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ORIGINAL ARTICLE

Development and usability of a virtual reality umbilical venous catheter placement simulator

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Abstract

Purpose Exposure to procedures varies in the neonatal intensive care unit (NICU). A method to teach procedures should be available without patient availability, expert oversight, or simulation laboratories. To fill this need, we developed a virtual reality (VR) simulation for umbilical vein catheter (UVC) placement and sought to establish its face and content validity and usability.

Methods Engineers, software developers, graphic designers, and neonatologists developed a VR UVC placement simulator following a participatory design approach. The software was deployed on the Meta Quest 2 head-mounted display (HMD). Neonatal nurse practitioners (NNPs) from a level 4 NICU used the simulator and completed an 11-item questionnaire to establish face and content validity. Participants also completed the validated simulation task load index and system usability scale to assess the usability of the simulator. Group 1 tested the VR simulation, which was optimized based on feedback, prior to Group 2's participation.

Results A total of 14 NNPs with 2–37 years of experience participated in testing. Participants scored the content and face validity of the simulator highly, with most giving scores $\geq$ 4/5. Usability was established with relatively high average system usability scores for both groups (Group 1: 67.14 $\pm$ 7.8, Group 2: 71 $\pm$ 14.1) and low SIM-TLX scores indicating manageable load while using the simulator.

Conclusion After optimization, Group 2 found the UVC simulator to be realistic and effective. Both groups felt the simulator was easy to use and did not cause physical or cognitive strain. All participants felt the UVC simulator provided a safe environment to make mistakes, and the majority would recommend this experience to trainees.

Keywords Virtual reality · Simulation · Procedures · Neonatology · Validation

Introduction

The pediatric residency review committee (PRRC) identified 16 procedures in which pediatric residents need "sufficient training." However, only half of residency program directors and few neonatal–perinatal fellowship program directors felt graduating pediatric residents are competent to independently perform neonatal procedures [1, 2]. Factors like duty hour restrictions, increased advanced practice providers, and decreased delivery room attendance may be partially responsible for this lack of preparedness [3].

The teaching of procedures in medicine has evolved in recent years. Sawyer et al. published the "learn, see, practice, prove, do, maintain" paradigm which incorporates an objective simulator assessment to prove the skill and maintenance with ongoing practice [4]. These additional steps are particularly important for infrequently performed procedures.

Multiple studies have demonstrated the rapid skill atrophy that occurs with infrequently performed procedures. One study looked at skills taught during the Neonatal Resuscitation Program and found a sharp decline only 2–3 months after certification [5]. One such skill is umbilical vein catheter (UVC) placement. The UVC allows fluids and medications to

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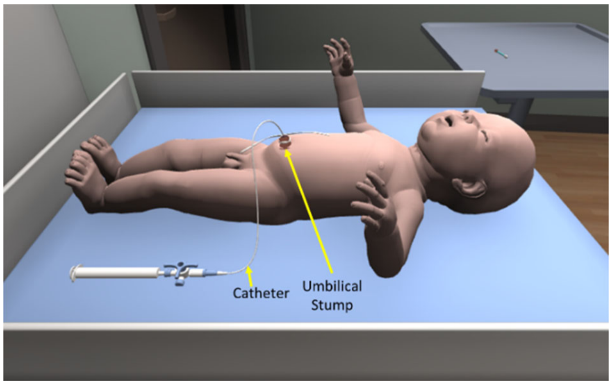

Fig. 1 Diagram of successfully placed UVC

be rapidly infused through a catheter in the patient's umbilical vein which can be lifesaving in emergencies (Fig. 1). Outside of academic centers, pediatricians are often the providers performing these lifesaving procedures. However, in an Australian study, pediatricians placed UVCs, on average, less than 1 time per year [6]. This infrequency of performance on patients is insufficient to maintain skills and places providers at risk for skill atrophy. Traditionally, UVC placement is taught with a mannequin. However, this is expensive and requires dedicated space with trained facilitators. A low-cost, self-paced solution could be beneficial as an adjunct for teaching and maintenance of this skill.

Virtual reality (VR) simulators have become increasingly popular in medical education for teaching and refreshing procedures [7, 8]. VR immerses users in virtual environments using a head-mounted display (HMD), and users interact with the virtual environment using handheld controllers. VR has many benefits compared to mannequins including enhanced visual realism and standardization of training. Furthermore, VR provides a learning environment to repetitively practice procedures without fear of making mistakes [9]. While VR has tremendous benefits, it can be costly to develop and maintain VR simulators, and integrating software seamlessly into the curriculum requires careful planning. Additionally, VR software requires intimate collaboration between engineers, artists, and subject matter experts [10].

If these disadvantages are overcome, VR would allow teaching of neonatal procedures (like UVC placement) without the need for patient availability, patient endangerment, expert oversight, or simulation laboratories, thus decreasing the financial burden on medical programs. Within this work, we describe the development of our VR simulator for UVC placement. We utilized a participatory design approach to gather clinical requirements and iteratively incorporate feedback. Additionally, we implemented a pipeline to rapidly create and modify the simulation allowing for frequent iterations and testing. Finally, neonatal experts evaluated the simulator's usability, usefulness, and realism to create one of the first VR simulators for neonatal procedures.

Previous works

VR training is established in industries like aviation, food safety, and mining [11–13]. Recently, VR simulators have appeared in the medical field, with two main types discussed in the literature: 360° video based and computer graphics based (CG based).

360° video-based VR simulators allow users to watch spherical videos from a first-person perspective through their HMD. Such simulators have been used for training about trauma experiences, sepsis prevention, echocardiography, and neonatal resuscitation [14–17]. 360° VR simulators are easily made and result in highly realistic environments. However, users only watch the video, consume the augmented educational content, and answer questions. It is an ongoing challenge to make these simulators more interactive [18]. While such offerings are adequate for scenario-based education, they become limited when observation is not enough, like in procedural learning. Furthermore, modification of such simulators is difficult once the video has been captured and requires the creator to re-record. While careful planning can circumvent some of these problems, making changes after simulator creation is often necessary.

In CG-based simulators, users interact with a virtual environment using handheld controllers, their hands, or robotic devices. Virtual assets representing the environment and interactable objects are created in 3D graphic software and imported into a game engine. Falah et al. developed a VR module demonstrating heart anatomy [19], and the CG-based VR simulator allows the user to translate, rotate, and scale the anatomical structures. Several studies have also demonstrated the benefits of the interactivity of CG-based VR systems for procedures in orthopedics and cardiology [20–23]. In the neonatal field, CG-based VR simulators have been developed to prevent neonatal infection, train neonatal workers for emergency evacuation, and teach midwifery students about neonatal resuscitation [24–26]. While CG-based simulators are more interactive than 360°-based simulators, they are more challenging to build due to the cost and technical expertise required [10]. In this paper, we discuss the creation of a CG-based UVC placement simulator due to the shortcomings of the 360°-based simulators in delivering procedural-based training.

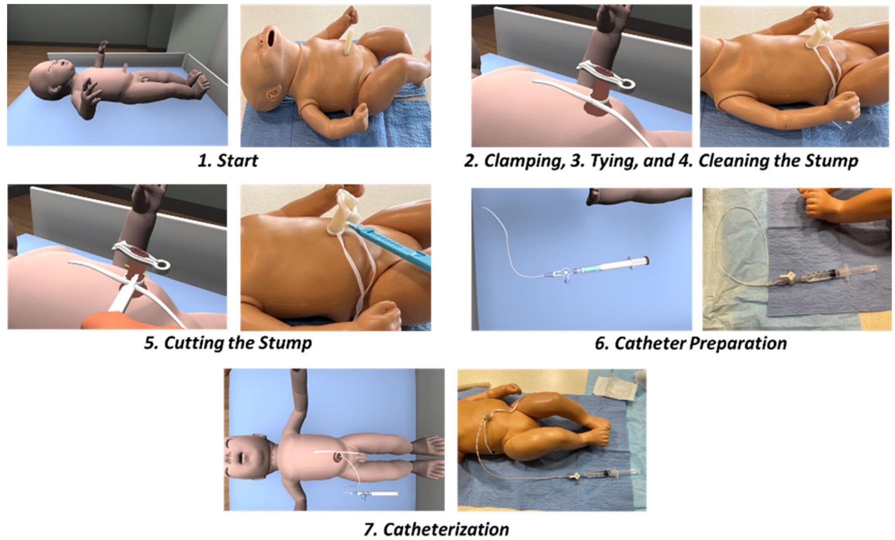

Fig. 2 Steps of UVC placement in VR and in mannequin

Methods

Clinical requirements gathering phase

Insertion of a catheter into the umbilical vein is performed in the delivery room in emergencies where blood, cardiac medications, or fluids are needed. This procedure has several steps (Fig. 2). The goals of the software were defined as follows:

1. The simulator steps should match the steps of the real procedure allowing the user to refresh their knowledge.
2. The user should be able to transition between steps to focus on a specific step of the procedure. As such, users should be able to skip to a step of interest without having to complete all prior steps.
3. The user should be able to reset the entire procedure as many times as desired so that they may complete the procedure multiple times.

A multidisciplinary team of neonatologists and engineers developed the UVC simulator. The neonatologists provided content expertise for emergent UVC placement including rubric of steps, procedural tools, and hospital environment references. The engineers provided expertise on VR simulation development by creating virtual assets, implementing virtual interactions, and creating a robust architecture allowing for rapid incorporation of feedback. A participatory design approach was utilized wherein the neonatologists led the software design and provided feedback frequently during development, leading to an iterative cycle [23].

Fig. 3 Virtual environment

Simulator development

The virtual environment and virtual tools were modeled from clinician input and were imported into Unity 3D. Figure 3 shows the virtual environment. The Unity XR Plugin framework and Interaction Toolkit Unity package were used to communicate with the Meta Quest 2 HMD and add VR interactions. The simulator contains tutorial and walkthrough modes. In the tutorial mode, users learned how to interact with the virtual environment, ensuring users were comfortable with the HMD. The walkthrough mode allowed users to perform the steps of UVC placement in the virtual environment.

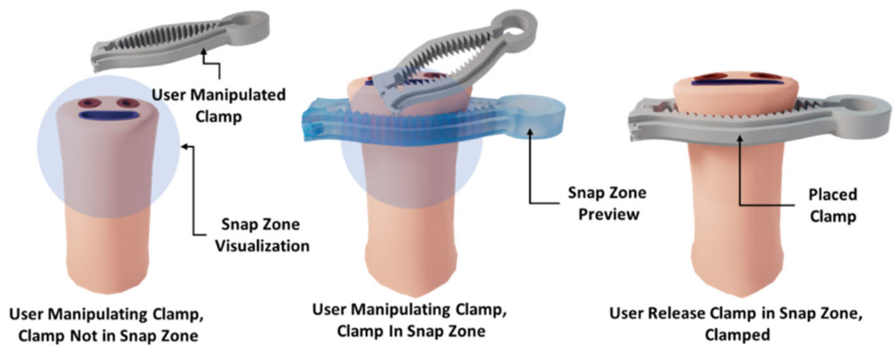

Fig. 4 Snap zone-based virtual interaction

Virtual interactions

Several techniques were used to create the virtual interactions. Grabbing objects was achieved by bringing either controller close to the object and pressing the correct button. The object is released once the button is released. Trigger zones were utilized for some steps like clamping the umbilical cord (Fig. 4). When the user brings the clamp to the correct spot, a placeholder mesh is rendered where the clamp will snap as a visual cue, prompting the user to release the clamp. Once released, the clamp snaps into place. A similar technique was used for tie placement, attaching the syringe and stopcock to the catheter, and catheter placement.

To simulate cleaning the umbilical stump with betadine, a ray was cast from the tip of the swab model. If the ray collided with the umbilical stump, the triangle where the ray intersected the model, and its n-nearest neighbors, was colored using a vertex color shader. The stump is considered cleaned once a certain percentage of triangles are colored. In the final version, n was set to 5 and 75% of the triangles must be colored (Fig. 5).

To simulate cutting the stump, a cutting animation was created. As the scalpel is manipulated, the nearest point amongst the m sampled points to the scalpel is determined. The cutting animation is then moved to the same t value as the closest point on the curve (Fig. 6). For example, if the scalpel is closest to a point halfway along the curve, the animation is automatically moved to the halfway point as well. The clinical team felt this appropriately represented cutting the umbilical stump.

Software architecture

The UVC simulation was modeled with a finite state machine (FSM). An FSM is a software design pattern that discretizes a complex system into finite states. A state is a predetermined configuration of the system. Each step was modeled as an FSM (Fig. 7). The initial state is Instruction Delivery where the user receives instructional audio and text. Once the dialogue is delivered, the FSM transitions to Task Completion which activates the virtual interaction associated with the step, enabling the interactability of virtual objects needed for the task. Each virtual interaction tracks when it is completed and can broadcast a message to the FSM to transition. Once the transition conditions are achieved for each step, the state advances to the next step's FSM. Each step can reset itself by storing the initial states of its associated virtual objects. If the user asks to go back a step, the current and previous steps are reset before transitioning to the previous state. If the user wants to skip a step, the virtual interaction for that step is completed programmatically and a transition is made to the next step. A user interface was created to show the user the instructions, their progress, and instructions for skipping and resetting steps.

Experimental design

Fourteen neonatal nurse practitioners (NNPs) were voluntarily recruited. These NNPs are experts in UVC placement,

Fig. 5 Left shows vertex coloring algorithm. Right shows user cleaning the stump

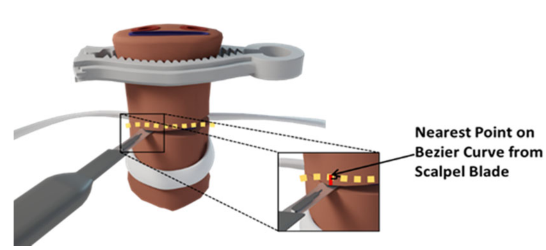

Fig. 6 Stump cutting virtual interaction

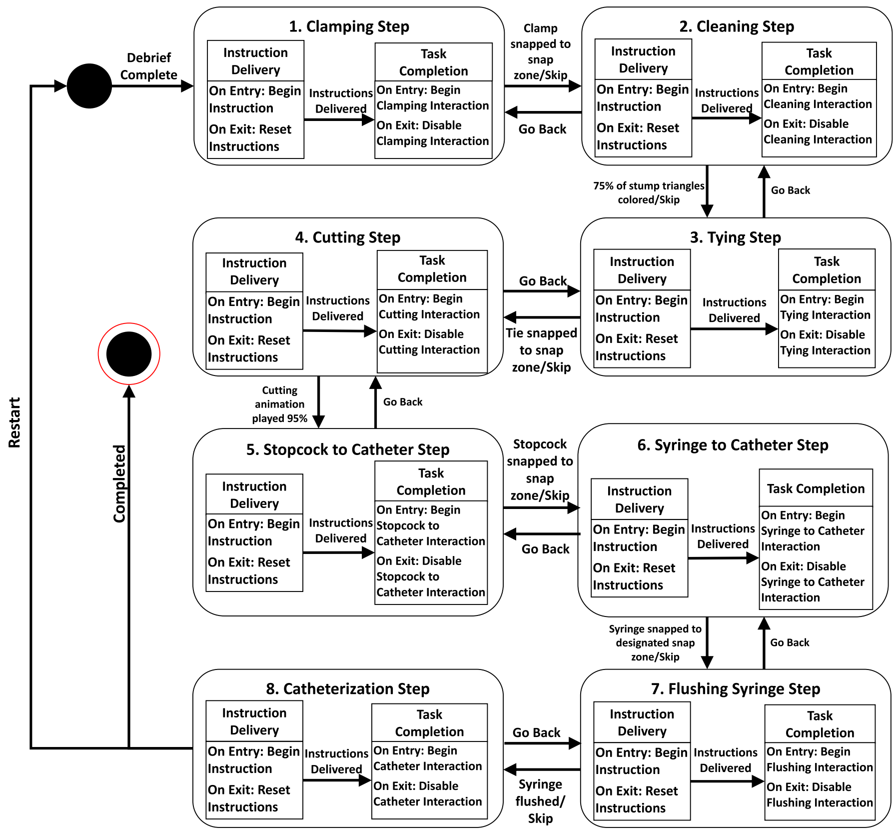

Fig. 7 UML diagram of UVC placement

routinely placing these lines as part of their clinical duties. Participants completed a tutorial explaining the functions of the module and controllers. Subsequently, participants completed a walkthrough of UVC placement. Occasional verbal guidance was provided to troubleshoot VR controller issues. Instructions were given that UVC steps could be skipped if the user was unable to complete the task or the testing could be terminated at any time. There were no time limits placed on the use of the simulation. After completion of the tutorial and walkthrough, the NNPs completed a survey regarding face and content validity (developed by our team), the SIM-TLX, and the system usability scale to collect feedback about the usability and effectiveness of the simulation. Figure 8 shows a participant using the simulator. As changes had been made to the simulation between testing with Group 1 and Group 2, the groups were analyzed independently using descriptive statistics.

Fig. 8 Participant using the simulator

Results

Study population

A convenience sample of 14 NNPs (Table 1) was chosen based on availability from our quaternary care level 4 NICU. Initial simulation testing occurred with seven NNPs (Group 1). After Group 1's feedback was incorporated into the module, an additional seven NNPs were recruited for testing (Group 2). Allocation of NNPs into each group occurred based on availability at the time of testing.

Table 1 Demographics

	Total	Group 1	Group 2
Gender			
Male	1	0	1
Female	13	7	6
Age (years), mean (range)	45 (33–67)	48 (35–65)	42 (33–67)
Years of experience, mean (range)	12 (2–37)	13 (3–28)	12 (2–37)
UVC proficiency			
Novice	0	0	0
Beginner	0	0	0
Proficient	0	0	0
Expert	14	7	7
VR proficiency			
Novice	12	6	6
Beginner	2	1	1
Proficient	0	0	0
Expert	0	0	0

Table 2 Face and content validity

Statement	Group 1 median, (range)	Group 2 median, (range)
The baby model is realistic	5, (4–5)	4, (4–5)
The patient preparation for UVC is realistic	4, (2–5)	4, (2–5)
The UVC tools are realistic	3, (2–4)	4, (3–5)
The instructions are very clear	4, (4–5)	4, (4–5)
The environment is realistic	4, (3–5)	4, (3–5)
The simulation was effective in teaching umbilical cord anatomical landmarks	3, (2–4)	4, (3–5)
The simulation was effective in teaching patient preparation	4, (3–5)	4, (3–5)
The simulation was effective in teaching catheter preparation	3, (2–5)	4, (2–5)
The simulation was effective in teaching UVC placement	3, (2–4)	4, (3–4)
The simulation was effective in simulating the environment	4, (3–5)	5, (3–5)
Overall teaching utility	4, (3–5)	4, (3–4)

Face and content validity questionnaire

Participants completed an 11-item questionnaire in which they agreed or disagreed, using a 5-point Likert scale, with statements relating to the face and content validity of the simulator (Table 2). “UVC tools are realistic,” “simulation was effective in teaching anatomical landmarks,” “simulation was effective in teaching catheter preparation,” and “simulation was effective in teaching UVC placement” were given neutral scores with a median of 3 out of 5 in Group 1 while Group 2 rated them positively with a median of 4 out of 5. “Baby model is realistic” and “instructions are very clear” were marked as agreed or strongly agreed upon by all fourteen participants. The remaining five questionnaire items had a median of 4 or 5 out of 5 for both groups. All NNPs strongly agreed the simulator was a safe environment to make mistakes. Overall, ten out of fourteen NNPs strongly agreed to recommend this simulator to trainees.

Usability

Both Groups 1 and 2 rated physical demands and distractions low, with a median of 1 (range 1–12) and 0.5 (range 0–4.5), respectively. Task complexity received higher scores for both Groups 1 and 2 at a median of 7 (range 3–11) and 8.5 (0.5–13.5), respectively. For task control, Group 1 gave a median of 10 (range 6–14) while Group 2 gave a median of 4 (range 0.5–8.5) (Fig. 9). The average system usability scale score for Group 1 was 67.14 ± 7.8 and 71 ± 14.1 for Group 2.

User feedback

Participants were asked three questions to obtain feedback not elsewhere assessed in the questionnaire. When asked “What changes to the VR experience would you recommend?”, Group 1 commented on the instruments being difficult to distinguish, the inability to enlarge the baby model, and the need for VR environment orientation. Group 2 had difficulty with the functioning of certain steps like flushing the syringe. When asked “Is there anything specific you liked about the VR simulation?”, Group 1 and Group 2 felt the VR environment was a realistic safe space to make mistakes without judgement. When asked “Is there anything specific you did not like about the VR simulation?” Group 1 and Group 2 mentioned difficulties getting accustomed to VR, controllers touching when trying to flush the catheter,

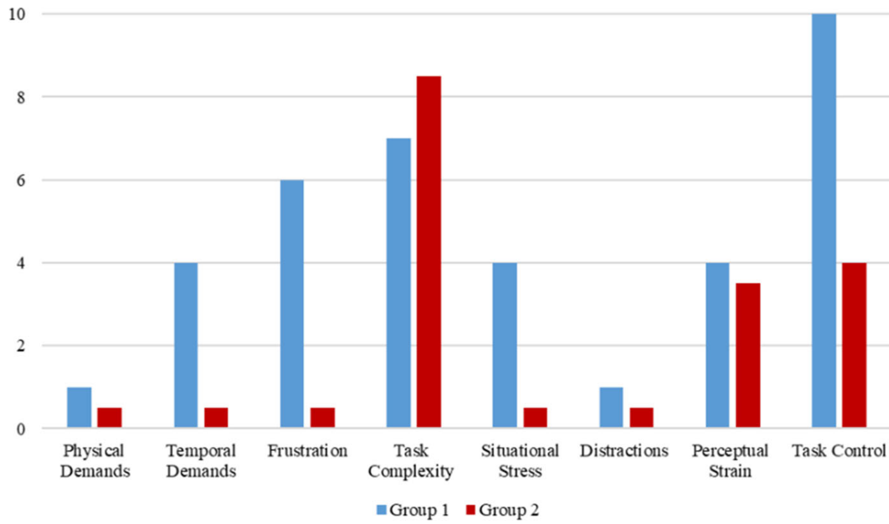

Fig. 9 SIM-TLX scores

and trouble seeing without glasses. No users reported any side effects such as motion sickness, dizziness, or general discomfort in these open ended questions or verbally during testing.

Discussion

Simulation of procedures has been shown to effectively prevent skill atrophy and distributed practice has been shown to improve skill retention [27]. However, this low-dose, high-frequency strategy is impractical for traditional simulation that requires a simulation laboratory and the dedicated time of the learner and facilitator. VR has the potential to supplement traditional simulation techniques by delivering on-demand, repeatable training. In this manuscript, we have described the development of our VR simulator. After expert testing, we feel that it offers an immersive and realistic training environment with the potential to explore its impact on skill retention in future studies.

After exploring the literature, we found most neonatal simulators used either 360° videos or computer graphics. Furthermore, CG-based simulators often included haptics to increase the realism of the simulation. While UVC placement could be taught through 360° video, we believe that allowing users to perform the steps of the procedure leads to a more interactive experience to ensure quicker skill refresh. Including haptics in our simulator was discussed but not included due to large costs, complex equipment requirements, and challenges with implementation of steps. Our goal was to build and validate a simulator for the fastest skill refresh rather than replace mannequin-based training through use of a haptics-based system.

Based on the software architecture, we were able to rapidly implement changes from Group 1's feedback between testing groups. These changes included making tools easier to distinguish, changing the orientation of the baby within the environment to match real-life conditions, fixing an issue with objects coming apart after being snapped together, and correcting the inability to insert the catheter after multiple uses of the module. As a result of these changes, Group 2 underwent module testing with less hindrance, which resulted in median scores of 4 or 5 out of 5 on all face and content validity survey questions, indicating the module was realistic and effective. All NNPs strongly agreed that the simulation was a safe environment and 10 out of 14 NNPs strongly agreed to recommend the simulation to learners. Additionally, the SIM-TLX median scores for Group 2 demonstrated the mental, physical, and cognitive demands of the simulation were low. We suspect that correcting the issue with items coming apart and not being able to insert the catheter resulted in the low scores in the domains of frustration, situational stress, and task control for Group 2. Perceptual strain and task complexity likely remained similar between groups as the visual representation of the environment and procedure as well as the complexity of the task were not altered by the simulation changes. The apparent differences in scoring between Group 1 and Group 2 for the other domains are likely explained by individual differences in participant perception rather than changes made to the simulation. Finally, the SUS, a validated overview of a system's usability of 71/100 for Group 2's testing demonstrated above-average usability for the operator.

The participatory design framework and pipeline based on finite state machines allowed us to easily correct issues and optimize the simulation between testing groups by enforcing a known structure in the development. We highly recommend that any team partaking in medical VR simulator development establish a framework that allows the clinical team to collaborate effectively with the engineering team. Frequent and detailed communication between these two teams is essential to the rapid development of clinically useful simulations. We also recommend that new projects start with a requirements-gathering phase (including goals of the simulation, necessary functions, development of a rubric of steps, and providing representative images of the procedure, tools, and environment), followed by prototype development. After prototype development, frequent simulator builds should be generated and tested by the clinicians. Finally, there should be a way for feedback to be easily incorporated without having to change large parts of the simulator.

This study has several limitations. First, it was conducted in a small and homogenous sample of experts in umbilical venous catheter placement. Second, there is no quantitative assessment of side effects from use of the VR. While no side effects were reported, this was not formally assessed in this study. Finally, while the simulation provides a foundational understanding of UVC placement, it currently lacks coverage of sterile technique preparation and management of complications, which are important aspects of the procedure.

While this study establishes the face and content validity and usability of our VR umbilical venous catheter simulation, further research needs to be done to determine if the simulation is effective as an educational adjunct. Additional work should explore the transfer validity of the software and how it compares to traditional educational modalities. Transfer validity involves understanding how the skills learned in the virtual environment translate to the real world. This would allow a comparison of performance on a real mannequin between traditional teaching methods and VR. Additionally, a longitudinal study including a larger and heterogeneous sample to evaluate the length of time to skill atrophy between traditional teaching methods and VR would add information on real-world usefulness and timing of skill refresh. Finally, we aim to use the approach discussed in this paper to develop simulators for other infrequently performed neonatal procedures and deploy these simulators to different types of extended reality hardware, such as mixed reality.

Conclusion

In this paper, a participatory design approach was used to develop a VR simulator for the training of UVC placement as well as test the module's face and content validity and usability. All fourteen neonatal nurse practitioners felt the emergency UVC placement VR simulation provided a safe environment to make mistakes and the majority of NNPs would recommend this experience to trainees. Many comments were provided to improve the environment and functionality of the VR simulation. Future work will focus on testing the transfer validity of the UVC VR module.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11548-024-03072-8.

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Declarations

Conflict of interest The authors have no conflict of interest.

Ethical approval University of Illinois College of Medicine at Peoria IRB 1 determined this project does not meet the definition of human subject research under the purview of the IRB according to federal regulations.

Consent to participate Verbal consent was obtained from all participants.

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