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The Use of Vibrotactile Haptic Feedback for a Neurosurgical Virtual Reality Training System

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Abstract **–** Virtual Reality (VR) in surgical simulation is an evolving field with the potential to overcome traditional limitations in surgical education. Depending on the curricular need, the addition of haptic feedback can improve the environment's realism. This work presents a novel haptics-enabled VR simulator designed to enhance the placement of an external ventricular drain (EVD) during neurosurgical training through the integration of haptic technology. The simulator, developed using open-source software such as Blender, GIMP, and Unreal Engine, offers high-fidelity 3D models and realistic material interactions. By leveraging the SenseGlove NOVA haptic gloves, the simulator provides force feedback and vibrotactile sensations, enhancing realism. Results demonstrated accurate simulation of the surgical procedure, with oscillating force feedback providing realistic burr hole creation, and haptic feedback providing necessary sensations throughout catheter insertion. Due to current limitations in providing solely vibrotactile feedback, future research involves seamlessly integrating kinesthetic feedback along with the vibrotactile feedback, to further enhance accuracy and realism. Although future improvements are required, this device shows that the integration of haptic feedback not only enhances the realism of surgical simulation, but also provides structured quantitative feedback, providing the potential to improve trainee proficiency. This simulator represents a significant advancement in surgical training, with the potential to revolutionize the field by bridging the gap between virtual training and immersive haptic technology.

Keywords**:** haptics, haptic feedback, virtual reality, surgical simulation, haptic gloves

1. Introduction

Virtual Reality (VR) in surgical simulation is emerging as a constantly evolving field with the potential to address the current limitations of the surgical education system. While the theory of 10,000 h to master a skill remains the norm in surgical programs [1], limitations to this system can include: limited access to cadavers and animals, high costs, and concerns to patient safety. The evolution of VR surgical simulators offers a method of addressing these limitations, while providing structured, quantitative feedback on the surgeons' performance [2].

A current focus of this field of research is the integration of realistic haptic feedback [3]. While existing studies showcase the acquisition of surgical abilities using inanimate simulators, these studies lack the ability to accurately quantify the surgeon's abilities. This can be attributed to the fact that many current VR simulators lack haptic feedback, resulting in low immersion within the environment, as well as inaccurate quantitative feedback on the surgeons' capabilities [4]. While certain studies have attempted to address these challenges, few were able to create a neurosurgical environment that offered a combination of both haptic feedback and an effective method of quantifying the trainee's abilities.

In response to these limitations and recognizing that haptic gloves are a new and emerging technology, the proposed simulator in this paper aims to develop residents' accuracy and speed during an External Ventricular Drain procedure, through the use of haptic gloves. This procedure is often done by the bedside, by junior residents on call, and therefore it is important for them to master the procedure early in their career [5], the proposed simulator aims to develop these skills in a way that can potentially minimize the risks associated with live patient operations [6], [7]. Insertion of an EVD starts with finding the correct spot, as well as trajectory, on the head of the patient. Then the skin is cut, and a drill is used to create a small burr hole on the skull of the patient. The dura is then open, and a catheter (about 5-6mm thick) is advanced in the brain using external landmarks to orient to the best trajectory, until the ventricle is reached. At that point, the wall of the ventricle (ependyma) is pierced which is felt by the surgeon as an increased resistance, followed by a quick loss of resistance.

This paper will present the development of a haptics-enabled VR simulator for the purpose of EVD placement, while emphasizing the use of SenseGlove NOVA haptic gloves. The proposed tool will evaluate the surgeon's proficiency in performing the operation by employing both haptic feedback and accurate performance assessment metrics. Recently, there has been a significant evolution in haptic gloves designed for hand-based human-computer interaction. These advancements include real-time tracking of hand and finger poses, coupled with vibrotactile feedback, thereby improving the user's ability to immerse themselves within the environment, thus enhancing the training experience.

2. Methods

The graphical environment was created through a combination of Blender**,** GIMP**,** and Unreal Engine. For the purpose of developing a simulation as realistic as possible, 3D models required realistic details, and the material interactions within the environment needed to have a high level of accuracy. As seen in the simulator flowchart presented in Figure 1, models were acquired and subsequently imported into Blender and GIMP for further refinement. This process involved implementing mesh repair algorithms within the software to rectify topological and geometrical errors as well as scaling and enhancing mesh resolution to align with the simulator's visual and computational demands. The collision detection algorithms for object interactions within the Unreal Engine platform proved to be sufficient in enabling the simulation of a burr hole in the patient's skull. Other elements in the environment underwent modifications using a combination of Blender and GIMP to ensure the creation of a precise graphical environment.

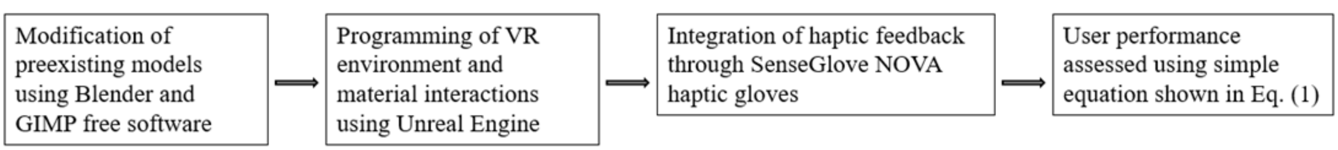

Fig. 1: Outline of the development of the proposed simulator.

The prominent feature of the simulator was the vibrotactile feedback generated by the SenseGlove NOVA haptic gloves. Once the user enters the VR environment, they can immediately synchronize the coordinates of the gloves into the haptic environment, as shown in Figure 2. The haptic gloves function by providing resistive force feedback to the user, through four brakes dedicated to each finger from the thumb to the ring finger. The variability in amount of force (which is transferred to the fingertips through mechanical wires) depends on the material properties of objects within the VR environment. Manipulating harder objects generates more resistive forces and this enables creating different haptic feedback during interaction with different objects. In addition, the SenseGlove NOVA haptic gloves can generate vibrations which proved immensely helpful in enhancing the realism of the simulator, especially in replication of drill operations. As the intensity of the haptic feedback varies during interactions with different objects, the vibrotactile sensation on the user fingers provide additional cues for the user to conduct the operation with more resemblance to actual surgery. For example, the intensity of the feedback oscillated as the drill passed through tissue and air before reaching the skull, at which point its intensity reached a maximum until the skull had been fully penetrated. After penetration, the intensity dropped to a minimum indicating that the surgeon should immediately stop the drill. Also, the intensity of drill vibration was scaled based on the contact of the drill with different material of skull. The detection of contacts was accomplished using the built-in collision detection algorithms in Unreal Engine. The calibration of these vibration intensities was meticulously determined through a rigorous process of trial and error, conducted in collaboration with expert neurosurgeons.

Fig. 2: User calibrating the SenseGlove NOVA haptic gloves prior to starting the procedure.

3. Results/Discussion

Accurate simulation of the surgical procedure was achieved through meticulous assignment of material properties within the Unreal interface. By modulating the provided force feedback as the drill passed through air then tissue prior to penetrating the skull, the creation of a realistic burr hole, as depicted in Figure 3, was effectively replicated. Optimal simulation accuracy was observed with oscillation levels set at a multiplication factor of 3 upon tissue contact and a factor of 5 upon skull contact. Furthermore, the sensation of drill vibration experienced by the user was simulated. This was made possible by generating resistive force feedback to the fingers in contact with the drill, proportionate to the degree of finger curling detected. Simulation of the insertion of the catheter was made possible through both the features of the haptic gloves used in the simulation, as well as the user interface of Unreal Engine. The user interface made it possible to apply feedback to the trainee once the catheter made contact with the patient's head, and using the features of the gloves, haptic feedback was generated to provide a "popping" sensation to the user when the ventricle was punctured. Additionally, the interface made it possible to add a "ghost hand" feature shown in Figure 4, in which the user could monitor the speed at which they moved their hand compared to how fast it should theoretically be moving. Using simple Euclidean geometry, the performance score of the trainee was calculated using a basic equation shown in Eq. (1). This equation ensured a comprehensive evaluation of trainee proficiency, through assessing the procedure completion time as well as the deviation from the ideal insertion trajectory.

$$\text{Score} = \text{N} - (t_h * d_h) - (t_c * d_c) \quad (1)$$

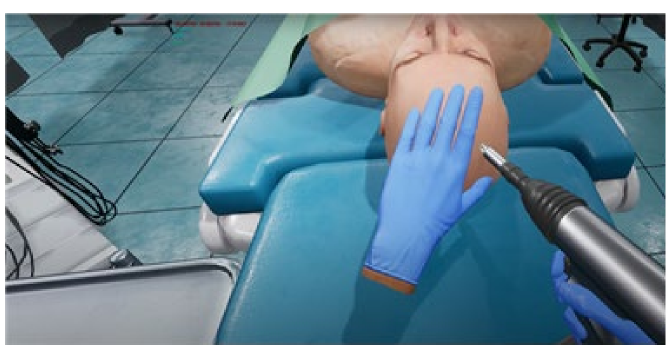

Fig. 3: Screenshot of user applying virtual drill to patient's head while haptic feedback is being applied.

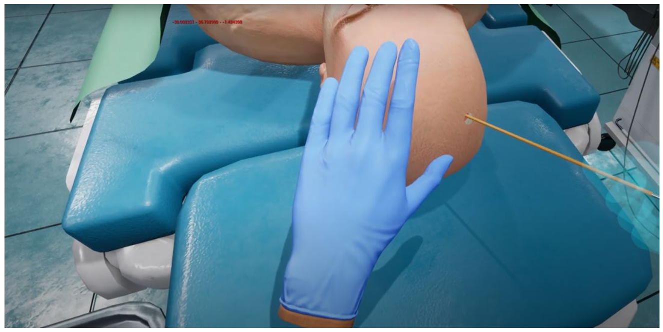

Fig 4: User inserting catheter into the virtual patient's skull. Transparent blue hand represents user's hand in real life, while the blue gloved hand represents the user's hand in the virtual environment.

4. Conclusion

The added haptic feedback to a neurosurgical simulator for external ventricular drain insertion allows for the trainee to have some constant and immediate feedback while advancing the catheter. A formal evaluation of the added value needs to be done, however a qualitative questionnaire given to trainees during a neurosurgical bootcamp showed that the addition of the haptic was appreciated. While the utilization of haptic technology in this simulator holds considerable promise, it is important to acknowledge the existing limitations. Despite the use of one of the latest commercially available haptic gloves, the current version of the simulator is restricted to providing solely vibrotactile feedback, lacking the inclusion of kinesthetic feedback. In addition, the number of procedures that can be trained using these types of gloves is also limited. This presents the conclusion that ongoing research and refinement is still needed to enhance the simulator's effectiveness. Future work should focus on exploring methods to seamlessly integrate both vibrotactile and kinesthetic feedback within the simulator, thereby enhancing its accuracy and realism. This is crucial for maximizing the efficacy of the training device. Nevertheless, the potential of the proposed simulator to revolutionize surgical training is present. Its ability to replicate not only the surgical procedure but also the nuanced vibrations and movements involved represents a significant advancement in the field of surgical education and performance assessment.

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