Comparative Design and Analysis of Multimodal VR Simulations for IV Needle Insertion Training

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***Abstract*— This study introduces a novel Haptic Virtual Reality (HVR) simulator for intravenous (IV) needle insertion training, aiming to enhance traditional methods like manikins. Developed using a Meta Quest 2 headset, it incorporates two haptic devices: a haptic glove (SenseGlove Nova) for stabilization and a haptic stylus (Geomagic Touch) for needle insertion simulation, all integrated within Unity. A second prototype using a VR touch controller was created for user performance comparison. Both prototypes provide immersive experiences for hand-eye coordination and psychomotor skills. An evaluation experiment with 23 nursing students compared the systems to a previously developed Haptic Mixed Reality (HMR) version. Over three weeks, with three 10-minute training sessions, improvements in success rates and confidence were observed. The study included a Task Load Index assessment, indicating a manageable workload. Results suggest the HVR IV needle insertion simulator's potential to enhance nursing education.**

Keywords*— *haptic feedback, multimodal touch interfaces, VR simulation, intravenous needle insertion, nursing education.

I. Introduction

Intravenous (IV) insertions are common but challenging procedures [1], with experienced nurses achieving a success rate of 71.2% to 77% [2-3]. Unsuccessful attempts cause unnecessary discomfort to patients. Traditional training methods using manikins have limitations, including rapid deterioration, a lack of variability, and a high waste of medical supplies. In addition, the manikins lack realism and do not provide the variability in skin color and texture, vein size, and stiffness that nurses encounter in real-life situations. Each practice on a manikin also requires a new IV needle, leading to waste.

Virtual reality (VR) and haptic technology can revolutionize biomedical education by providing a safe, realistic environment for practice. Wang and Fenster [4] developed an interactive 3D simulation for needle insertion in brachytherapy, implementing dynamic soft tissue deformation. A 2-degree of freedom (DOF) haptic injection simulator, providing a realistic feeling of a needle penetrating various tissues, was introduced in [5]. A haptic-enabled VR renal puncture system was proposed in [6]. The system utilizes a novel force model for trocar needle puncture on a multi-layered kidney simulation. A dynamic insertion force model for needle insertion simulation was introduced [7]. A multimodal VR platform for dermatological surgery procedures was developed in [8] and [9], enhancing user performance and realism with haptic feedback.

In addition, Abounader et al. [10] developed a bimanual haptic VR simulator for ingrown toenail removal surgery, including needle insertion for anesthesia, using two Geomagic Touch devices. Several studies have proposed VR training simulators for different ultrasound-guided needle insertion procedures, including biopsy training [11], regional anesthesia administration [12], percutaneous transhepatic cholangio-drainage [13], and articular and soft tissue injections [14]. A visuo-haptic simulation framework for needle insertion, capable of rendering patient breathing motion, was introduced [15]. A novel force model for a biopsy therapy training simulator, accounting for respiratory motion, was proposed [16]. The studies show that VR training improves learning motivation, competency [17], efficiency, and quality with reduced error rates in medical students [18]. A recent systematic review explored that 2/3 of the studies reported faster learning and better performance with haptic feedback in VR training for surgeons [19].

Several studies have demonstrated alternative approaches using augmented reality (AR) or mixed reality (MR). The system proposed in [20] employs a PHANToM haptic device to provide force feedback during insertion. In [21], an AR-based haptic neurosurgical simulator provides surgeons with a natural way to learn neurosurgical skills while demonstrating its high accuracy. In our prior study, Kim et al. [22] introduced a bimanual haptic mixed reality (HMR) simulation for IV needle insertion using a Geomagic Touch and a Dexmo haptic glove. This simulation system showed potential as a training tool, but further studies are needed to evaluate its effectiveness in learning within schools or clinics. A subsequent study [23] explored visual and haptic variabilities that create perceptual challenges in real clinical settings when performing IV needle

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insertion procedures. Despite its potential, the HMR system has limitations. For instance, the realism of its graphical image can be affected by lighting conditions, a problem not present in VR systems. Consequently, our work extends beyond the HMR-IV framework by incorporating VR technology instead of MR technology. This expansion aims to investigate the learning impact across different hand-eye modalities: VR with a haptic glove, VR with a touch controller, MR with a haptic glove, which has not been explored before.

II. Development of Haptic-VR IV Needle Insertion Simulation

For an IV needle insertion procedure, nurses are trained to stabilize the patient's hand with their non-dominant hand, while using their dominant hand to insert the needle. As shown in Fig. 1, several devices are used to create a realistic training setting that facilitates the development of bimanual coordination between the hands and eyes. For the graphic rendering, 3D models of a medical needle and a patient in a hospital bed are displayed using the physically based shader [24] via Unity's built-in render pipeline. The scene is rendered on the PC and displayed on Meta Quest 2 through Quest Link. The haptic rendering module is designed to simulate the interaction between target mesh objects (a virtual patient's hand and a vein) and two virtual haptic objects (a user's hand for stabilization and an IV needle for insertion). These virtual haptic objects are synchronized with their corresponding haptic devices, the SenseGlove (SG) Nova and the Geomagic Touch. The module detects collisions between these entities and calculates real-time force feedback. This allows the user to experience a realistic sensation of touching a virtual patient's hand and the feeling of inserting a needle.

The HVR needle insertion simulator is a VR adaptation of the bimanual HMR simulator presented in [23]. This HVR simulator also allows the user to hold the VR touch controller instead of using a haptic glove, but in this case, only vibrational feedback is provided. The VR controller was integrated into this system as an interaction method for several reasons: Firstly, the use of VR introduces an interface that is not available in MR

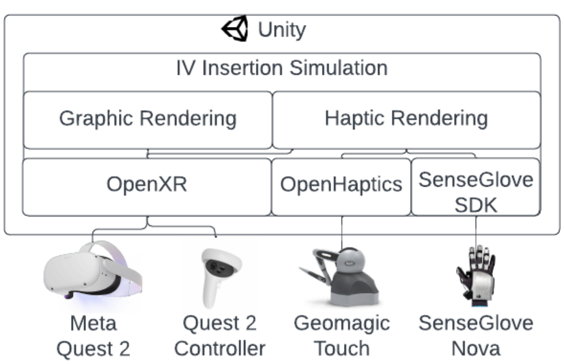

Fig. 1. The system architecture of the bimanual HVR IV needle insertion simulator.

(e.g., robustness against varying lighting conditions); Secondly, reducing the number of haptic devices makes the system more cost-effective and accessible; Lastly, comparing the training effectiveness between the controller and the haptic glove may provide valuable insights and new design guidelines.

Making the system VR-compatible required removing the MR components, such as the Mixed Reality Toolkit, and adding the OpenXR plugin. An XR Origin object containing the main camera was added to the hierarchy in the Unity scene, and the left-hand controller profile prefab was assigned to the left-hand controller object. The XR Origin object is a prefab in the OpenXR plugin with all the necessary scripts and objects to incorporate a VR device, allowing for a quick setup. Next, the hand mesh model, provided by the SG SDK, was added as a child object of the left-hand controller so that it would follow the user's hand as they held the controller. Since the left hand can be controlled by either the haptic glove or touch controller, two hand objects exist in the Unity scene hierarchy: one for the glove mode and one for the controller mode. A script managing the logic of which mode is active enables the respective hand model and deactivates the other. For the hand object associated with the glove, an SG prefab was used, and the touch controller was assigned as the tracking object.

The SG SDK only provides interaction with simple colliders, so a box collider was placed around the patient's hand so that when the Nova glove was used to grab the patient's hand, it would interact with the box collider and appear and feel like it is grasping the patient's hand. When stabilizing the patient's vein, nurses are instructed to place their thumb below the insertion site. To simulate this, a small sphere collider was placed below the target insertion area to interact with a sphere collider on the user's virtual thumb. Two other sphere colliders were placed at incorrect locations on the patient's hand (by the thumb and wrist), so the user would have to choose the correct location. Only when the thumb is colliding with the correct sphere collider and the fingers are underneath the patient's hand is the grip considered correct.

When using the controller, the virtual hand does not have any physics applied, allowing it to pass through objects to keep immersion intact. If the hand had physics and collided with an object, it would stop or roll over the object, breaking immersion. To strike a balance with pass-through and still be able to interact with the patient's hand, the hand is designed to snap into position when the controller is touching the sphere collider and the select button on the controller is pressed. The controller also vibrates when they initiate the grasping to confirm their stabilization. This allows the virtual hand to follow the controller's position when necessary and provides an easy way to grasp the patient's hand when the user intends.

The Geomagic Touch is used to control the virtual needle by attaching it to the haptic grabber prefab provided by OpenHaptics. Haptic rendering for needle insertion utilizes the force-profile-based haptic rendering algorithm developed in [22]. The simulator was designed to offer two distinct modes: the training mode and the test mode. In the training mode, the user can see the virtual patient's hand and some data readouts indicating the needle's angle and the needle tip's state (outside skin, inside skin, inside vein, and passed vein) as seen in Fig. 2.a. In the test mode, the user cannot see live visual feedback such as the needle angle, needle state, or if they are grasping the patient's hand correctly. The exception is that the user will still see blood entering the needle upon successful vein entry, as shown in Fig. 2.b.

III. Experiment

We conducted an experiment to assess the usability and learning impact of the HVR IV needle insertion simulator. The study involved three groups, each assigned to a different condition. The first group used the haptic glove for the stabilizing (left) hand interface and VR for the graphical rendering (HVRG). The second group used the touch controller for the left-hand interface and VR for the graphics (HVRC). The third group used the haptic glove and the Microsoft HoloLens 2 for visualization (HMRG).

It is essential to conduct a comparative analysis between the newly developed HVR system and the previously developed HMR system to assess any improvements in learning potential during the transition. This comparison will evaluate both systems' usability and learning outcomes, revealing any benefits introduced by the VR version. For consistency, all participants used the same patient model despite the system's ability to provide visual and haptic variability. The study's learning impact portion included 23 participants (7 males, 16 females, 1 non-binary) with an average age of 22. Among them, 16 were majoring in nursing and 7 in computer science. Participants were divided into 3 groups with an even distribution of nursing students. Participants comprised 14 novices and 10 intermediates regarding IV insertion experience. Handedness distribution was 22 right-handed and 2 left-handed. All participants were Kent State University students and signed the informed consent form as required by the Institutional Review Board. We used a usability questionnaire to gather qualitative data and automatically collected quantitative data through the simulator. The measured data collected includes needle position, needle state, needle angle, insertion time, and thumb position. Based on these metrics, the success of each participant's attempts can be determined. The system also records the number of successful insertions and failures due to missing the vein, passing the vein, having the wrong insertion angle, and having the wrong grip, allowing for a quick assessment of the participant's success rate.

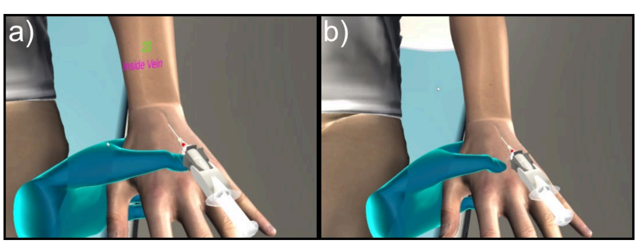

Fig. 2. Simulation of hand stabilization and needle insertion using virtual haptic objects, corresponding haptic devices, the SenseGlove Nova and the Geomagic Touch: (a) Example scene in the training mode. (b) Example scene in the test mode.

The experiment lasted for 3 weeks. Each participant had a scheduled time to practice on the simulator for 10 minutes once a week. In the first session, the participants were allowed to familiarize themselves with the system. Then, they performed a pre-test, where they attempted to execute 5 needle insertions, receiving no performance cues other than seeing a flash of blood enter the needle if they entered the vein. After the pre-test, they received 10 minutes of training with feedback on their performance. In the second session, participants only performed the 10-minute practice session. In the third and final session, participants performed the 10-minute practice session first, followed by the post-test, which was identical to the pre-test. Following each attempt, participants were prompted to evaluate their confidence level in their insertion on a scale from 0 to 100.

IV. Results and Discussion

A. *Evaluation of Usability*

This system intends to provide bimodal control for IV needle insertion training. Ensuring a proper grip to stabilize the patient's hand is key to a successful insertion and is one of the metrics used to determine success. While the HMRG group shows a consistent grip (stabilization) success rate between pre-tests and post-tests, the HVR groups do not demonstrate the same consistency, as shown in Fig. 3. This inconsistency suggests that further study is necessary to investigate the causes of grip and stabilization failures over time in a VR environment within the HVR system. This investigation will form the basis of our future research to improve usability.

At the end of their first session, participants completed a NASA Task Load Index (TLX) and usability questionnaire. They rated the task load in terms of mental demand, physical demand, temporal demand, performance, effort, and frustration. The total workload is determined by taking the average rating of all dimensions except performance. Fig. 4 shows a comparison of the ratings for all three groups. According to NASA TLX data and subjective user comments, users generally find it comfortable to use either combination - a haptic glove with an IV haptic needle or a VR touch controller with an IV haptic needle - in the VR simulation environment. It was also observed that while the VR touch controller offers relatively

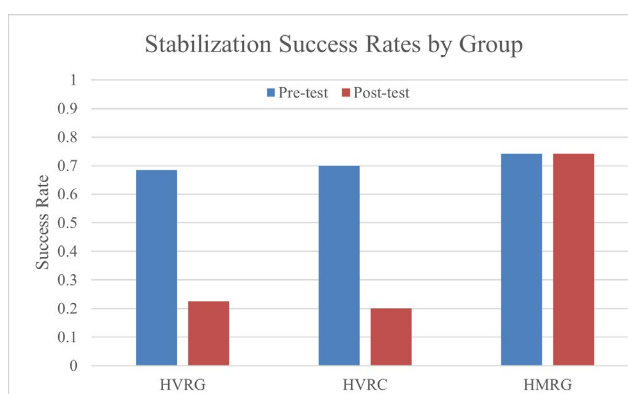

Fig. 3. A comparison of the successful grip rates across all groups

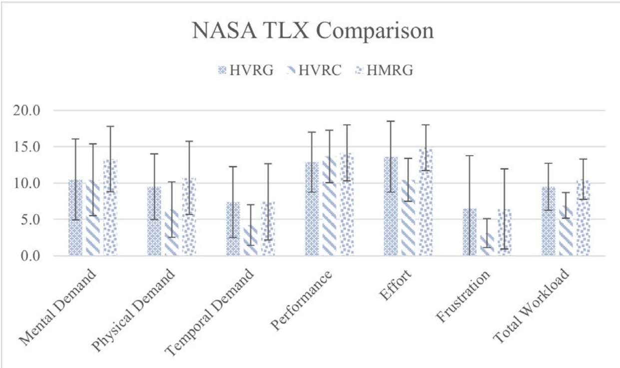

Fig. 4. A comparison of group mean NASA TLX ratings.

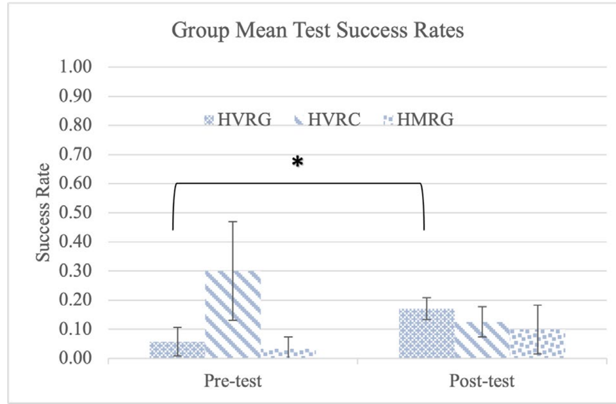

Fig. 5. A comparison of group mean success rates for pre-test and post-test.

easier grip and stabilization through the use of controller buttons, it may not contribute to the improvement of natural grip and stabilization motor skills required for IV needle insertion procedures as effectively as a haptic glove. This observation suggests a need to redesign the VR controller interface to advance its effectiveness in motor skill learning, which is part of our future plan.

B. Assessment of Learning

The simulator automatically collected participants' performance data during the test and training sessions. The success rate is determined by several criteria. First, when the user inserts the needle into the patient's vein, the needle must be between 10 and 30 degrees. Second, the needle must enter the vein. Third, the needle must not penetrate past the vein. Fourth, the user must correctly stabilize the patient's hand with their left hand while inserting the needle. If all these criteria are met, the attempt is successful. An individual's success rate is calculated by dividing the number of successful attempts by the total number of attempts. After collecting all data, outliers were removed using the Interquartile Range method [25]. While test success rates are low across all groups, the HVRG and HMRG groups show an improvement from pre-test to post-test scores, as shown in Fig. 5. A paired t-test conducted on the HVRG group showed a statistically significant improvement in post-test success rates ($p = 0.03$). In contrast, t-tests conducted on the other groups did not reveal statistically significant differences in their success rates. This result validates the effectiveness of the HVR system using a haptic glove in training IV needle insertion skills over a short period of time (3 weeks). While the HVRC group shows an overall decline in success rate, the pre-test scores show much higher variability compared to the other groups, indicating there still may be improvement from individuals within the group.

Participants only received three ten-minute training sessions sequenced one week apart. Even with a small amount of training, participants experienced an improvement in success rates. While test success rates appear low, participants were observed having failed attempts due to improper stabilization, even though participants were generally grasping the correct area. This error stemmed from two issues: First, many participants in the HVRG group had smaller hands and struggled to maneuver the virtual hand accurately. This was due to the haptic glove's inability to detect the full range of motion of their fingers. Second, participants in the controller group occasionally found it challenging to maintain their grip on the patient's hand. This was because the controller's grasping feature depended on the collider attached to the controller staying in contact with the sphere collider on the patient's hand. If the participant's hand waivered, the virtual hand would lose connection with the patient's hand. If this disconnection occurred during needle insertion, the system would count that as a grip failure. Future iterations should focus on addressing these issues to enhance usability and training efficacy.

The mean confidence level for each group is depicted in Fig. 6. While there is variability among the groups, all of them experienced an increase in confidence from the pre-test to the post-test. Paired t-tests for each group show a significant difference in mean confidence between the pre-test and post-test for the HVRC ($p = 0.045$) and HMRG ($p = 0.03$) groups. This suggests that training with this simulator has a positive influence on participant's perceived confidence, regardless of modality.

V. Conclusion

This study presents a bimanual HVR simulator for IV needle insertion, addressing the challenges faced by nursing students in mastering this critical skill. We developed an HVR simulator using Unity, offering an immersive and repeatable training

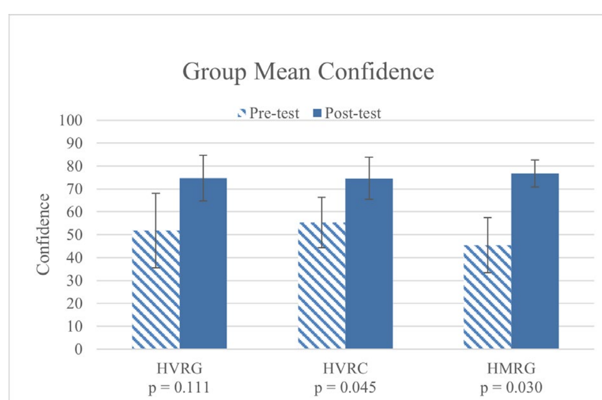

Fig. 6. A comparison of group mean confidence for pre-test and post-test.

experience. The presented simulator integrates haptic feedback, enhancing realism and skill development. The experiment results indicate an overall improvement in success rates and confidence over the training sessions. The NASA TLX and usability questionnaires revealed a manageable workload across groups. Overall, our HVR IV needle insertion simulator demonstrates the potential to enhance nursing education by providing a cost-effective, repeatable, and realistic training solution for this essential skill.

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