

LETTER OPEN ACCESS

Comparative Evaluation of Ultrasound-Guided Peripheral Intravenous Catheter Insertion Techniques in a Virtual Reality Simulator

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ABSTRACT

Peripheral intravenous catheter (PIVC) insertion is a common yet challenging procedure. Although ultrasound guidance improves procedural accuracy and patient outcome, its complexity limits its routine adoption to highly experienced clinicians. This paper introduces a virtual reality (VR) simulator developed specifically for training in ultrasound-guided PIVC insertions. This study aims to validate the simulator's realism and relevance through face, content, and construct assessments, and to demonstrate its utility as a platform for comparing various approaches to PIVC insertion. Thirty participants from diverse medical backgrounds and levels of expertise completed three scenarios, each featuring a different procedural technique, within the simulator's controlled virtual environment. The simulator demonstrated strong face and content validity, with participants rating its realism at 7.1/10 and enjoyment at 8.2/10. Performance data showed that expert participants maintained higher success rates and performance across all procedural scenarios, supporting the simulator's construct validity. In the standard approach scenario, novices required 230.91 ± 158.77 s to complete the task and achieved only a 45% success rate compared to experts' 95.48 ± 65.74 s and 80% success rate. In the procedural scenario involving an alignment assistance device, where needle insertion was aligned with the ultrasound image plane, novice success rates increased to 75% and the number of attempts decreased from 8.95 ± 6.69 to 2.75 ± 2.67 , narrowing the performance gap with experts. These findings highlight the simulator's potential not only as an effective training tool but also as a platform for the objective evaluation of different procedural techniques.

1 | Introduction

Peripheral intravenous catheter (PIVC) insertion is a common hospital procedure for establishing quick and reliable intravenous access, with over two billion catheters used annually worldwide [1–3]. Despite its frequency and critical role in patient care, first-attempt failure rates reach 39%, with complications affecting up to 50% of patients [4–7]. While ultrasound guidance improves success rates by enhancing vein and needle visualization, it remains a challenging procedure due to the added complexity of tracking both the needle and vein in 2D ultrasound imaging [8]. As a result, only highly experienced clinicians are typically

comfortable performing this technique [9, 10]. Virtual reality (VR) has emerged as an effective tool for medical training, improving procedural skills, knowledge retention, and confidence [11–15]. VR-based ultrasound training systems have been developed for biopsy procedures [16], regional anaesthesia [17, 18], and, more recently, ultrasound-guided PIVC placement [13, 19]. However, the goal of this work is to assess whether VR simulations can extend beyond training and serve as a controlled environment for comparing different tools and techniques. This paper presents a custom VR simulator designed to train users in ultrasound-guided PIVC insertion and to compare two approaches for this procedure: the standard approach (Free Hand) and an assisted

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method using a tool in the early stages of development which aids in aligning and guiding the catheter needle (Install-VASC by Sononurse VS). According to Aggarwal et al. [20], medical simulators can be classified based on the skills they aim to develop: cognitive (knowledge of the procedure), motor (manual dexterity), and teamwork (collaboration and communication). While the present simulator was not explicitly designed using a specific simulation framework, it aligns most closely with the cognitive skills category, as it focuses on developing the knowledge required to position the ultrasound probe and catheter for ultrasound-guided PIVC insertion. This study aims to compare participants' performance between the two presented approaches within the simulator's controlled virtual environment and to validate the simulator through face, content, and construct validity [21–24]. To the best of our knowledge, no existing studies have used a VR simulator to conduct a comparative evaluation of PIVC procedural techniques based on task-based performance metrics collected directly within the VR environment. This study represents a novel application of VR, not only for skill acquisition but also as a controlled platform for assessing and comparing PIVC insertion techniques by analysing performance across varying skill levels.

1.1 | The Ultrasound-Guided PIVC Procedure

Ultrasound-guided PIVC placement involves using real-time ultrasound imaging to visualize the target vein and guide the needle during insertion, improving success rates compared to traditional methods. Two approaches are routinely employed for this procedure, the longitudinal (In-Plane) insertion and transverse (Out-of-Plane) insertion [8]. Both approaches are illustrated in Figure 1a.

In the longitudinal approach, the ultrasound probe is aligned parallel to the vein, displaying it as a continuous tube. The needle is carefully and accurately inserted at the side of the probe and

remains visible along its entire length, allowing real-time tracking for precise placement. In the transverse approach, the probe is positioned perpendicular to the vein, showing a cross-sectional view. The needle appears as a bright point on the screen, requiring careful probe adjustments to maintain visibility of the needle's tip during the insertion. After successfully cannulating the vein, the catheter is advanced, the needle is removed, and the catheter is secured in place. Both techniques require precision, coordination, and experience to align the needle with the target vein while maintaining continuous ultrasound visualization.

Although the longitudinal technique offers the advantage of continuous visualization of both the needle and the vessel throughout the procedure, it can be challenging to master due to the difficulty of maintaining precise alignment between the probe, vessel, and needle [8, 25]. As noted in the AIUM's *Practice Guideline for the Use of Ultrasound to Guide Vascular Access Procedures* [8], ultrasound-guided peripheral venous access is almost always performed using the transverse orientation, as smaller vessels with frequent turns are more difficult to keep in view longitudinally. However, the transverse approach can make it more challenging to track the syringe tip during advancement. Both approaches are viable in clinical practice, and the choice of technique depends on the vessel selected as well as the operator's preference and experience.

Several approaches have been developed to address these challenges in needle guidance, including mechanical needle guides designed to stabilize the transducer and needle. In this study, we focus on the Install-VASC exoskeleton developed by Sononurse VS, which is in the early stages of development and is still under evaluation for clinical approval (Figure 1b). This exoskeleton supports both insertion techniques. In the longitudinal (In-Plane) configuration, this tool stabilizes and maintains the needle within the ultrasound plane, while in the transverse (Out-of-Plane) configuration, it keeps the needle aligned with the vertical centre of the ultrasound image. Both configurations are shown in

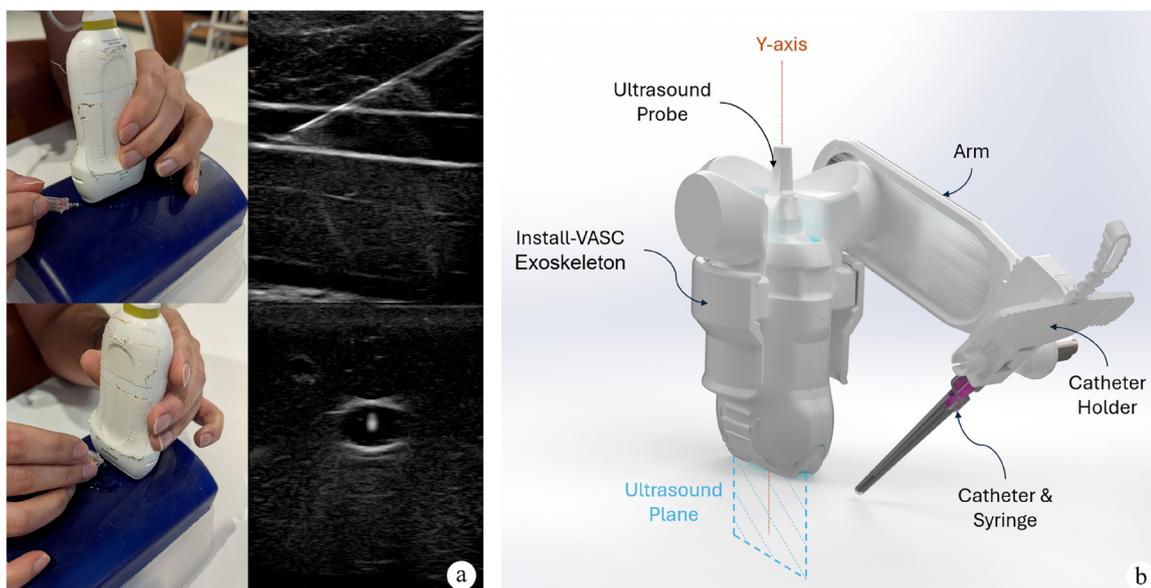


FIGURE 1 | (a) Ultrasound-guided PIVC placement on CAE's Blue Phantom (for illustrative purposes only) with longitudinal approach (top row) and transverse approach (bottom row). (b) Diagram of Install-VASC in the In-Plane configuration.

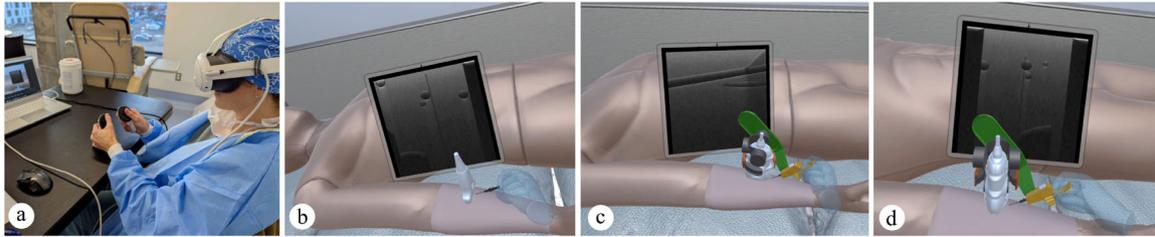


FIGURE 2 | (a) Participant performing the study; View from the VR simulator, displaying the ultrasound image, probe positioning and needle insertion. (b) Free Hand Out-of-Plane. (c) Install-VASC In-Plane. (d) Install-VASC Out-of-Plane.

Figure 2c,d. The Install-VASC tool constrains needle motion by guiding the catheter within a defined plane using the arm and catheter holder of the exoskeleton (Figure 1b). The arm of the Install-VASC tool allows free movement of the catheter within this constraint plane while preventing any deviation outside of it. Depending on the configuration, the arm can be adjusted so that the catheter either follows the ultrasound imaging plane (In-Plane configuration) or a plane perpendicular to it, centred on the probe (Out-of-Plane configuration). The exoskeleton also allows rotation of the ultrasound probe along its vertical axis, allowing the user to transition between transverse and longitudinal views while keeping the targeted vessel aligned and the catheter constrained within the intended plane.

2 | Materials and Methods

2.1 | System Description

A simulated virtual environment, representing a medical classroom, was developed. Within this scene, a mannequin with a simulated anatomical forearm is placed on a bed in front of the user, as shown in Figure 2. A full-body mannequin was used to increase immersion and the sense of presence in the virtual environment. This setup aimed to replicate the experience of performing the procedure in a real hospital room, where a patient's entire body would be present. While a simpler partial-arm or forearm block simulator could have sufficed for the cognitive tasks assessed in this experiment, the full-body configuration was intended to encourage participants to adopt realistic positioning, ergonomics, and interaction patterns consistent with clinical practice.

The user interacts with a catheter needle and an ultrasound probe using the VR controllers, which can either be used independently or together when using the Install-VASC exoskeleton. To replicate the physical device's behaviour, the real movement and constraints of the Install-VASC were simulated using a simple inverse kinematics solution, which restricts the needle's motion to specific planes matching those of the real tool. To ensure the simulator's general clinical realism and alignment with clinical practice, face and content validity were addressed during its development by involving two experts in ultrasound-guided PIVC insertions. Their feedback ensured that the simulator accurately reflects the essential components of the venipuncture procedure, appears realistic, and is relevant to users. The simulator is configured to collect key performance metrics, such as task completion time, the number of skin perforations (indicating

the number of attempts), and whether the user successfully positioned the syringe tip within a blood vessel.

Our VR simulator was developed using Unity 2022.3, in combination with PlusToolkit's Ultrasound Simulator. The simulation was run on a Razer Blade 15 laptop equipped with an Intel Core i7-9750H CPU, 16 GB of RAM, and an NVIDIA GeForce RTX 2070 Max-Q graphics card, providing sufficient performance for this simulation. We used a Meta Quest 3 headset with the OpenXR Unity Plugin for VR interactions. The ultrasound image presented to the user is simulated using the PlusToolkit Ultrasound Simulator [26, 27]. Our VR simulator uses the OpenIGTLink protocol to transmit the probe and needle position to PlusToolkit's simulator, which returns the simulated ultrasound image for display within the VR environment [26, 27]. The forearm of the virtual mannequin contains 3D mesh models of a vein and artery system, as well as the ulna and radius bones, which serve as the basis for generating the simulated ultrasound image of the forearm's anatomy.

2.2 | User Study

During the data collection phase, participants were instructed to insert the needle tip as accurately as possible into the centre of a blood vessel and maintain its position by releasing the needle. This procedure was repeated for each of the three technical approaches studied: (1) Free Hand insertion with Out-of-Plane needle placement, (2) assisted insertion using the Install-VASC tool in the In-Plane configuration, and (3) assisted insertion using the Install-VASC tool in the Out-of-Plane configuration. The order of these approaches was randomized for each participant to minimize potential learning effects or biases related to procedural scenario sequence. A total of thirty participants from diverse medical fields, each with varying levels of experience, were recruited. Once a participant believed they had accurately positioned the needle tip in a blood vessel, they informed the experimenter, who then ended the scenario.

Participants who needed it received a brief overview of the basic concepts of ultrasound-guided intravenous (IV) insertions. All participants were introduced to the simulator's functionalities and given up to 10 min to familiarize themselves with the system, practicing both the Free Hand (Out-of-Plane) method and the use of Install-VASC tool in both configurations. A study-specific socio-professional questionnaire collected information on participants' professional background, prior IV catheter insertion experience, ultrasound-guided insertions experience, and

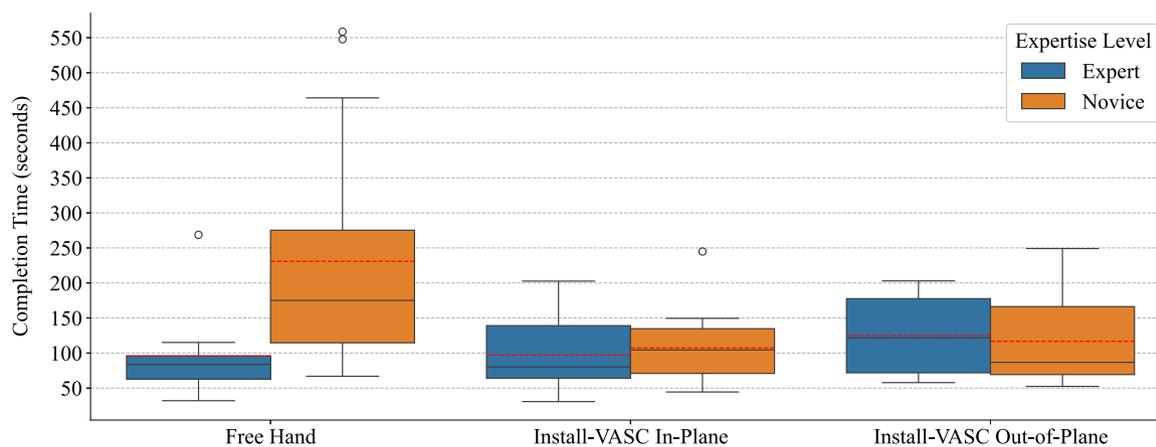


FIGURE 3 | Task completion times by expertise levels across procedural scenarios.

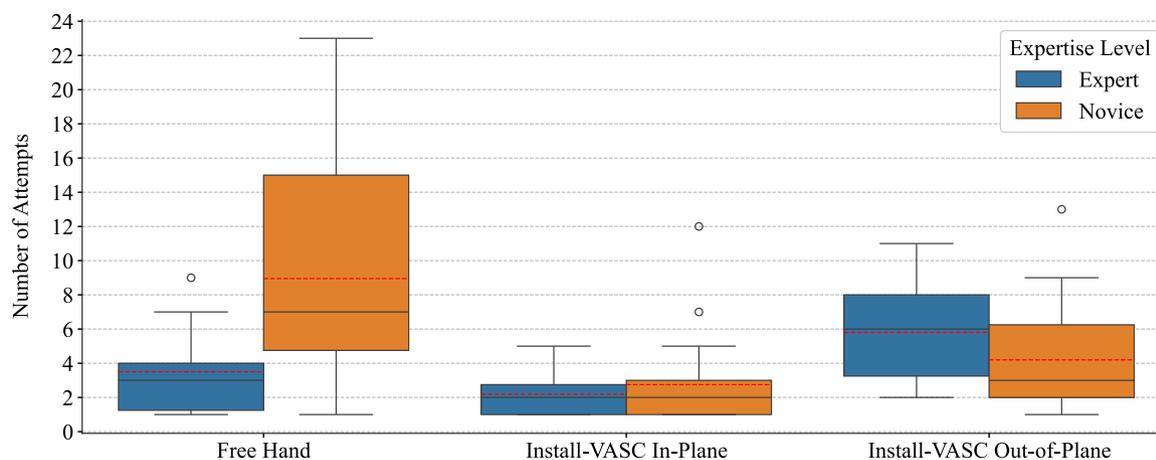


FIGURE 4 | Number of attempts by expertise levels across procedural scenarios.

VR familiarity. After completing the three procedural scenarios, participants filled out a custom post-study questionnaire to provide feedback on the simulator and the Install-VASC tool. All participants were informed about the experimental procedure and provided written informed consent prior to enrolment in the study. The study protocol was reviewed by the École de Technologie Supérieure's ethics committee, which determined that formal ethics certification was not required, granting an exemption from ethical approval.

3 | Results

Participants were classified as experts or novices based on their socio-professional questionnaire responses. Among the 30 recruited participants, 10 were classified as experts with substantial experience in ultrasound-guided PIVC placement, having performed the procedure regularly as part of their clinical practice. This group included emergency physicians (6), anaesthesiologists (2), one intensivist, and one resident. The remaining 20 participants, classified as novices, had little to no experience with ultrasound-guided PIVC placement, regardless of their standard IV insertion experience. This group included undergraduate nursing students (13), licensed nurses (2), hospital physicians (4) and one respiratory therapist.

During the data collection phase, three key metrics were recorded for each procedural scenario: the time taken by the participant to complete the scenario (task completion time), the number of times the participant had to perforate the skin to realign the syringe (number of attempts), and whether the participant successfully placed the tip of the syringe inside a blood vessel at the end of the procedural scenario (success). These results are presented in Figures 3–5, respectively.

A multiple factor repeated measures ANOVA revealed a significant interaction between procedural scenarios and expertise for both task completion times ($p = 0.012$) and the number of attempts ($p = 0.0069$). To further investigate this interaction, a single-factor repeated measures ANOVA showed no significant difference in task completion times across scenarios for experts ($p = 0.32$), whereas novices exhibited significant variation ($p = 0.001$). For the number of attempts, both experts ($p = 0.0053$) and novices ($p = 0.0004$) showed significant differences across procedural scenarios, indicating scenario-dependent variation in performance for both groups. A chi-square test was conducted to assess procedural success. Some categories had low sample sizes (fewer than five occurrences), potentially affecting the reliability of the p -value. Despite this limitation, Figure 5 shows a clear trend. When aggregating all procedural scenarios, the test yielded a significant result ($p = 0.015$), indicating a meaningful difference

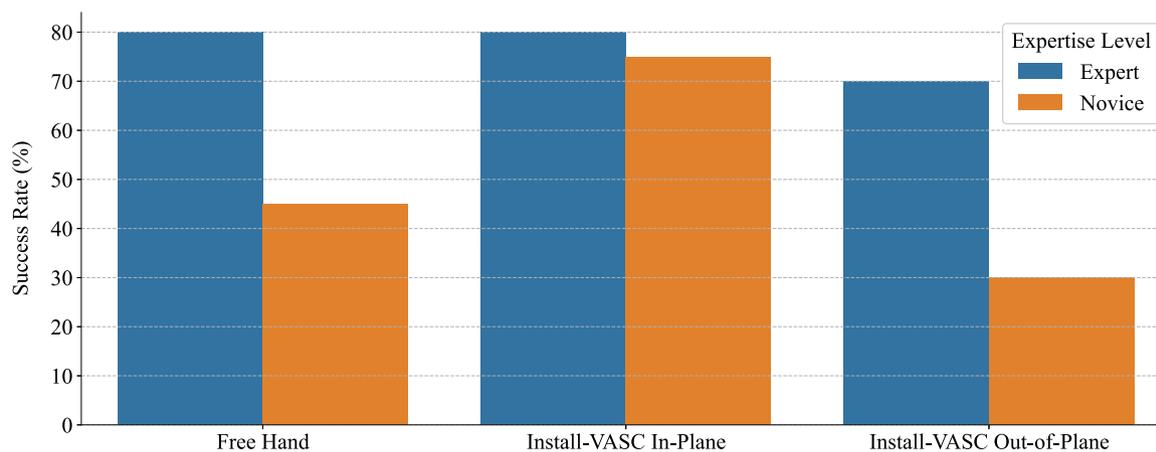


FIGURE 5 | Success rate by expertise levels across procedural scenarios.

between experts and novices. However, scenario-specific analysis revealed a p -value of 0.7602 for the Install-VASC In-Plane scenario, while the free hand and Install-VASC Out-of-Plane scenarios yielded p -values of 0.0682 and 0.0371, respectively.

In the post-study questionnaire, participants rated their enjoyment of the simulator, its overall realism, and the precision and realism of tool manipulation on a scale from 0 to 10, where 0 indicated a poor experience, 5 represented an average experience, and 10 reflected a highly positive experience. The simulator received an average enjoyment score of 8.2/10 (SD = 1.27), a perceived realism score of 7.1/10 (SD = 1.56), and a tool manipulation precision and realism score of 6.5/10 (SD = 1.61). Additionally, 97% of participants agreed that the simulator could serve as an effective learning tool. Among them, all experts (100%) agreed, with 80% noting that refinements were needed. Only one novice disagreed, while the remaining novices (95%) agreed, with 55% also suggesting improvements. All experts (100%) and 85% of novices selected the Install-VASC In-Plane scenario as their preferred method, while the remaining 15% of novices preferred the Free Hand method.

4 | Discussion

The study results reveal significant trends. As shown in Figures 3–5, experts exhibited consistent performance, with minor variations in task completion time and number of attempts across procedural scenarios. This suggests that their advanced clinical knowledge, particularly in understanding how to position the ultrasound probe to obtain the desired view and how to align the needle with the probe, minimized the added benefits of the Install-VASC tool in the virtual environment. Their ability to adapt seamlessly to different tools and methods highlights the role of expertise in maintaining reliable performance regardless of the procedural scenario. In contrast, novices faced greater challenges, particularly in the Free Hand and Install-VASC Out-of-Plane scenarios, resulting in longer task completion times, lower success rates, and often a higher number of attempts. These findings highlight the steep learning curve of this procedure and the need for improved training tools. The statistical analysis supports these observations, showing that while novices' performance varied across procedural scenarios, experts remained

consistent. The Install-VASC tool in the In-Plane configuration demonstrated strong potential for bridging the performance gap between experts and novices. In this procedural scenario, task completion time, number of attempts and success rate became significantly more consistent between the two groups, likely due to the tool's alignment and guidance features. Despite the limited reliability of the p -value for the success rate, statistical analysis did not show significant differences between the two groups, suggesting similar success rates. However, in the Install-VASC Out-of-Plane scenario, novices had a lower success rate despite task requiring fewer attempts than experts, indicating premature task termination or difficulties in completing the procedure. Experts, despite requiring more attempts, achieved significantly higher success rates, demonstrating greater adaptability and precision in this more challenging procedural scenario. These findings emphasize the importance of evaluating multiple performance metrics, such as the number of attempts alongside success rates, to fully understand task efficiency and accuracy. The challenges novices faced in the Install-VASC Out-of-Plane scenario, such as limited familiarity with ultrasound imaging and the Out-of-Plane technique, mirrored those observed in the Free Hand method.

Furthermore, the consistency and overall superior performance of experts in the base Free Hand scenario compared to novices indicate that the simulator effectively captures performance differences reflective of real-world skill levels. Participants' expertise significantly influenced performance, supporting the simulator's construct validity. Construct validity refers to a system's ability to measure what it is intended to assess, in this case, the impact of expertise on procedural performance [22]. The observed differences in performance metrics between experts and novices in the Free Hand scenario confirm that the simulator provides a realistic environment where clinical expertise translates into measurable outcomes. Face and content validity were further supported by post-study feedback, with high average scores for enjoyment and perceived realism, indicating that participants found the simulator engaging and lifelike. Experts noted that the simulation closely resembled real procedures and evoked a sense of presence in the virtual environment. These results align with the objectives of face validity, which assesses the realism and believability of the simulation experience compared to the real-world activity [22]. Similarly, scores for tool manipulation realism support content validity, suggesting that the simulator

tends to accurately represent key aspects of the ultrasound-guided PIVC procedure. However, lower ratings in this area prompted constructive feedback on improving needle movement realism and ultrasound imaging. The most frequent suggestions from the participants included enhancing the realism of ultrasound images (e.g., noise, depth, anatomical detail), improving needle movement realism, particularly the ability to make subtle adjustments once inserted, and adding tactile elements like skin and vessel resistance and pressure. Several comments also noted that VR controllers should better replicate the shape, orientation, and handling of real probes and syringes, with reduced sensitivity to unintended movement. All written feedback from the post-study questionnaire is provided in Appendix A. Addressing these refinements could further enhance the simulator's realism and usability. Most participants agreed that the simulator could serve as an effective learning tool, reinforcing its value for clinical training and medical technique evaluation. Additionally, 90% of participants selected the Install-VASC In-Plane scenario as their preferred option, citing its ease of use and enhanced visualization for syringe insertion. This positive feedback, combined with the quantitative results, suggests that the Install-VASC tool simplifies the procedure and improves user confidence, particularly for novices.

5 | Limitations and Future Work

One limitation is that the simulator's construct validity was assessed using performance metrics from the Free Hand scenario, where expertise appeared to have a substantial influence on participant performance. These same metrics were then used to compare Free Hand and Install-VASC performance, which could introduce a risk of circular reasoning and limit the strength of the conclusions regarding the tool's impact.

Another limitation is the use of standard VR controllers to simulate the manipulation of the ultrasound probe and catheter. While suitable for cognitive training and procedural sequencing, these controllers do not fully replicate the tactile sensations, weight distribution and fine motor control required for real-world catheter insertion. This limitation was also noted by multiple participants of the study. Future studies could explore the integration of haptic-feedback robotic devices with probe-like and syringe-like form factors to study whether adding realistic tactile sensations and motion resistance enhances the acquisition of fine motor skills required for ultrasound-guided PIVC insertion.

Future studies should also aim to further validate the simulator against real-world performance. One approach would be to assess whether performance in the VR environment is comparable to performance on a phantom model or in vivo. This could involve comparing expert and novice results on both the simulator and a phantom to examine correlation and transferability. Similarly, conducting a phantom-based study comparing the standard ultrasound-guided PIVC procedure with the procedure using the Install-VASC tool would help determine whether the performance differences observed in VR are reproduced in real procedures. Such studies would provide stronger evidence for both the simulator's validity and the potential clinical utility of the Install-VASC tool. Finally, it would be valuable to evaluate the simulator's training effectiveness by comparing the performance

of a group trained using the simulator with that of a group receiving conventional instruction, with both groups subsequently tested on a phantom model, similar to Andersen's et al. study [13].

6 | Conclusions

This study demonstrated the potential of our VR simulator for training and systematically comparing two medical techniques and tools for ultrasound-guided PIVC insertions. Participant performance and feedback strongly supported its face, content, and construct validity. Expertise significantly influenced outcomes, with experts completing tasks faster, requiring fewer attempts, and achieving higher success rates, reinforcing construct validity. The Install-VASC tool, particularly in the In-Plane configuration, improved novice performance, narrowing the gap with experts. These findings highlight the versatility of VR-based simulators for medical training and device evaluation, offering a safe, controlled, and repeatable environment for performance assessment.

Author Contributions

Alejandro Olivares led the research as part of their Master's degree project, including conceptualization, software development, methodology design, data collection, data analysis, and manuscript preparation. Canelle Schuhler-Husson contributed to planning, software development, and conducting the initial pilot study. Yahia Zine provided ongoing professional feedback throughout the project and assisted with participant recruitment. Simon Drouin supervised the project, contributing to study design, planning, and critical review of the manuscript.

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Conflicts of Interest

One of the authors (Dr. Yahia Zine) is the founder and CEO of SonoNurse VS, the company that developed the Install-VASC tool used in this study. At the time of conducting this research, the main author (Alejandro Olivares) was employed by SonoNurse VS. Funding for this work was partially provided in collaboration with SonoNurse VS. The authors declare that this work was conducted as part of an academic research project and that the company had no influence on the data collection, analysis, or interpretation of the results.

Data Availability Statement

Research data are not shared.

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Appendix A: Summary of Participant Feedback

Anonymized participant feedback collected from the post-study questionnaire, listing individual suggestions for simulator improvements (Table A1).

TABLE A1 | Participant feedback from the post-study questionnaire.

Participant ID	Expertise level	Feedback
P02	Expert	The precision and functionality of the simulator need to be improved. It is currently not very realistic due to the physical limitations of the controller size, which cause the two tools to bump into each other when it's time to insert the needle. In addition, the skin lacks depth, making it difficult to properly see the surface and follow the needle during insertion. There is room for improvement, but it's a nice proof of concept for now which, if improved, could be very useful.
P03	Novice	Optimize the ultrasound screen in virtual reality. (Here the participant was referring to the ultrasound image needing more realism in terms of noise, image depth and inner anatomical structures.)
P05	Expert	Images need improvement to replicate reality more closely, with vessel compressibility, skin resistance, and the option for Doppler. Lack of realism. Too sensitive when moving the needle. No idea of the depth of my needle. The right hand cannot rest on the table, which is not easy.
P06	Expert	The feeling is not the same as a real ultrasound, patient. The movements of the virtual catheter could be improved, ex adjusting angle, also a control more similar to a real probe, would be ideal, if possible.
P08	Novice	Controllers need to closely resembling an ultrasound probe (thinner) to allow for greater immersion and the simulation should allow for probe orientation similar to typical clinical contexts (left of the screen = left of the patient).
P09	Expert	Sometimes in the Install-VASC Out-of-Plane scenario, when moving the probe the needle moves a little, making it difficult to clearly see the needle's progression because everything shifts. The needle moves in all three directions even when inserted, resulting in less stability than on a real arm.
P10	Novice	There were a few glitches in the simulator, but overall pretty good in my opinion!
P11	Novice	I find the simulator to be pretty accurate of the use of ultrasound. It was quite steady and allowed for a good representation of the reality. Angle of insertion could be adjusted to reality setting. I believe that usually the angle of insertion is about 45° but quickly change to 15° to not go too deep. Adjusting the angle could be a great add!
P12	Novice	It is a really good, smooth and close to reality experience. It did not crash or bugged. It followed all of my movements and gives the impression that in reality might feel the same way. Maybe the arrow on the ultrasound screen could be bigger because it is difficult to look at it (it kind of moves). (In this comment, the participant refers to an arrow added to indicate the middle of the ultrasound screen.)
P13	Novice	Sometimes the probe shows you a dark screen so it takes lots of manipulating to find the correct placement (that may be just a matter of the person itself not the simulator). She simulator is pretty good to use and easy to understand. I like how when using the non-traditional method, you do not have to worry about the probe since it turns on its own with the needle. I will admit that the VR headset is heavy but that is beyond the simulation itself.
P14	Novice	I think it is a good simulator, and I liked that there were vibrations when the needle was inserted into the vein, and when the needle went too far.
P15	Novice	We usually install the catheter facing the patient, not sitting next to them.
P16	Novice	I think it just needs a little bit less sensitivity on the handle controllers.
P17	Novice	It was a little difficult to use and understand how to use the controllers at first but the practice session was very helpful.
P19	Novice	Just takes long to adjust, perhaps multiple training sessions would be advantageous.
P20	Novice	Participants need more practice to be able to use it well.
P22	Novice	I found it hard to keep my hand steady, harder than it normally is in real life. The screen kept shaking, maybe because the controllers were too sensitive to movement. Otherwise it felt realistic.
P26	Expert	Well designed. Integrate the notion of pressure for the skin and the vessels. Ensure catheter placement with the arm aligned with the needle. Include smaller arms (children). Arm is rounded in reality.
P27	Expert	The biggest element of realism to work on, in my opinion, is the movement of the needle in the soft tissues. It should be possible to move the needle slightly once inserted, and to see this lateral movement on the ultrasound image.

^aAll participant IDs are anonymized. Suggestions are taken from two questionnaire items: *comments about the simulator*, and *suggestions regarding the simulator itself*. They are reproduced with minimal editing for clarity, and some responses have been translated from French.

^bNot all participants submitted written feedback in the post-study questionnaire.