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Evaluating Variability in a Haptic Mixed Reality IV Needle Insertion Simulation

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Abstract—As virtual training simulators prove to be an effective learning method, we set out to develop a haptic mixed reality training system for intravenous (IV) needle insertion with variability. IV needle insertion is an essential skill for nurses to master. Traditional learning methods for IV insertions do not offer much variability, which can lead to lower confidence when a new nurse faces an IV insertion task on patients with high variability. This study first looks at what visual variable factors most influence the perception of difficulty for needle insertion through text and image-based surveys. These variables are skin color, vein size, and tattoos. Next, it implements these variables into a mixed reality scene where nursing students can visualize a 3D patient with variable characteristics. After gathering data on the perceived difficulty of variable characteristics, this study combines the visual variability in mixed reality with a virtual training system with haptic feedback, allowing nursing students to train with variability.

Keywords—haptics, mixed reality, needle insertion, training, education

I. INTRODUCTION

Inserting an IV catheter into a patient's vein is an essential yet difficult skill for nurses in the healthcare field to master. To add to the task's difficulty, nursing students do not have a way to practice these skills safely yet robustly. Most low-risk practice scenarios do not provide enough variability to prepare students for real-life scenarios. Additionally, after many practice rounds on a manikin IV training arm, it becomes apparent where the student should place the IV since they can see all the holes from previous practice rounds. With the rising popularity and use of haptic rendering, there has been growing interest in using simulation-based training. This work aims to contribute to those investigations by creating a haptic simulation for IV needle insertion. This system could provide an alternative or supplemental training method for IV needle insertion by combining elements in mixed reality and haptic feedback.

Virtual Reality (VR) gives the user an immersive experience by visually blocking out the user's surroundings and displaying a virtual 3D environment. Creating an immersive 3D environment is commonly done through a VR headset that the user wears on their head. Mixed Reality (MR) is like VR, but instead of completely blocking out the user's environment, it blends the virtual environment with the real world. Haptics allows a user to feel a virtual object through kinematic and/or tactile feedback, allowing users to interact with objects using their sense of touch, which enhances immersion when combined with VR or MR. Haptic feedback can also give direction, like in [1], where haptic feedback was used in a system to help surgeons guide the needle during a brachytherapy treatment. In [2], vibrotactile feedback is an intuitive guidance feedback method for virtual grasping tasks. Training simulators for surgery and healthcare have become very popular since they provide a more cost-effective and repeatable learning method. Hollensteiner et al. developed a patient simulator to provide novice surgeons with a safe training method for instrument insertion and injection into the vertebrae [3].

Many studies have found success with VR and haptic training simulators, like Alamilla et al. [4], who created a training simulator for ultrasound-guided needle insertion. Many other works have created VR ultrasound-guided needle insertion simulators, including [5] and [6]. Other VR training simulations include a virtual environment for practicing breast cancer screenings with haptic feedback for needle insertion [7]; a VR simulator with haptic feedback to provide supplemental training to novice urologists in renal puncture procedures [8]; and a simulation framework for needle insertion that can simulate the breathing motion in virtual patients [9]. The study in [10] compares the effectiveness of a VR training simulator with the traditional apprenticeship training method and shows that VR training improves efficiency in the trainee's surgical practice. The system developed in [11] and [12] can be adopted as a training and measuring system for dermatological skills. Many simulators utilize MR. For example, [13] describes an augmented reality (AR) training simulator for kyphoplasty and vertebroplasty. This system relies on a specific foam phantom to simulate realistic insertion forces. The study in [14] presents an AR simulation for spinal needle insertion training using a haptic device. The AR simulator in [15] is an effective training tool for ultrasound-guided percutaneous

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renal access. The study in [16] describes an AR haptic training simulator for a Ventriculostomy. Another AR-based neurosurgical training simulator, described in [17], allows brain surgeons to practice brain tumor removal procedures. In [18], the study shows the effectiveness of an AR haptic simulation for nursing students to learn the physical attributes of certain diseases. Haptic training simulators will only become a more viable option as haptic feedback is improved to provide more realistic force profiles [19]-[20]. Though many simulation systems exist for training in healthcare and surgery, there is currently no MR bimanual haptic training simulator for IV needle insertions. This work presents the development and initial testing of such a system. In the following section, we discuss the development of each study leading up to the Haptic Mixed Reality (HMR) simulation. We cover the initial survey, a text-based questionnaire to observe nursing students' perceptions of the impact of variability; the visual perception of difficulty study, a 2D image survey based on the initial survey that gives participants a visual representation of the variability factors; the MR visual variability study, a usability study that showed participants a 3D representation of the variability factors; and the HMR needle insertion simulation, a pilot study that combines the visual variability with haptic feedback.

II. Methods

A. Initial Survey

The Institutional Review Board (IRB) approved this study, which was conducted online. The initial survey was designed to determine how nursing students perceive what variability factors most impact the difficulty of performing a Peripheral Intravenous Catheter (PIVC) insertion. The participants had a wide variety of expertise levels, ranging from students who have been trained but have had no successful PIVC insertions in the field to practitioners who do PIVC insertions monthly/weekly. The list of factors in the questionnaire include *dark skin, large veins, rolling veins, excess hair, geriatric, can palpate, tattoos, light skin, small vein, thick skin, cannot visualize vein, smooth skin, superficial veins, can visualize veins, cannot palpate, thin skin*, and *deeper veins*. The participants rated each characteristic on a scale from 0 (easiest) to 10 (most difficult). Forty-two nursing students and twenty-seven faculty completed the survey. Section IV presents the results.

B. Visual Perception of Difficulty Study

Based on the initial survey results regarding what factors most impact the difficulty of needle insertion, this study aimed to collect how nursing students would rate the perceived difficulty of inserting an IV into a hand represented by a generated model with varying factors. Seventeen participants were students who had been trained to insert a PIVC. Eight of the participants had no prior PIVC insertion experience. Rather than text-based descriptions of the variable factors, participants could see an image representation on a 2D screen. The hand model was produced with three variables, each having three levels of variability, resulting in 27 unique images. Fig. 1 shows an example of the hand images. The factors chosen for variability, based on the results of the previous survey, were skin color, vein size/visibility, and tattoos. Throughout the survey, participants were presented with the 27 images one at a time in random sequence to reduce fatigue bias. Participants rated each image based on perceived difficulty on a scale of 1 (easiest) to 10 (most difficult).

C. MR Visual Variability Study

The MR visual variability system consists of two major parts: graphic rendering and computation. After collecting data on how students would rate the perceived difficulty of performing a needle insertion based on a 2D image, the next step was to see how that visual perception translated to a 3D image presented through the HoloLens. In this study, we used the same hand model from the 2D images and created a 3D simulation in mixed reality. The graphic rendering relied on the Microsoft HoloLens 2 to produce the 3D images. To access the HoloLens display, we used the Mixed Reality Tool Kit (MRTK), allowing us to stream the image to the HoloLens. The computation part of the system was run on a laptop and developed using the Unity engine.

The virtual model featured in the images was a 3D human model (CGTrader, 27834 vertices). For this study, we focused on the left hand. To simulate vein size/depth, we created a skin deformation script to raise the mesh vertices on the hand where the vein would be, which caused a bulge over the vein, giving it the appearance that it was protruding from the hand, simulating a more prominent vein. We added a blue line to the color map and the normal map over the vein area to further simulate vein protrusion. We changed the albedo value of the model's material to change the skin color. The three skin colors we used for the study were white, tan, and black. The third difficulty factor was tattoos. The three levels

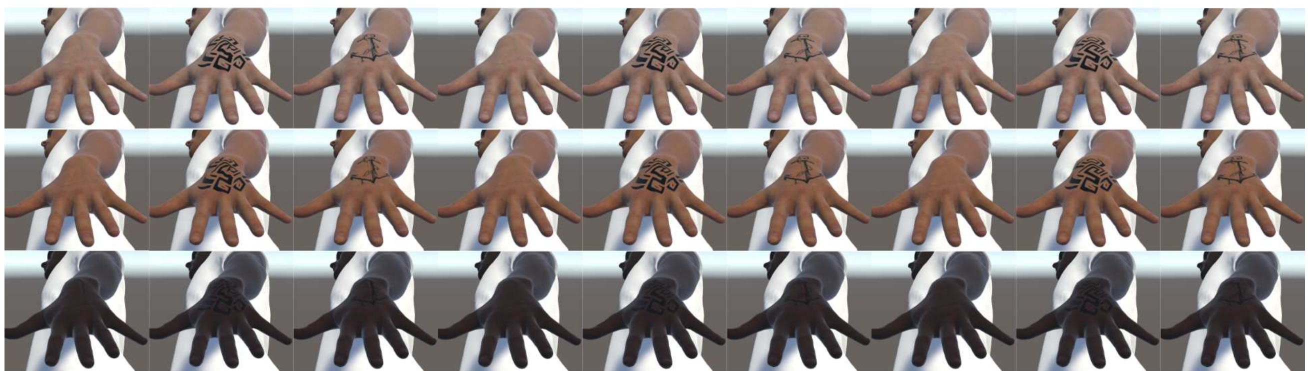

Fig. 1. Example of hand images with three variabililty factors: skin color(white, tan, black), vein size(small, medium, large), and tattoos(none, pattern, anchor).

of difficulty for the tattoos were no tattoo (easy), pattern tattoo (medium), and anchor tattoo (hard). We changed the color map to a hand texture with the tattoo overlayed to apply the tattoos.

In this study, participants sat in a small room with the lights turned off and a small amount of natural light allowed in through a window. The participants wore the HoloLens, allowing them to see an image of one of the 27 hand models displayed randomly. We asked participants to rate how difficult they thought it would be to insert an IV needle on a scale of 1 to 10, with one being the easiest and ten being the hardest. The participant gave their rating verbally, and the proctor keyed in the corresponding rating on the computer, which would output all the ratings to a file.

D. HMR Needle Insertion Simulation

The next step was to combine the variability difficulty levels informed by the MR visual variability study with the HMR system. While the visual variability factors inherit from the MR visual variability study, an expert in the medical field selected the haptic feedback parameters. The system development comprises mixed reality graphic rendering, haptic rendering, and hand tracking. The mixed reality graphic rendering is precomputed in a laptop so that the see-through head-mounted display (HMD), HoloLens 2, only displays the holographic objects without additional computation. The graphics create a scene of needle insertion to a patient on a bed using 3D mesh models, rendered in Unity's built-in render pipeline that provides forward rendering with a single pass. Users could get information such as insertion angle and state of the needle insertion (inside skin, inside the vein, passed vein) by texts as virtual guidance feedback. The haptic rendering development consists of needle insertion and a haptic glove. Users are provided haptic feedback through a 3-degrees of freedom (DOF) haptic device, Geomagic touch using the OpenHaptics plugin through the Unity engine. The haptic parameters were adjusted to differentiate the skin and the vein of the patient hand to let trainees recognize the vein by the haptic feedback. Next, the glove haptic rendering is implemented using a SenseGlove Nova and the SenseGlove Unity plugin. The SenseGlove provided the position joints, fingertips, and wrist for local glove tracking. To provide global glove tracking, the Vive tracker was attached to the haptic glove and tracked by the Vive base station. Fig 2 shows an example of the system setup.

Fig. 2. An example of the HMR system setup.

III. Experiment

A pilot study was designed to obtain data from subjects of varying experience and skill levels in performing an IV needle insertion in a variable environment. The data collected includes quantitative data such as task completion, the haptic needle's position and speed, the stabilizing hand's position and rotation, and the needle insertion angle. We also collected qualitative data such as the needle insertion state and the hand model type. We tested the general usability of the simulation using a NASA Task Load Index (TLX) sheet.

A. Participants

The participants included eight healthy nursing students (three males, five females, six novices, two intermediates, all right-hand dominant, average age of 21). All the participants in the study provided written informed consent as required by the Institutional Review Board.

B. Experiment Procedure

The participants sat in front of the HMR IV Needle Insertion Training Simulation for the experiment. They wore a Microsoft HoloLens 2 MR headset to visualize the virtual patient, wore a Sense Glove haptic glove on their left hand to hold and stabilize the virtual patient's hand, and used the Geomagic Touch haptic device to control the virtual IV needle using their right hand as shown in Fig. 3. Each participant completed a practice session (5-10 minutes) until they got familiar with the system and the procedure. Once they finished practicing, we asked them to complete at least 12 trials in 10 minutes. We instructed the participant to maintain an angle of 20 degrees for the needle insertion. After each insertion, the participant must pull the needle back out of the vein completely to register each attempt. To succeed, the participant must insert the virtual haptic needle into the virtual patient's vein while maintaining a needle angle between 10-30 degrees and pull the needle back out. The participant fails the attempt if they do not maintain an insertion angle between 10-30 degrees, remove the needle before entering the vein, or completely penetrate it, pushing it through the other side. Each trial consisted of four attempts

Fig. 3. A participant using the HMR IV Needle Insertion Simulation system during the experiment.

for four types of randomized hand models of the virtual patient (as shown in Fig 4). Each hand model reflects a different difficulty level in vein visibility and stiffness. Hand model 1 (easiest) is light skin with high vein visibility and low stiffness. Model 2 (second easiest) is light skin with medium vein visibility and medium stiffness. Hand model 3 (second hardest) is darker-skinned with low vein visibility and medium vein stiffness. Hand model 4 (hardest) is dark-skinned with a tattoo, low visibility, and high vein stiffness. The system randomized the order of the hand models shown to the participants to avoid learning bias. Once the participant completes each trial, the system records their data. Once the allotted 10 minutes had passed, participants were given a NASA TLX sheet to rate how they felt while using the HMR IV Needle Insertion Training Simulation.

IV. Results

A. Initial Survey Results

The results from the initial survey were all qualitative since participants rated each variable characteristic based on their perception of the difficulty. As rated by nurses, the top six most difficult variability factors are *dark skin, rolling veins, small veins, cannot visualize, deeper veins*, and *cannot palpate.* The six least difficult variability factors, as rated by nurses, are *large veins, can palpate, light skin, smooth skin,* and *can visualize*. Based on these results, the chosen factors for variability were *skin color*, *vein size*, *vein depth*, and *tattoos.* These variables were chosen based on the perceived impact on difficulty and ability to implement them.

B. Visual Perception of Difficulty Results

Like the initial survey, this study's results are all qualitative since participants based their ratings on their perceptions of difficulty. We used a simple three-digit code to refer to each image to track which image corresponds to which variables. The first digit relates to the skin color variable, the second relates to the vein size, and the third relates to the tattoo. For example, the image code *1-1-1* corresponds to the lightest skin color, the most prominent vein, and no tattoo, and the image code *3-3-3* corresponds to the darkest skin color, the smallest vein, and the anchor tattoo. The image codes were not revealed to participants. As suspected, the higher the image code, the higher participants rated the difficulty. Fig. 5 shows the mean perceived difficulty rating of the 27 images.

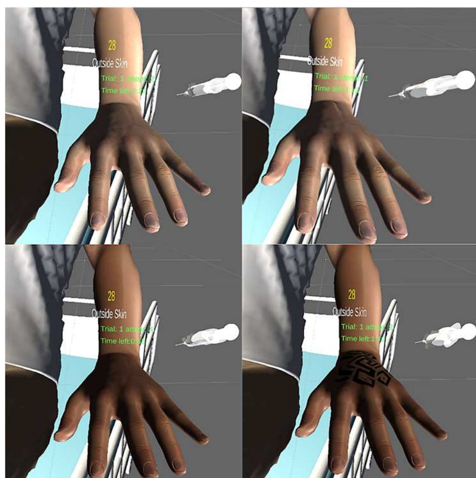

Fig. 4. A representation of the 4 hand models used in the HMR training simulation. Top left: Hand 1 (easy). Top right: Hand 2 (easy). Bottom left: Hand 3 (hard). Bottom right: Hand 4 (hard).

C. MR Visual Variability Results

Like the two previous surveys, this study only provides qualitative results, as the data pertains to participants' perceptions of difficulty. This study used the same convention to track which image corresponds to which variables. The mean rating for difficulty in MR follows a similar pattern to the 2D perception of difficulty survey. However, the vein size and tattoo variables have a more significant impact on the MR implementation. The vein size may have had a higher impact because the MR version allows the user to look around the hand freely, giving different perspectives, which makes the vein protrusion more noticeable. A more noticeable vein protrusion on the hand models with more prominent veins makes the hand models with smaller veins (and therefore less protrusion) comparatively more difficult. The tattoos may have made the MR version more difficult because the dark overlay of the tattoo made the hologram more transparent, making it harder to see the vein. Fig. 6 compares the mean ratings between the MR visual variability study and the 2D perception of difficulty study.

D. HMR Needle Insertion Simulation Results

1) Quantitative Results

The quantitative results from this study include the time, angle, and 3D motion data. We calculated the time participants took to insert the needle into the vein (1 attempt) and the time to complete each trial (4 attempts). We also calculated the angle maintained by the participants during the needle insertion to determine the relative position of the vein. The 3D motion data (position, rotation, and speed in the needle's x, y, and z axes, stabilizing hand and thumb) provided additional insight as to the quality of movement during the task. With the limited number of participants in this pilot study, it is unclear whether the different hand models had a significant impact on success rates, as some participants show a clear pattern of the difficulty levels and some do not, as seen in Fig. 7. We need to collect more data with a large number of trials to acurately draw a conclustion.

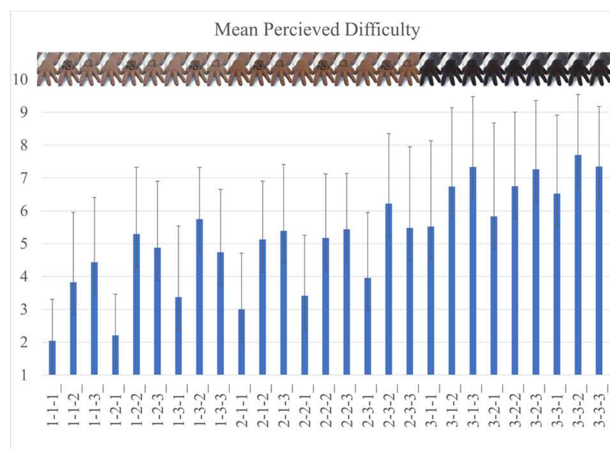

Fig. 5. Mean perceived difficulty rating for 27 hand images.

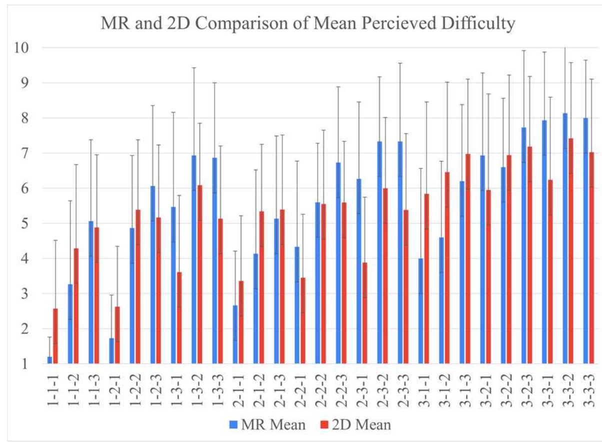

Fig. 6. Comparison of mean ratings between MR visual variability study and 2D perception of difficulty study.

To calculate the trajectory of each participant's needle during the simulation, the program captured the x, y, and z coordinates for each frame and wrote them into a text file. From that text file, each coordinate was read into JupyterNotebook and mapped onto a 3D plane using Matplotlib. The trajectories' colors correspond to the type of success/fail, with blue being a successful insertion, purple being a failure of the upper skin, red being a passed vein fail, and green being an angle fail. We mapped the vein location into the 3D plane with its upper, lower, and midpoints visible. Since each hand type has different vein sizes, they are color-coded, like the success/fail type. Hand number one is orange, hand two is brown, hand three is gold, and hand four is olive.

Each trial and attempted trajectories were created and stored for every participant. Fig. 8 shows four representative trajectory graphs. Table 1 shows the average trajectory length (success and fail) as well as the average insertion time. On average, the trajectory length for a failed attempt is about 0.5 cm longer than a successful attempt, which suggests that participants are missing or over-penetrating the vein by approximately 0.5 cm. Participants took slightly longer on the more difficult hands (Hand 3 and Hand 4), taking on average almost 5.5 seconds, whereas Hand 1 (easy) took an average of about 5 seconds. Hand 2 (easy) was the quickest to complete, averaging about 4.4 seconds.

2) Qualitative Results

The qualitative results include the needle insertion state, the hand model type, and the data from the NASA TLX form. The data from the NASA TLX help to understand the cognitive, physical, and temporal demands of the system,

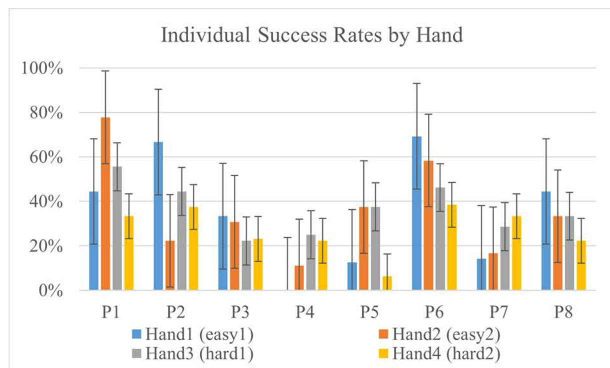

Fig. 7. A bar chart showing the average success rate of each person by hand.

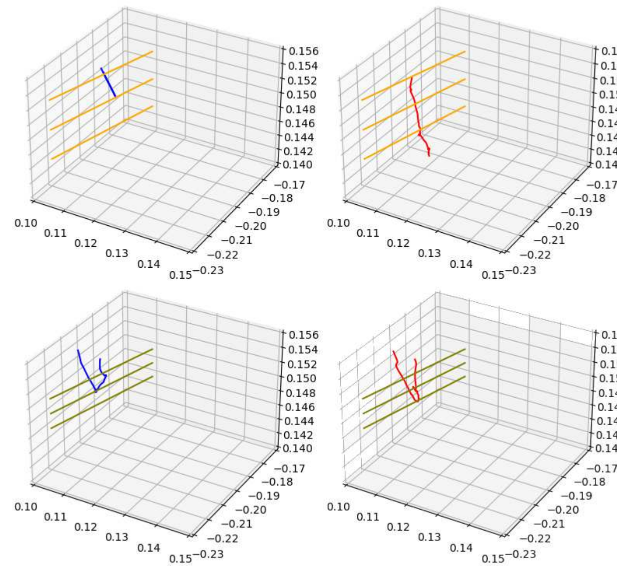

Fig. 8. Representative trajectories for a success and fail for hand 1 (easy) and hand 4 (hard).

how the user felt they performed, the effort they had to produce, and the frustration they felt while using the devices. Participants rate each of these categories on a scale of 1 to 21, with 1 being the lowest and 21 being the highest level they experienced. Fig. 9 shows the mean rating for each category on the NASA TLX. Participants put much effort into their attempts, with an average effort rating of 17.375. This high effort led participants to believe they were performing better than they were. Participants rated their performance, on average, at 11.375 (about 50% on a scale of 1 to 21), but most participants had a success rate under 40%, as Fig. 7 shows.

V. Discussion

Variability is essential in practicing needle insertion because it better prepares nurses for situations they will likely encounter. We know certain variability factors contribute to the perceived difficulty of needle insertion in virtual simulation and real-life practice. The initial survey determined that the most impactful variables for perceived difficulty are skin color, vein size, and whether a tattoo covers the vein. The visual perception of difficulty survey and the MR visual variability study confirmed that, generally, the darker the skin, the smaller the vein, and the more hidden the vein by a tattoo, the more challenging the insertion is

Table I

Average Trajectory Length and Insertion Time.

	Avg. trajectory length (cm)		
	Success	**Fail**	**Avg. insertion time (s)**
Hand 1 (easy)	1.13	1.72	4.97
Hand 2 (easy)	1.08	1.68	4.40
Hand 3 (hard)	1.13	1.46	5.49
Hand 4 (hard)	1.13	1.73	5.47

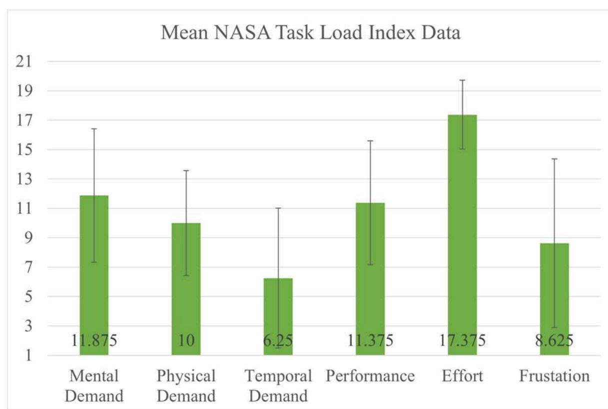

Fig. 9. Mean rating of each category in the NASA TLX

perceived to be. The range in difficulty ratings from these studies showed that manipulating three variables provides enough variability to create scenarios that can be perceived as easy or difficult. Participants rating their performance higher than actual suggests the system requires more post-attempt feedback to determine if they succeeded. Participants in this pilot study of the HMR needle insertion simulator had primarily positive feedback. All participants found the haptic feedback useful when performing the needle insertion. All participants thought using the system was valuable for training. Furthermore, all participants wanted to use this type of training experience in the future.

VI. Conclusion

We developed a training simulator allowing nursing students to practice IV needle insertion with variability to better prepare them for more realistic scenarios. The quantitative data collected from the HMR system itself is variable. We are iteratively refining the system to acquire more data and better teach the entire procedure of IV insertions. We plan to compare this HMR training system to the traditional learning methods in a classroom setting in the future.

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References

[1] C. Rossa, J. Fong, N. Usmani, R. Sloboda and M. Tavakoli, "Multiactuator Haptic Feedback on the Wrist for Needle Steering Guidance in Brachytherapy," in IEEE Robotics and Automation Letters, vol. 1, no. 2, pp. 852-859, July 2016, doi: 10.1109/LRA.2016.2528295.

[2] H. Jeong, J. Kim and K. Kim, "Programmable and Portable Vibrotactile Feedback for Intuitive Virtual Grasping: A Preliminary Study Towards Upper Limb Rehabilitation," 2021 4th International Conference on Bio-Engineering for Smart Technologies (BioSMART), Paris / Créteil, France, 2021, pp. 1-4, doi: 10.1109/BioSMART54244.2021.9677766.

[3] M. Hollensteiner et al., "Procedure-Specific Validation of Artificial Vertebrae," in IEEE Transactions on Biomedical Engineering, vol. 65, no. 8, pp. 1852-1858, Aug. 2018, doi: 10.1109/TBME.2017.2782797.

[4] M. A. Alamilla et al., "A Virtual Reality and Haptic Simulator for Ultrasound-Guided Needle Insertion," in IEEE Transactions on Medical Robotics and Bionics, vol. 4, no. 3, pp. 634-645, Aug. 2022, doi: 10.1109/TMRB.2022.3175095.J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[5] D. Fortmeier, A. Mastmeyer, J. Schröder and H. Handels, "A Virtual Reality System for PTCD Simulation Using Direct Visuo-Haptic Rendering of Partially Segmented Image Data," in IEEE Journal of Biomedical and Health Informatics, vol. 20, no. 1, pp. 355-366, Jan. 2016, doi: 10.1109/JBHI.2014.2381772.

[6] T. M. Deserno, J. E. E. De Oliveira and O. Grottke, "Regional Anaesthesia Simulator and Assistant (RASimAs): Medical Image Processing Supporting Anaesthesiologists in Training and Performance of Local Blocks," 2015 IEEE 28th International Symposium on Computer-Based Medical Systems, Sao Carlos, Brazil, 2015, pp. 348-351, doi: 10.1109/CBMS.2015.61.

[7] A. L. Brazil, A. Conci, E. Clua, L. K. Bittencourt and L. B. Baruque, "A virtual environment for breast exams practice with Haptics and gamification," 2017 IEEE 5th International Conference on Serious Games and Applications for Health (SeGAH), Perth, WA, Australia, 2017, pp. 1-7, doi: 10.1109/SeGAH.2017.7939273.

[8] Yonghang Tai, L. Wei, H. Zhou, S. Nahavandi, Junsheng Shi and Qiong Li, "Integrating virtual reality and haptics for renal puncture surgical simulator," 2016 2nd IEEE International Conference on Computer and Communications (ICCC), Chengdu, 2016, pp. 480-484, doi: 10.1109/CompComm.2016.7924747.

[9] D. Fortmeier, M. Wilms, A. Mastmeyer and H. Handels, "Direct Visuo-Haptic 4D Volume Rendering Using Respiratory Motion Models," in IEEE Transactions on Haptics, vol. 8, no. 4, pp. 371-383, 1 Oct.-Dec. 2015, doi: 10.1109/TOH.2015.2445768.

[10] Portelli, M., Bianco, S. F., Bezzina, T., & Abela, J. E. (2020). Virtual reality training compared with apprenticeship training in laparoscopic surgery: a meta-analysis. The Annals of the Royal College of Surgeons of England, 102(9), 672-684.

[11] J. W. Kim, B. T. Carroll, H. Jeong, K. Kim and D. P. DeMeo, "Immersive Haptic Interface Simulating Skin Biopsy for Dermatological Skill Training," 2022 8th International Conference of the Immersive Learning Research Network (iLRN), Vienna, Austria, 2022, pp. 1-8, doi: 10.23919/iLRN55037.2022.9815896.

[12] J. W. Kim, H. Jeong, K. Kim, D. P. DeMeo and B. T. Carroll, "Image Based Virtual Reality Haptic Simulation for Multimodal Skin Tumor Surgery Training," 2021 4th International Conference on Bio-Engineering for Smart Technologies (BioSMART), Paris / Créteil, France, 2021, pp. 1-4, doi: 10.1109/BioSMART54244.2021.9677802.

[13] D. Fuerst, D. Stephan, P. Augat and A. Schrempf, "Foam phantom development for artificial vertebrae used for surgical training," 2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society, San Diego, CA, USA, 2012, pp. 5773-5776, doi: 10.1109/EMBC.2012.6347306.

[14] C. Sutherland, K. Hashtrudi-Zaad, R. Sellens, P. Abolmaesumi and P. Mousavi, "An Augmented Reality Haptic Training Simulator for Spinal Needle Procedures," in IEEE Transactions on Biomedical Engineering, vol. 60, no. 11, pp. 3009-3018, Nov. 2013, doi: 10.1109/TBME.2012.2236091.

[15] Mu, Y., Hocking, D., Wang, Z. T., Garvin, G. J., Eagleson, R., & Peters, T. M. (2020). Augmented reality simulator for ultrasound-guided percutaneous renal access. International journal of computer assisted radiology and surgery, 15, 749-757.

[16] Yudkowsky, R., Luciano, C., Banerjee, P., Schwartz, A., Alaraj, A., Lemole Jr, G. M., ... & Frim, D. (2013). Practice on an augmented reality/haptic simulator and library of virtual brains improves residents' ability to perform a ventriculostomy. Simulation in Healthcare, 8(1), 25-31.

[17] Si, WX., Liao, XY., Qian, YL. et al. Assessing performance of augmented reality-based neurosurgical training. Vis. Comput. Ind. Biomed. Art 2, 6 (2019). https://doi.org/10.1186/s42492-019-0015-8

[18] M. Bektic, A. Tischler, N. Fahey, K. Kim and L. Onesko, "Efficacy of AR Haptic Simulation for Nursing Student Education," 2021 4th International Conference on Bio-Engineering for Smart Technologies (BioSMART), Paris / Créteil, France, 2021, pp. 1-5, doi: 10.1109/BioSMART54244.2021.9677828.

[19] H. Wu, C. Chen, Y. Zhou, J. Wang and Y. Xie, "VR-based Haptic Simulation for Dynamic Needle Insertion," 2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), Hong Kong, China, 2019, pp. 924-929, doi: 10.1109/AIM.2019.8868373.

[20] F. Li, Y. Tai, Q. Li, J. Peng, X. Huang, Z. Chen, and J. Shi, "Real-time needle force modeling for VR-based renal biopsy training with respiratory motion using direct clinical data," Applied Bionics and Biomechanics, vol. 2019, pp. 1–14, 2019