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Use of 3- Dimensional Modeling and Virtual Reality in the Education of Posterior Spinal Instrumentation

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To watch the surgical videoclip, please visit https://turkishneurosurgery.org.tr/uploads/jtn-46204-video.mp4

ABSTRACT

AIM: To assess the effectiveness and safety of Virtual Reality (VR) simulations for education of posterior spinal instrumentation.

MATERIAL and METHODS: Participants were instructed to apply Cervical-Thoracic-Lumbar and Sacral posterior instrumentation techniques using the VR. Each participant underwent a qualitative assessment of the use of the VR. Patient-specific computed tomography (CT) studies were obtained to build a whole spinal model. Bone segmentation was performed upon the CT images. The participants can easily interact with the spinal model and evaluates the outcome from all the angles.

RESULTS: A total of 63 participants who used VR stimulation as a primary application during the 4-day course were included in this study. The majority of our participants agreed with the benefit of the VR spinal instrumentation module, stating that it was useful for learning the 3D anatomy of the spinal region. Overall, according to the questionnaire and evaluations, the participants stated that this application was most beneficial in the education and preoperative planning.

CONCLUSION: VR-based surgical training is a promising solution for surgical education, particularly for junior residents, for improving the understanding of spinal instrumentation. In addition, modelling of patient-specific CT scans on VR provides a unique opportunity for improving pre-operative planning and preventing surgical complications.

KEYWORDS: Virtual reality, Spinal, Instrumentation, Training

INTRODUCTION

In the last decade, advancements in technology and modernization of surgical instruments have improved outcomes and reduced complication rates in several surgical cases (9). However, instrumentation of a deformed spine with pedicle and lateral mass screws can be challenging even for the most experienced surgeons (19). Given the inherent risks to vital structures, the availability of instruments that enhance surgical safety is crucial in the field of spine surgery.

Despite these advancements, there remains a critical gap in standardized surgical training worldwide, leading to inadequate training and suboptimal practice. This gap is considered to be a primary contributor to the occurrence of surgical complications. In the United States alone, the financial bur-

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den associated with one million spinal surgery training-related complications is reportedly 5 billion dollars. Recent technological developments have paved the way for easily accessible, cost-effective, and portable virtual reality (VR) and interactive simulators in medical education (1,13).

Medical education provided through computer simulations has increased in popularity with the emergence of augmented reality (AR) and VR in spine surgery. The advantage of this approach is the ability to repeatedly perform surgical procedures in a risk-free environment without incurring additional expenses or time constraints (3,11). Therefore, VR-based training not only enhances speed and accuracy but also provides valuable feedback for practical applications, making it a cost-effective and low-risk method for surgical training. Furthermore, it eliminates the need for access to patients, cadavers, or synthetic models (15,16). Another application of VR-based tools is preoperative planning. With specific MRI- or computed tomography (CT)-based imaging techniques, a three-dimensional (3D) model of each patients' surgical procedure can be created and implemented in VR simulations. This will enable preoperative planning.

In our study, the anatomy of the whole posterior spinal bone was visualized using 3D models obtained from the patient's CT slices. Subsequently, a VR simulation was developed for pedicle and lateral mass screw placement on a 3D model. We aimed to investigate the results of 3D volumetric modeling of the whole spine and assess the use of 3D modeling in surgical training and preoperative planning of posterior spinal instrumentation surgeries in a VR environment (Figure 1).

MATERIAL and METHODS

All procedures in this study were performed in accordance with the ethical standards of the institutional and national research committees and the 1964 Declaration of Helsinki and its later amendments or other comparable ethical standards (Koc University Hospital, 2022.021.IRB.016).

Figure 1: Virtual Reality (VR) environment, designed to closely resemble an operating room, providing a realistic surgical simulation experience. The setting allows for training, rehearsal, and planning of surgical procedures in a lifelike operating room scenario, enhancing surgical preparedness and skill development.

Development of VR Experience

The VR experience consisted of two discrete scenes: a welcoming/onboarding scene and an operating scene. These scenes were inspired by the surgical scrub and operating rooms. The operating room loads after the interaction in the onboarding scene. The rooms and objects within were modeled using Blender, an open-source software, and from an inspiration board created with various reference images from operating rooms. Some objects inside the room were built and placed only to enrich the operating room experience without any interaction, such as the operating table, wheeled tables, and surgical lighting arms. Screwing tools, screws, screw-holding boxes, and the patient's vertebra were the only interactable modeled objects. In addition to polygon modeling, UV layout, mesh optimization, and shading processes were completed using Blender.

The critical model for experience is the spine. A ready-to-use life-like spine model from patient-specific 3D CT studies was optimized for VR usage using Blender. Because the experience was designed with an emphasis on surgical education rather than a realistic simulation, we decided to place the spine model on top of the operating table without any cover or other body parts.

The models were exported to the FBX format, which allows embedding of the shading and texture data in the documents. Thereafter, the FBX format models were imported to Unity 3D and gathered inside the scenes, where lights were set up and VR interaction adjustments were completed. Open XR libraries were used to integrate basic VR interactions, such as teleport, grab, and throw, in addition to tailored interactions. Tailored interactions consisted of functions to operate the screwdriver as well as guide users to specified screwing points on the spine.

Participants experienced this educational tool with a standalone VR headset, Meta Oculus 2, which optimized the 3D models, content, and interactions.

Screwing Points

Visual hints (Figure 2) to guide the user during the screwing process were built inside Unity3D. Two-dimensional UI objects were employed as point indicators to demonstrate the optimal screwing point, and 3D cylindrical objects were used to demonstrate the optimal screwing angle (Figure 2).

The screwing point was developed as an interactive object to maintain the screwing experience by integrating instructional feedback for each vertebra. This interactive object was designed to retain and demonstrate individualized optimal screwing angle and point to the user as well as validate user interaction, screwing point, and screwing tool angle. Screwing points were embedded on both sides of each vertebra. Thus, 114 points in total were placed on the spine, which only interacted with the loaded screwing tool. The screwing process was detailed according to the anatomical region and technique. The posterior transpedicular and mass screw fixation techniques were preferred for the cervical region. For the thoracic, lumbar, and sacral regions, the posterior transpedicular screw fixation technique was preferred.

The screwing process includes the following three phases: approach, placement, and screwing. During the first phase, when the user approached one of the screwing points with the screwing tool, the trigger box activated the indicators (point and target angle indicators) for that point.

During the placement phase, the activated point started tracking the screwdriver angle with constraints and continuously calculated the β angle in 3D (Figure 3), which is the difference between the user angle and the target angle in quaternion format. If the user placed the screw in the right place and the β angle was smaller than the threshold angle, the screwing tool clung to the vertebral point and activated the screwing phase. If one of the parameters was invalid, the algorithm did not activate the last phase, and the screwing tool was retained in the user's hand. The screwing phase also activated several other components in the screwing tool.

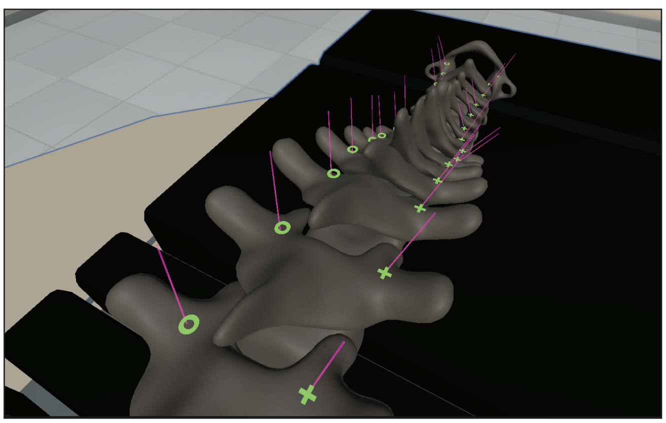

Figure 2: Visual hints to guide the surgeons during the screwing process are built inside Unity3D. Purple lines indicates the calculated target angle and green circles and dots indicate the target point, facilitating an easier learning environment.

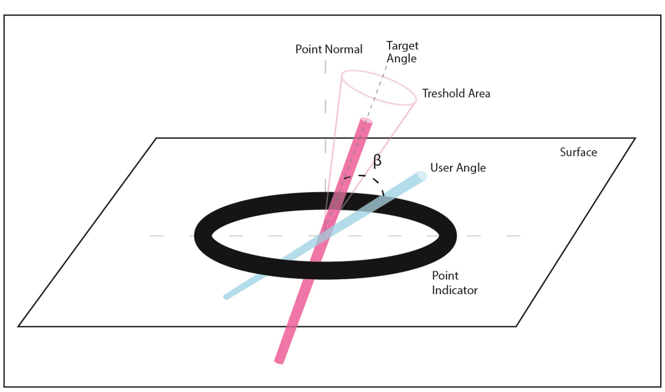

Figure 3: Screw placement phase, where the activated point within the VR environment continuously tracks the screwdriver angle, imposing constraints. It calculates the β angle in 3D, representing the difference between the user's angle and the target angle in quaternion format.

Screwing Tool

The screwing tool had two parts and was based on original screwing tool images. The first part was the body, which was the visible and interactive component of the tool. It enabled users to hold the screwing tool in designated positions using either the grip or the ears (Figure 4). Unlike in real life, users could not hold the screwing tool with both hands in our VR experience.

The second part was the screw part, which was designed for interactions with screwing points and visualization of the screw. By default, the screw part was hidden and could only be activated by touching the screw-holding boxes on the table. This interaction mimicked the loading action of a screwing tool in real life.

Only loaded screwing tools (Figure 4), where the screw part was activated, were allowed to interact with the screwing points. During the screwing phase, the screwing tool snapped to the screwing point and allowed the user to screw-down (Figure 5). During this process, the screwing tool rotation

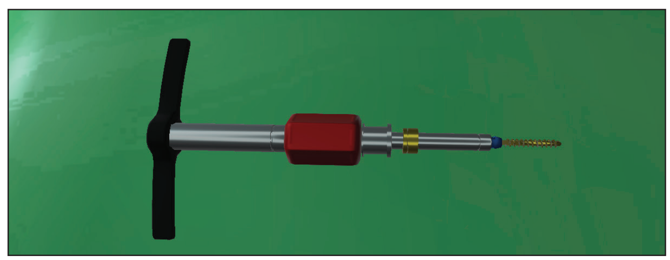

Figure 4: Screwing tool that is used in the VR simulation.

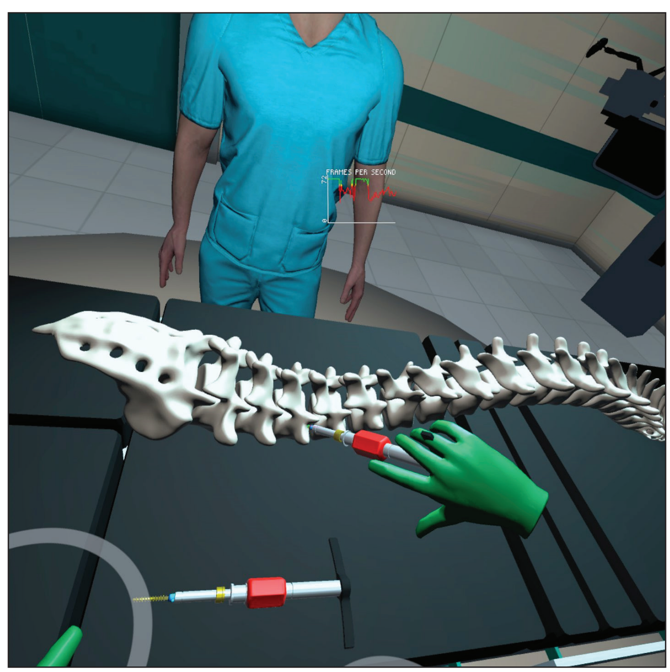

Figure 5: Screwing phase within the VR application. Surgeons navigate the virtual environment to precisely position spinal screws, simulating a real surgical procedure.

angle was calculated, and the screwing tool was moved in the vertical axis. The screwing phase ended when the screwing tool moved more than the targeted distance, and the screw was set to the point as a child object.

Assessment Tool

Participants, consisting of neurosurgery and orthopedic residents and specialists, were instructed to apply cervical, thoracic, lumbar, and sacral posterior screws using the VR module. Each participant underwent a qualitative assessment of the use of the VR module and quantitative testing before and after the module.

Instructions were provided on manipulating and positioning the spine model and selecting and using the tools available in the simulation. After familiarization with the environment, the participants were taught the steps involved in spinal instrumentation in VR. The screw entry points and their relationship with neural structures that could be damaged during instrumentation were also taught. The participants easily manipulated the model and evaluated it from all angles. The same standardized test was administered after the procedure. A second questionnaire was administered to the participants to objectively assess the acceptability, usability, and satisfaction of the VR simulator. The entire process of screwing on the VR platform is shown in Video 1.

Statistical Analyses

All statistical analyses were performed using IBM SPSS (version 20.0; IBM Corp., Armonk, NY, USA). Descriptive and inferential statistical analyses were performed on the standardized pretest and posttest scores following the simulation session. Data were aggregated across training levels, and trends were analyzed using paired sample t-tests to assess differences in performance between junior and senior trainees. A two-tailed p-value of <0.05 was considered statistically significant.

RESULTS

VR Instrumentation

In this study, standard surgical techniques and methods were employed for each anatomical region during screw placement. In the cervical region, lateral mass screw placement was performed following the well-established Magerl technique. The procedure involved delineating the lateral mass, marking all its boundaries, and creating a reference square by drawing both horizontal and vertical lines. The optimal screw entry point was identified slightly inferomedial to the intersection of these lines. The screw was inserted with a precise orientation, involving a lateral angle of 25° and a superior angle of 25°-30°.

In the lumbosacral and thoracic regions, the junction of the lateral edge of the superior articulated process and the transverse process was employed as the anatomical landmark. The entry point was positioned 2 and 3-mm (mean distance 2 mm) caudal and medial, respectively, to this landmark. The sagittal and axial trajectories adhered to a perpendicular or orthogonal alignment to the sagittal and axial planes of the isthmus laminae. Screw fixation was initiated only when the screw was placed at the correct entry point and angle.

Table I: Summarized Data of Trainees

Variables	Trainees (n=63)
Age, (years)	33.69 ± 9.26
Male/Female	49/14
Training Level	
Junior resident	25
Senior resident	19
Senior surgeon	19
Post-simulation test score improvement	
Junior resident	13.8%
Senior resident	8.7%
Senior surgeon	1.3%

Assessment Questionnaire

A total of 63 participants who used the VR stimulation as a primary application during the 4-day course were included in this study. Of the 63 participants; 25 were junior residents (<3 years in residency),19 were senior residents (≥3 years in residency), and 19 were senior surgeons with at least 2 years of spinal surgery experience.

After engaging with the VR simulation module, the junior residents demonstrated a statistically significant improvement in test scores ($p<0.05$), with an improvement of 13.8% in their postmodule exam scores. Similarly, senior residents also exhibited a significant improvement in their test scores ($p<0.05$). However, the amount of improvement (8.7%) was slightly lower than that in junior residents. The senior surgeons demonstrated only a 1.3% improvement in the postmodule exam scores, which was not statistically significant ($p>0.05$) (Table I).

The majority of our participants found the VR module highly beneficial for their learning process. Specifically, 91.36% of the participants agreed that it was invaluable for comprehending the intricate 3D anatomy of the spinal region, and 82.27% believed it greatly enhanced their understanding of screw entry points and orientations. Approximately 98.18% of the participants expressed that the 3D models created from patient-specific thin-section CT images could potentially enhance preoperative planning (Figure 6). Furthermore, 52.65% of the participants believed that the VR simulation not only improved surgical efficiency but also provided an opportunity to grasp technical intricacies with greater clarity and detail (Table II). Overall, the questionnaire (Supplementary 1) responses and evaluations collectively highlighted the significant utility of the VR application as a potent tool for preoperative planning and surgical training, as evidenced by the statistical significance of the results ($p<0.05$).

DISCUSSION

VR employs a computer processing unit coupled with a head-mounted display to provide users with immersive sen-

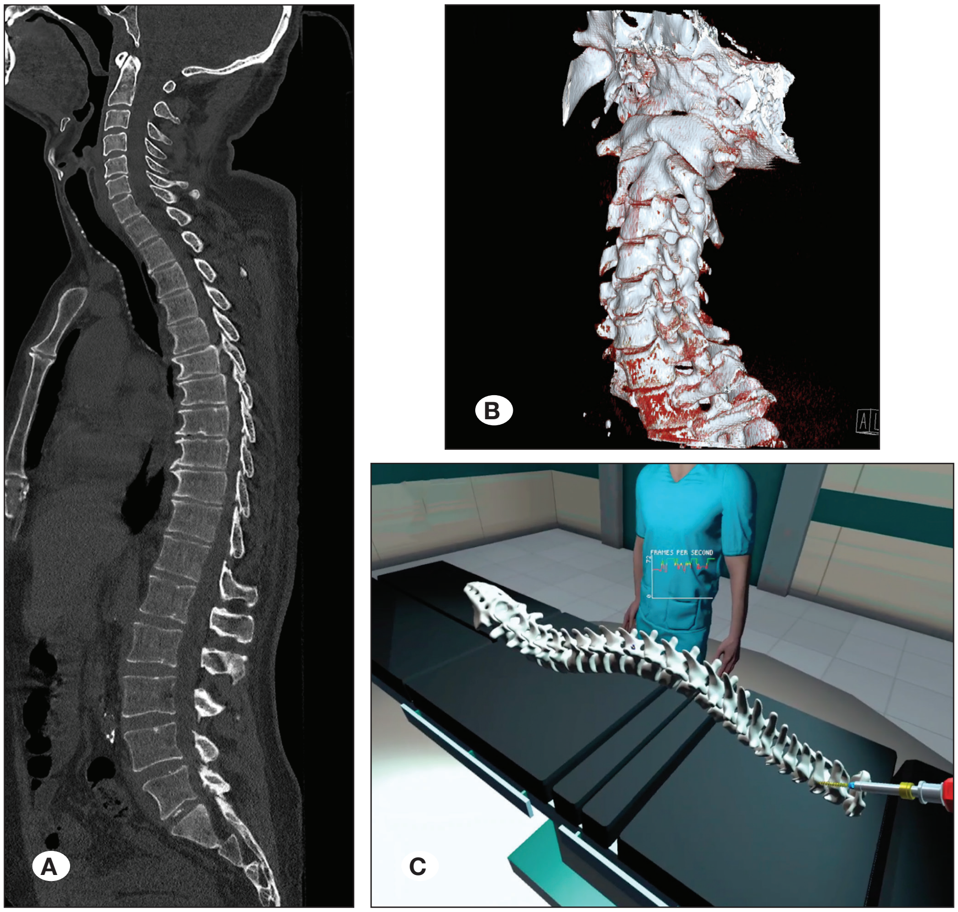

Figure 6: Patient-Specific computed tomography (CT) scan images; **A)** sagittal Section CT image of the patient that was used for virtual reality (VR) modeling, **B)** 3D Multiplanar reformation (MPR) image of the patients cervical region, **C)** patient-specific spine on the virtual reality (VR) simulation.

Table II: Post-Simulation Questionnaire Results of Trainees

Statement	Agreement Rates (%)
Useful tool in preoperative planning	98.18
Teaching tool in learning spinal instrumentation	92.25
Useful for learning the concepts of a screw delivery	82.27
Useful for learning the 3D anatomy of the spinal region	91.36
Benefit in surgical practice	71.27
Useful for learning new techniques	73.89

sory experiences. It goes beyond visual and auditory cues, incorporating controllers with position trackers and force feedback which enhance engagement (17). Applications of VR simulations within the healthcare sector are evolving parallely with the rapid technological developments in computer processing. Over the past decade, the acceleration of these technological advancements has driven a surge in the adoption of AR and VR in healthcare. This acceleration is particularly prominent in the fields of neurosurgery and orthopedic surgery, where VR can be used for educational purposes, preoperative planning, and immersive surgical simulations (5,17,22).

Our VR education tool was meticulously crafted through a series of ideation and focus group studies and involved the collaboration of educators, researchers, and designers. In the ideation study, we delved into potential approaches for developing the VR educational resource by addressing the research problem and objectives at hand. Subsequently, in the first focus group study, our designers unveiled a prototype based on the insights gained during the ideation study. This initial prototype featured early renditions of scenes and object/tool models. During this stage, we meticulously discussed the finer points of the model design and user experience. Based on these discussions, a second focus group study was conducted, the prototype was further refined, and the final VR simulation used in this study was developed.

Limited patient exposure, the high cost of time-consuming practical studies and malpractice proceedings, and increased patient safety concerns have paved the way for the development of novel and highly effective educational approaches (6). Given the complex and variable nature of the spinal anatomy, the ability to virtually visualize and interact with a patient's spine from all angles preoperatively confers significant advantages in preoperative planning (20). In the field of spine surgery, VR has emerged as a subject of great interest and is increasingly being integrated into educational simulations. Its potential lies in enhancing surgical techniques while minimizing the margin for errors that could have dire consequences for live patients (21). There are plans to incrementally expand the use of VR simulations in preoperative planning within clinical settings. One of the major benefits of these systems is that they afford medical students and residents the opportunity to practice surgical procedures in a controlled environment before performing them on live patients. Thus, they enhance cost-effectiveness and utility.

Our VR tool, designed for surgeon education and preoperative planning in the field of spinal surgery, offers several invaluable benefits. One of its key advantages lies in its ability to provide an immersive, 3D visualization of a patient's spinal anatomy. Because it uses patient-specific thin-sliced CT images, this simulation can be used in the preoperative planning of difficult cases. This not only enhances the surgeon's understanding of the complex and variable spinal structures but also allows for meticulous examination from every conceivable angle. By simulating surgical scenarios in a risk-free virtual environment, our tool facilitates in-depth exploration of the surgical procedure, refinement of techniques, and minimization of the possibility of errors. Furthermore, it fosters a dynamic learning environment for medical students and residents, enabling them to practice surgical procedures extensively before engaging in live surgeries. Beyond these educational merits, our VR tool is a cost-effective solution, significantly reducing the training expenses associated with traditional methods.

Cadaveric dissection is the most important part of microsurgical neuroanatomy training. Identifying the complex neural spinal structure and the neighboring structures in detail is an important step in spinal surgery. However, because cadavers are expensive and disposable, the necessity of a good neuroanatomy laboratory and the inability to practice everywhere are among the most important issues. With the VR system, it is possible to practice repeatedly in any environment. In addition, it will significantly reduce the training costs. In a previous study, we emphasized that with the VR system, various approaches in addition to spinal instrumentation can be performed, such as cadaver microdissection (2). In this VR simulation, we developed a dynamic learning environment for medical students and residents. Our VR tool is a cost-effective solution that significantly reduces the training expenses associated with traditional education methods.

The risks associated with instrumentation are well known. The desire to perform instrumentation with minimal complications, which is indispensable in today's practice, has been the driving force for many platforms simulating pedicle screw fixation. The correct placement of a pedicle screw requires a good understanding of the 3D anatomy of the spinal canal (4,7). With VR simulations, the patient-specific whole spine 3D models can be examined from all aspects, allowing for accurate preoperative planning. In addition, watching videos with theoretical information before screw placement in each region ensures that residents and students are always up-to-date. Thus, the VR simulation method, which is considered an important learning tool, is increasing in popularity in spinal surgery (8).

Hou et al. conducted a study in which 5 of 10 residents with no prior surgical experience were instructed on cervical pedicle placement using VR simulation. They compared the success of screw placement in cadavers by the five trained residents with that of the residents who did not receive VR simulation training. In the study, the VR training tool demonstrated better results than the standard teaching techniques in improving the performance of novice residents in appropriately placing cervical pedicle screw. The 3D model used for simulation in the study by Hou et al. was derived from 3D CT section; simulation with real cadaver images would have been even more beneficial (10).

In a cadaver study, Zhou et al. reported that more accurate and faster screw placement was performed on the side where surgical planning was performed with VR simulation than on the side without preoperative planning (25). In another similar study by Zheng et al., they found better fluoroscopic and positional timing when VR was used for preoperative planning than when not used (24). Lafage et al. investigated the use of VR to compare preoperative and postoperative images of patients with adult spinal deformities. They reported that the use of VR for 3D reconstruction could greatly benefit this assessment and potentially assist in decision-making (12). Zawy Alsofy et al. concluded that the VR technique can help in planning surgical approaches and treatment strategies, and the simulation effect was reported to be moderate (23).

Additional benefits of VR have also been mentioned in the literature. In a study that highlighted new and exciting opportunities to improve patient function and outcomes, Maresca et al. reported better responses in balance, motor, and cognitive skills when VR was combined with traditional rehabilitation protocols than traditional protocols alone (14). Sengupta et al. demonstrated the positive effects of VR games on rehabilitation programs in patients with spinal cord injuries (18).

In this study, we found that the junior residents benefited the greatest from using the VR spinal instrumentation module as a learning tool. Even after a brief learning session and hands-on interaction with the module, junior residents demonstrated significant enhancements in their understanding of spinal instrumentation and screw entry points. This module allowed various screw application techniques to be practiced repeatedly in different spine segments and offered the advantage of tracking screw placement from several perspectives due to its comprehensive 3D spinal model. Strong endorsement for this educational tool was evidenced by the fact that 92.25% of the participants recognized its pivotal role in mastering spinal instrumentation. Furthermore, 82.27% of the participants highlighted its significance in elucidating the complexities of screw placement, which affirms the substantial utility of VR simulations in the educational domain.

CONCLUSION

This study highlights the promising role of VR-based surgical training, particularly for junior residents, in improving the understanding of spinal instrumentation. Although senior surgeons demonstrated limited improvement, the technology's potential in facilitating preoperative planning and skill acquisition is evident. These findings support the integration of VR as an essential tool for enhancing neurosurgical education and patient care, with particular value for new neurosurgeons.

Declarations

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Availability of data and materials: The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Disclosure: The authors declare no competing financial interests and no sources of funding and support, including any for equipment and medications.

AUTHORSHIP CONTRIBUTION

Study conception and design: MYA, OB, OA

Data collection: MYA, EO, EAU, TO, GA, AFO

Analysis and interpretation of results: EAU

Draft manuscript preparation: MYA, OB, EAU, OA

Critical revision of the article: MYA, OB, OA

Other (study supervision, fundings, materials, etc...): MYA, OB, EO, TO, GA, AFO, OA

All authors (MYA, OB, EO, EAU, TO, GA, AFO, OA) reviewed the results and approved the final version of the manuscript.

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