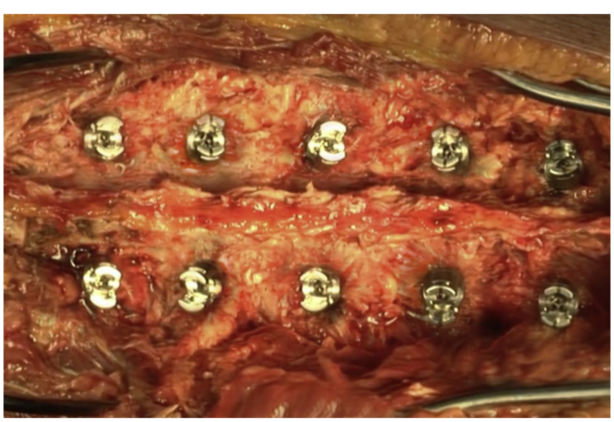

Figure 3. Macroscopic observation of the bilateral pedicle screw placement in the lumbar spine (L1-L5).

RESULTS

A total of 80 screws were placed in ST and control groups including 40 screws in each group, respectively. There were 35 screws with grade I and 5 screws with grade II in ST group, respectively. No screw with grade III or IV was observed (Table 1). One of the 5 screws with grade II had a medial pedicle breach, and the other 4 screws had lateral pedicle breaches. There was no screw penetration of the superior or inferior pedicle wall and the anterior margin of vertebral body in ST group. The average screw penetration distance was 1.37 ± 0.62 mm. The acceptable rate of lumbar pedicle screws in ST group was 100%.

A total of 25 screws with grade I, 9 screws with grade II, 4 screws with grade grade III, and 2 screws with grade IV were observed in control groups. The numbers of screws with lateral and medial pedicle wall perforation in control group were 7 and 3, respectively. In addition, 4 screws had a superior pedicle wall breach and 1 screw had an inferior pedicle wall breach in the control group. No screw penetration of the anterior wall of vertebral body was observed, and the average screw penetration

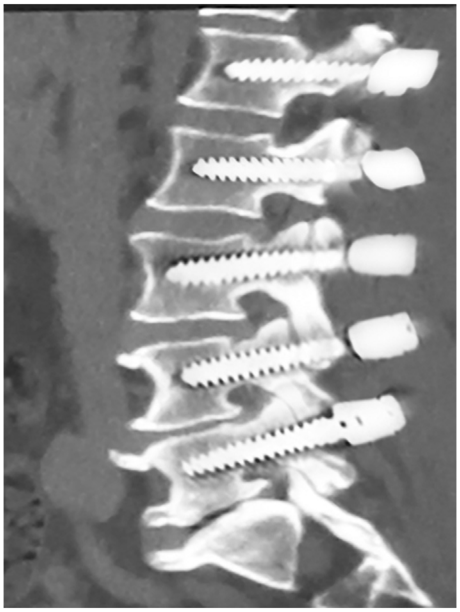

Figure 4. Sagittal computed tomography images of the lumbar spine showing the position of pedicle screws.

distance was 2.42 mm ± 0.51 mm. The positions of 6 perforated screws were considered to be unacceptable, and the acceptable rate of lumbar pedicle screws in the control group was 85%.

The rates of screws inside the pedicle (grade I) in the ST and control groups were 87.5% and 62.5%, respectively. Meanwhile, the screw penetration rates were 12.5% and 37.5%, respectively. There existed statistically significant difference in these 2 parameters between the 2 groups ($P < 0.05$), indicating that the ST group had higher screw placement accuracy compared with the control group. In addition, a statistically significant difference in acceptable rates of screws also occurred between the ST (100%) and control (85%) groups ($P < 0.05$). The independent Student's *t*-test showed that the average screw penetration distance in the ST group was significantly lower than in the control group ($P < 0.05$). **Figure 6** showed the number of displaced screws per individual in the ST and control groups. The distribution of the number of pedicle violations per individual in each group is relatively uniform, which ensures comparability between the 2 groups.

DISCUSSION

Malposition of pedicle screws can lead to various complications. Screws breaching the pedicle pose a potential threat to adjacent neural structures, and the most serious consequence is neurologic deficit.[8] The improved performance of pedicle screw placement for inexperienced orthopedic surgeons usually requires repetitive practice and accumulation of surgical experience. Gonzalvo A et al.[9] reported that there was a steep learning curve in performing accurate pedicle screw placement. They found that there was a significant reduction in the number of misplaced screws and the development of an asymptote after approximately 80 pedicle screws.

In order to enhance the accuracy of pedicle screw placement, a number of guidance techniques have been developed in spine surgery to assist the surgeon in real time.[8,10-12] The currently available guided screw insertion mainly includes intraoperative fluoroscopy and CT-guided computer-assisted surgery (CAS). The advantage of intraoperative fluoroscopy is the broad intraoperative availability with the disadvantage of limited image quality in some regions of the spine such as the upper thoracic spine.[13] The advantage of the CAS is its accuracy, especially in difficult anatomic regions including the cervical and upper thoracic spine, and possibility of preoperative planning. Both techniques significantly improve the accuracy of pedicle screw placement.[6] The major problem of CAS is the anatomy changes during surgery, which are not reflected in the preoperative images. This discrepancy could result in navigation errors that could increase risks of pedicle screws misplacement and cause serious neural or vascular injuries. The other disadvantages of the CAS include the increased radiation exposure to the patient, additional preoperative preparation time, limited field of view, registration inaccuracies, etc.[6]

Virtual surgery simulation is a promising alternative to freehand or navigated techniques, aiming to improve screw placement accuracy while at the same time reducing radiation exposure and surgical complications of patients. The earliest VR spine simulator for pedicle screw insertion was developed by Eftekhar et al.[14] Recent advances in computer and additive manufacturing technology have led to a more sophisticated and practical application of VR simulation in spine surgery during the past decade with promising results.[15-17]

Luciano et al.[15] evaluated the learning retention of thoracic pedicle screw placement on a simulator with 3D and haptic feedback. Virtual screws were drilled into a virtual patient's thoracic spine derived from a CT data set of a real patient. The results showed a 15% mean score improvement of the performance accuracy from practice to test session. Klein et al.[16] developed a 3D, patient-specific simulator for pedicle screw insertion. The simulator allowed the user to practice insertion of pedicle screws into a 3D model of a patient-specific spine and had both visual and quantitative feedback provided to the user. The simulator was proved to better prepare surgeons to perform pedicle screw insertion surgery and help reduce the risk of pedicle screw misplacement. Gottschalk MB et al.[17] conducted a blinded, randomized control study to analyze the effect of surgical training using 3D simulation on the placement of lateral mass screws in the cervical spine. The findings of the study showed that training with 3D navigation significantly improved the ability of orthopedic residents to properly drill simulated lateral mass screws.

Previous studies initially proved the validity of VR simulation for screw insertion in spine surgery. However, the subjective evaluations of participants in these simulation trials could reduce the reliability of the study and affect the applicability of the experimental results. Therefore there is still a lack of convincing evidence on the advantages of VR simulation in comparison with traditional teaching methods. In order to enhance the credibility of the current study, CT scan of the screw positions was used as an objective method for the

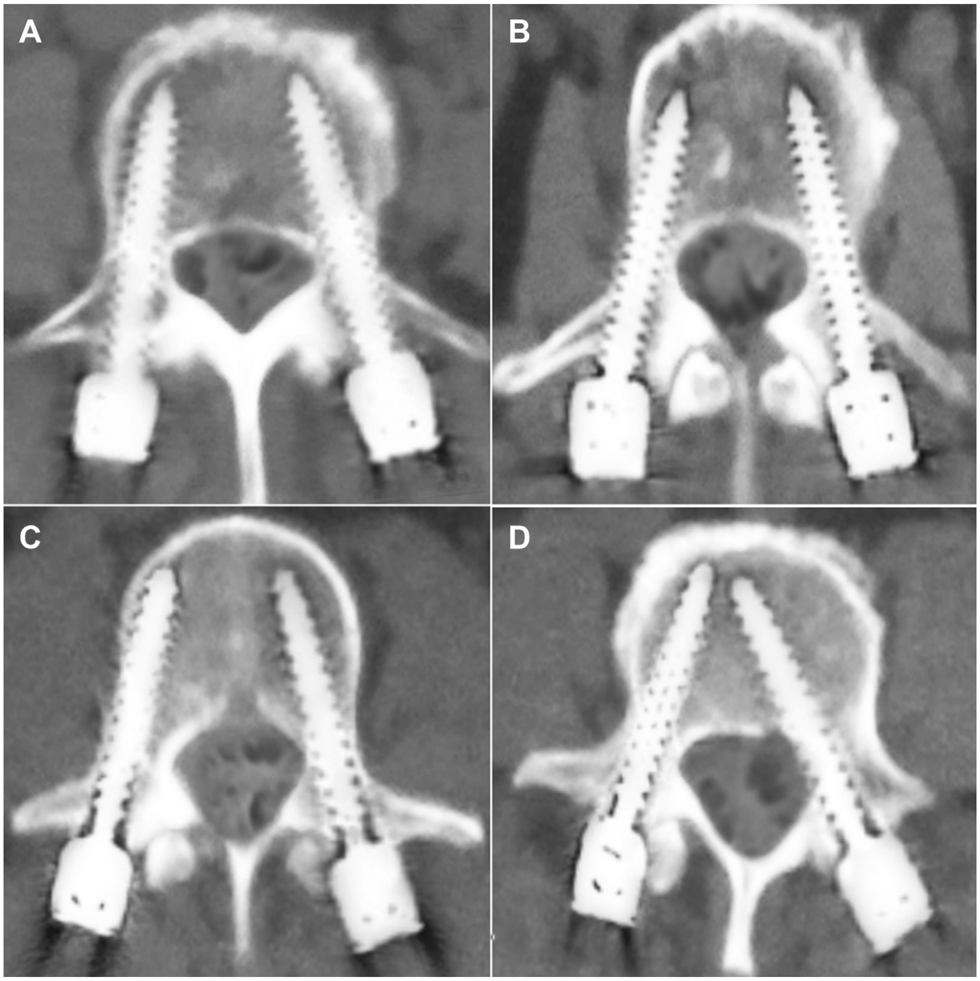

Figure 5. Axial computed tomography images showing the pedicle screw perforation. (**A**) Both screws were completely contained within the pedicle and were classified as grade I. (**B**) Right lateral wall breach of a screw being classified as grade II (<2 mm). (**C**) Right lateral wall perforation of a screw being classified as grade III (2—4 mm). (**D**) Severe medial wall breach of a left screw being classified as grade IV (>4 mm).

comparative analysis. We first performed this osteometric study of cadaver specimens to evaluate the validity of the VSTS with force feedback function in pedicle screw placement training.

Force feedback is the key to successfully reproducing the spine surgery in the virtual surgery simulator. We have constructed a bone drilling force model for haptic rendering based on calibration and validation experiments in fresh cadaveric bones with different bone densities.[18] According to the mean density of the cortical bone, the specimens were correspondingly divided into high- and low-density groups. A commonly used drill bit geometry (2-mm diameter), feed rates (20—60 mm/min) and spindle speeds (4000—6000 rpm) in orthognathic surgeries were

Table 1. Classification of Screws in Simulation Training (ST) and Control Groups

Group	Screws (n)	Screws with Grade I (n)	Screws with Grade II (n)	Screws with Grade III (n)	Screws with Grade IV (n)
ST group	40	35	5	0	0
Control group	40	25	9	4	2

Grade I, screw completely in pedicle; grade II, screw <2 mm outside of pedicle; grade III: screw 2—4 mm outside of pedicle; grade IV: screw >4 mm outside of pedicle.
CAS, computer-assisted surgery; CT, computed tomography; VR, virtual reality; VSTS, virtual surgical training system.

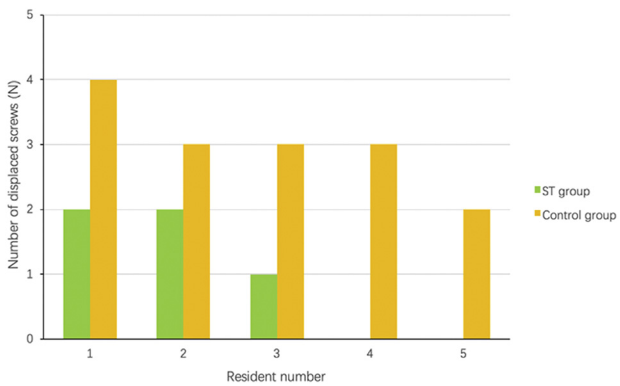

Figure 6. Number of displaced screws per individual in simulation training and control groups.

used to evaluate the bone drilling forces of specimens from the 2 groups. In addition, the calibration coefficients of the specific normal and frictional pressures were also determined. By comparison of the predicted forces and measured forces from validation experiments with a large range of feed rates and spindle speeds, the results demonstrated that the proposed bone drilling forces can predict the trends and average forces well. The presented bone drilling force model was used for haptic rendering in the virtual surgery simulation system. The haptic forces were computed in real time on the basis of the experience force model and multipoint collision detection using Omega.6 as the haptic device. The Omega.6 is a penlike haptic device that has 6 degrees of freedom (6DoF) and 3 degrees of force feedback (3DoFF). The true 3D stereo performance in high resolution can be clearly shown on the computer monitor. The graphic user interface was supported by the OpenGL graphics library and the Computer Haptics and Active Interfaces (CHAI3D). The procedure of lumbar pedicle insertion can be perfectly realized in this simulator. The user is able to practice the screw insertion procedure with guidance through the interface.

The experiment results showed that the inexperienced residents had a screw penetration rate of 37.5% and an average screw penetration distance as high as 2.42 ± 0.51 mm for placing lumbar pedicle screws in cadavers. This indicated that surgeons in training should repeatedly practice this technique in the laboratory before proceeding to the operating room. In the simulation training, the entry and target landmarks were visible during the practice. The participants had to learn to not only identify the entry and target landmarks from the anatomy of the lumbar spine but also remember them. Through force feedback during the drill operation, the participants can acquire a firm feeling similar to the tactile sensation experienced during surgery and better understand the anatomic knowledge of lumbar spine by repetitive exercises.

Due to the difficulties in obtaining cadaver specimens, the sample size of this study is relatively small, which may produce statistical bias. However, the statistical analysis showed a uniform distribution of the number of pedicle violations per individual in each group, which could not have made a large impact on the study results. The subsequent study with a large sample size will be conducted to further validate the results of the current study in our future works.

CONCLUSIONS

This cadaveric study revealed significant difference in screw penetration rates, screw placement accuracy, acceptable rates of screws, and average screw penetration distance between the ST and control groups. To our knowledge, this is the first randomized cadaveric study comparing virtual surgery simulation versus traditional teaching method in surgical training of lumbar pedicle screw placement. This cadaver study demonstrates that VR simulation is superior to the traditional teaching method in pedicle screw placement and shows the promising potential of the virtual surgery simulation for novice resident training of neurosurgical procedures.

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