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Virtual Reality-Based Donning and Doffing Simulator

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Abstract

Ensuring healthcare workers properly don and doff personal protective equipment is crucial in preventing the spread of contaminants. This study introduces a virtual reality (VR) simulator to enhance training in donning and doffing, aiming to complement or serve as an alternative to conventional methods. The VR simulation incorporates advanced features such as microfacet bidirectional reflective distribution, full-body avatar animations with inverse kinematics, and cloth simulation with Extended Position-Based Dynamics for increased immersion. Performance tests demonstrate real-time functionality even on low-end setups, with high-end systems consistently supporting 120Hz. A user study with 43 participants reveals that the VR group outperformed the non-VR group by 26.88% in donning and 26.16% in doffing tasks, with statistically significant results. Experienced VR users within the group exhibited notable advantages in various metrics. Overall, participants rated the VR simulation as effective (4.47) and realistic (4.13) on a five-point scale.

Keywords: Surgical simulation, virtual reality, donning, doffing.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Software and its engineering—Software organization and properties—Contextual software domains—Virtual worlds software—Virtual worlds training simulations

1 Introduction

With the continuing threat of COVID-19, new healthcare workers must be familiar with sanitary practices to prevent any possible virus spread between other workers and their patients. One of the many procedures to prevent this spread is the proper donning and doffing of personal protective equipment (PPE). Following the donning and doffing technique is vital to ensure that the healthcare worker minimizes the chances of contracting a disease from the patient or accidentally infecting the patient during procedures and examinations [1].

According to a study by Phan et al. [2], it was observed that 90% of doffing performed by medical workers was incorrect. These healthcare workers performed the doffing sequence or technique incorrectly or did not use the appropriate PPE. This depicts the need for a training platform to ensure that the healthcare workers correctly follow the donning and doffing techniques and protect the safety of their peers and patients.

Conventional training methods exist for donning and doffing PPE, such as instructor-led training and video lessons [3]. However, these methods have their deficiencies. Video lessons do not provide hands-on practice, and while instructor-led training is effective, it is expensive due to requiring new disposable PPE or sanitation of reusable PPE for every training session, and it exposes the learners to potential hazards due to interactions with other people.

Several studies investigating VR in various medical fields have demonstrated its effectiveness. Li et al. [4] reviewed VR-based simulators for diverse medical applications, highlighting their positive impact on surgery training, pain management, and psychological therapy. Similarly, Portelli et al. [5] compared VR training with apprenticeship training in laparoscopic surgery, reporting improved efficiency among trainees using VR simulations. For laparoscopic surgery, specific VR simulations exist, such as VR laparoscopic simulation [6] for fine dissection, peg transfer, and cholecystectomy tasks, VBLaST-PC [7] for pattern-cutting tasks, and Gentleness Simulator [8] for measuring surgeons' skill level.

Orthopedic surgery also benefits significantly from VR training. Hasan et al. [9] delved into recent VR applications in orthopedic surgery training, recognizing challenges like cost and integration into educational curriculums while highlighting the benefits of VR-based training. Moreover, Verhey et al. [10] explored VR, augmented reality (AR), and mixed reality (MR) applications in orthopedic surgery, showing the promising future of these technologies to visualize patient data in real-time and enhance surgical precision.

Beyond laparoscopic and orthopedic surgeries, VR's potential extends to diverse fields like spine surgery [11], plastic surgery [12], and neurosurgery[13]. While these simulations exhibit some limitations, such as hardware dependencies, cost, and ethical considerations, these studies acknowledge virtual simulations' advantages and future potential in medical surgery training.

Numerous medical simulations leverage haptic feedback to enhance surgical training by providing real-time feedback to surgeons, amplifying their immersion within the simulated

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environment[14], [15]. For instance, ViRCAST [16] introduces an arthroscopy simulation where touch-sensitive haptic devices were employed to manipulate camera and tool movements within the virtual space, providing a highly realistic surgical experience. Similarly, Demirel et al. [17] developed the Virtual Airway Skill Trainer, combining an HMD with a haptic device to train surgeons in airway management skills for procedures like endotracheal intubation and cricothyroidotomy.

A recent study by Kravitz et al. [18] explored the effectiveness of VR for training medical students in proper PPE donning and doffing techniques. This VR alternative was tested against an e-module training. The overall outcomes of this study showed that VR training had better results, however, the difference was not statistically significant. The VR training platform didn't replicate a virtual operating room setting; instead, avatars stood before a table in a limited space, lacking certain PPE items like shoe covers and surgical masks. Additionally, grading conducted by reviewers might introduce bias into the study.

In this work, we developed a training environment to simulate the donning and doffing sequence of PPE in VR and carried out a user study to reveal the effectiveness of our VR-based donning and doffing simulator. This study utilizes the current VR technology with an HMD, Oculus Quest 2, to allow users to see their training environment in three dimensions with binocular vision for increased immersion instead of two dimensions on a single screen. Two handheld wireless motion controllers also allow the user to interact with and grab the objects without much restriction on their movement. Our simulator automatically grades the participants' performance for an objective assessment. We also measured the simulator's performance, aiming to provide a smooth visual experience without breaking the immersion for the trainee on reasonably priced hardware, as it is vital to be visually and physically accurate while maintaining real-time computational performance. This VR-based donning and doffing simulator aims to provide: a) a cheaper and safer option compared to conventional instructor-led training, b) a hands-on approach compared to the conventional video-based training method, c) quantitative feedback, d) complete simulation of the clinical environment, and e) 24/7 availability and accessibility.

The following sections delve into the methods employed for creating the VR environment including the development of user avatars, cloth simulation, training scenarios, design of the user study and the test setup for the simulation's performance evaluation. Subsequently, the results section presents findings from simulation performance tests and a comparative analysis of VR and non-VR user study results. The discussion section explores the implications of these results, and finally, the conclusion provides a comprehensive summary of the study's contributions and potential applications in enhancing healthcare worker training.

2 Methods

2.1 Virtual Reality Environment

This work spans several different aspects of a virtual reality environment. Some of the developed features, such as detailed avatar interactions and movements add a sense of presence when the trainee uses the simulation. These humanoid rigged avatars, equipped with animations facilitated by inverse kinematics (IK), significantly contribute to the user's immersion by replication human skeleton physics. On the other hand, additional features, including dynamic deformable cloth simulations, high-resolution mirrors, and advanced lighting techniques are designed to enhance the scene's realism. The simulation places the user in a virtual setting with an anteroom and a contaminated operating room, as seen in Figures 1a and 1b. In the anteroom, the PPE that the trainee must equip is organized on a table. The 3D PPE models used in the virtual scene can be seen in Figure 2. In the scene, a GGX bidirectional reflective distribution formula [19], [20] is being used alongside post-processing effects (vignette, exposure, shadows, tone mapping, and color adjustment) to increase the realism for higher immersion.

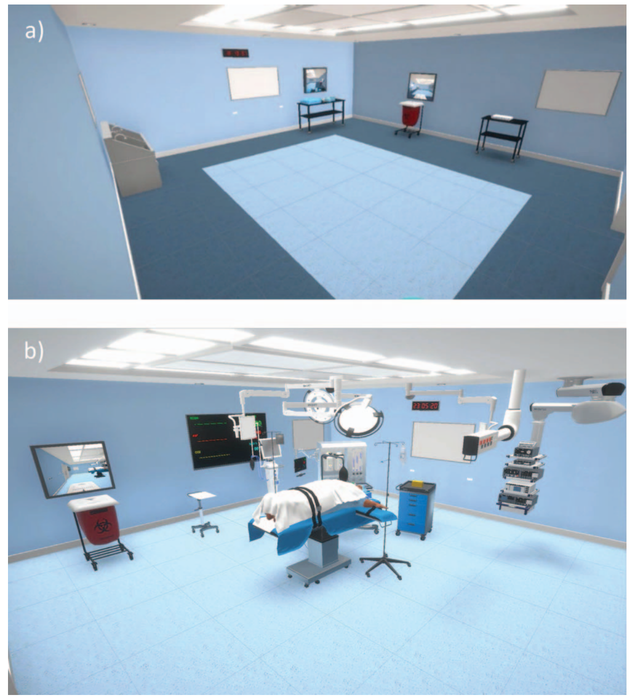

Figure 1: a) Anteroom and b) Contaminated operating room.

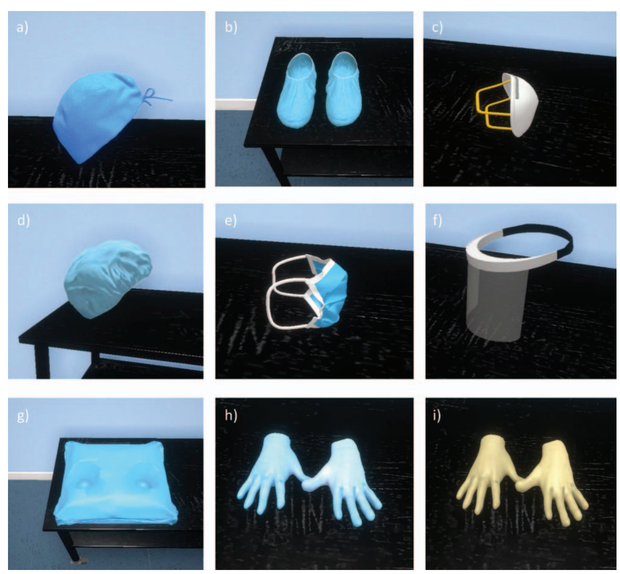

Figure 2: a) Surgical scrub cap, b) Shoe covers, c) N95 respirator, d) Bouffant head cover, e) Surgical mask, f) Visor, g) Surgical gown, h) Nitrile gloves, and i) Surgical gloves.

2.2 User Avatar and Animation

We developed an avatar animation system that animates avatars based on how a human skeleton moves by using a rigged 3D model. The avatar is animated by information such as position and rotation retrieved from the HMD and the controllers. We determine where the avatar's head and hands should be based on the transformation points sent from the HMD and the controllers. An example of an avatar is shown in Figure 3a.

After placing the head and the hands in the correct position, the avatar's body takes shape using IK [21]. The avatar requires reference points for each joint that a human has, so it can use IK to move and rotate the bones according to the endpoint of the limb. IK is an alternative to forward kinematics, where each bone is positioned statically by rotation of each joint, posing the limb from the base to the goal. An example of IK is shown in Figure 3b. The distance from the ground determines the position of the torso and feet. The feet are not automatically positioned on the ground, so IK repositions them accordingly, sending a ray cast to the ground below the waist. The user's velocity determines how the legs should animate, whether rotation or walking. Additionally, depending on the controller button presses and trigger movement, the hands make a grabbing or a releasing motion. An example of different hand poses is shown in Figure 4.

We provide two options for the user to move around in the environment. Since the HMD will move the user in the scene based on their position from the sensors, users can walk around the room to navigate the operating room or use the controllers.

When trainees use this simulator, their height needs to be accounted for, so every user has the same experience with the scale of every object. A calibration process is recommended at the start of the scenario to adjust the avatar's height so the user's camera height can be changed. The camera shifts up or down depending on the height compared to the avatar. This feature also allows for a seated mode if the trainee desires to remain seated for the training.

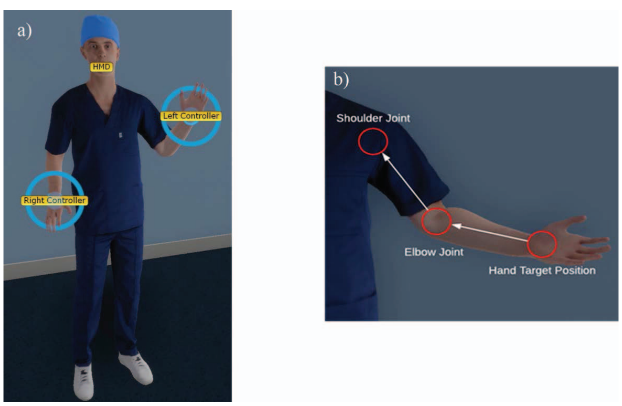

Figure 3: a) Avatar and b) Avatar arm animated with IK.

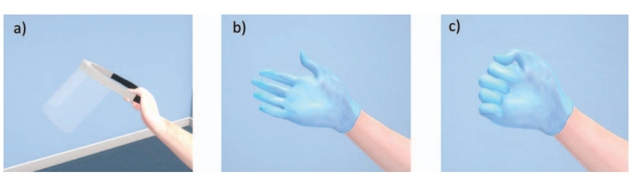

Figure 4: Hand poses: a) Object being grabbed, b) Open palm hand pose, and c) Closed fist hand pose.

2.3 Cloth Simulation

We implemented a cloth simulation system to simulate cloth physics on specific PPE such as face masks and gloves. This system uses a deformable body algorithm by Macklin et al. [22], Extended Position-Based Dynamics (XPBD). XPBD is a variation to the Position-Based Dynamics (PBD) cloth dynamics algorithm, fixing several performance and accuracy issues. It achieves this by approximating a step in PBD, which involves calculating a Hessian matrix, which speeds up calculations and reduces the stiffness of the geometry.

The cloth simulation allows models to be affected by gravity and collide with each other and other solid objects in the scene. The models can also be deformed with specified cloth thickness and stretch resistance. Each cloth-simulated object is linked to a static non-simulated anchor to allow the user to grab it at that point.

While the cloth simulator increases the fidelity and improves the immersive experience, it is a highly costly operation due to continuous physics calculations. We implemented mesh-based optimization techniques to prevent dramatic framerate drops while preserving the quality of the cloth objects. We used mesh decimation algorithms to reduce the complexity of the cloth's mesh. Mesh decimation is a process to reduce the mesh's triangle count without changing the main shape of the mesh. Using the mesh decimation algorithm, we reduced the number of physics calculations to as little as possible without losing the fidelity of the clothes. Despite the simple mesh, deformable cloth simulation requires significant resources to deform each frame. Therefore, we only carried out physics calculations when specific conditions were met. The cloth simulation is paused unless it is visible to the camera. Also, the static meshes are used until the cloth object is grabbed. The cloth simulation runs as soon as it is grabbed by the hand and continues until it is released or disposed of. These optimizations ensure that cloth simulation runs only when needed and prevent unnecessary resource usage. Figure 5 shows how the cloth simulation deforms the surgical gloves, N-95 mask, and surgical face mask during motion.

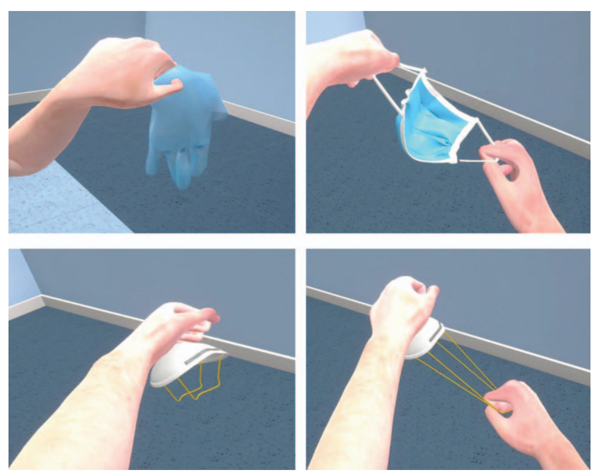

Figure 5: Cloth simulation during motion.

2.4 Training Scenarios

In medicine, donning and doffing procedures vary depending on the level of protection needed based on the pathogens present in the clinical environment. The donning and doffing procedure we included in the scenario is similar to what is included in the article by John et al. [23]. Some steps are simplified, as this simulation aims to train the user for the general donning and doffing process.

All PPE items used in the virtual scene can be seen in section 2.1. Once the user finishes calibration and avatar selection, they will begin the donning scenario. The user is presented with a clean room with all necessary PPE on a table, a sink for sanitation, and a disposal bin. To prevent the trainee from learning the sequence from the position of the PPE items, the PPE table and the disposal bin appear randomly in the anteroom with the PPE positions spawned randomly on that table. Also, there are two mirrors in the environment, one above the PPE table and another at the disposal bin, so the learner can view their avatar and see which PPE they have equipped. The donning process presented in the simulation is shown in Figure 6. In the donning simulation, some additional choices have been added to increase the accuracy of the donning process, such as specifying where to place the glove's cuff. The glove options and the process are shown in Figure 7. After completing the donning, the doffing procedure will start. The doffing procedure we followed in the simulation is presented in Figure 8.

Figure 6: Donning order: a) Perform hand hygiene, b) Equip N95 respirator, c) Equip surgical mask, d) Equip head cover, e) Equip visor, f) Equip shoe covers, g) Equip surgical gown, h) Perform hand hygiene, i) Equip gloves

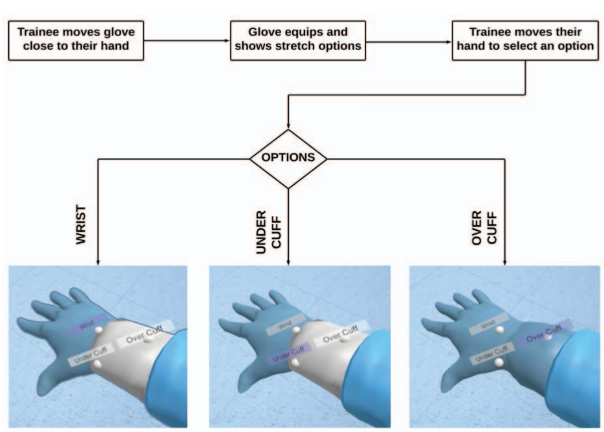

Figure 7: Glove donning options

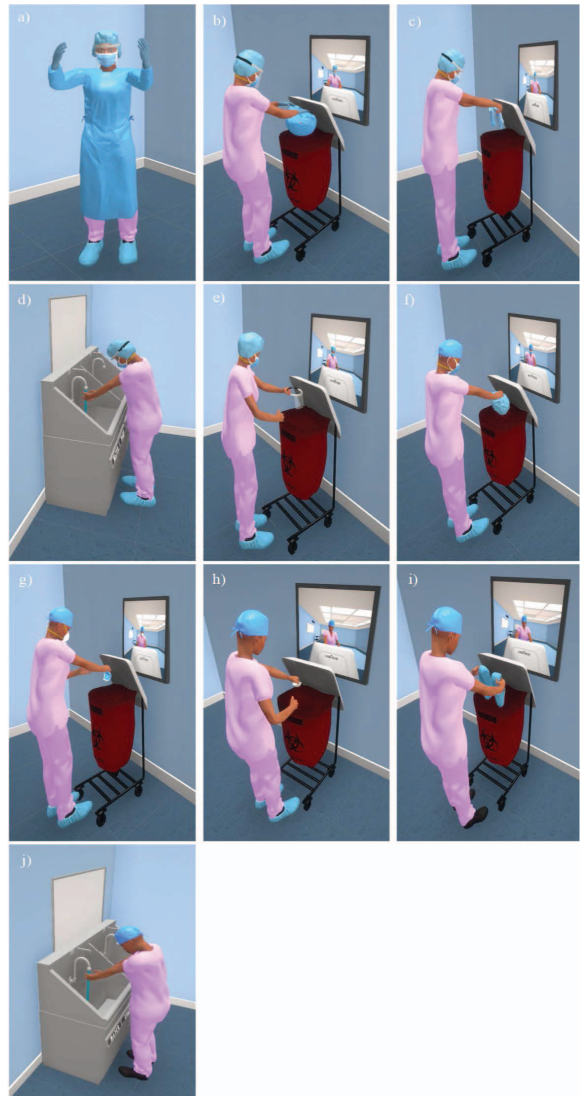

Figure 8: Doffing order: a) Fully donned avatar, b) Doff surgical gown, c) Doff gloves, d) Perform hand hygiene, e) Doff visor, f) Doff head cover, g) Doff surgical mask, h) Doff N95 respirator, i) Doff shoe covers, j) Perform hand hygiene

2.5 User Study Design and Data Collection

To test the validity of our simulator, we conducted a study at the Florida Polytechnic University with the IRB-approved protocol # 23-006. The objective of this study was to compare the effectiveness of two different methods of instruction, only video-based training (non-VR group) versus video-based training coupled with VR simulation (VR group), in educating individuals on the proper sequence for donning and doffing PPE. The study involved 43 distinct participants, 23 in the VR group and 20 in the non-VR group. The participants were randomly assigned to one of the two training scenarios.

Participants in both groups were provided with a pre-questionnaire. In the pre-questionnaire, anonymous demographic information (age, gender, highest level of education), experience with healthcare, donning and doffing PPE, video games, and VR technology were asked. The participants in the VR group watched a video tutorial on the donning and doffing sequence, followed by the VR-based simulation practice session. Participants in the non-VR group only received the video tutorial to simulate the conventional educational models. After the training sessions, both groups completed two post-questionnaires. The first questionnaire tested their knowledge of the correct order for donning PPE, and the second tested their knowledge of the correct order for doffing PPE. Additionally, participants in the VR group were asked to complete a survey to provide feedback on the effectiveness and immersion of the VR simulator.

2.6 Simulation Performance Test Setup

To analyze the computational performance of this simulation, we measured the frame rate during the simulation. The frame rate is measured by taking the time between each frame and calculating its reciprocal.

We conducted our performance tests by using the VR headset Oculus Quest 2. The headset is paired with the computer through the Oculus software over a link cable. The target refresh rate of the headset is 72Hz, which means that the headset limits the requested frames to 72 frames per second (fps) for each eye. Even if the computer can render more than 72 frames, due to the limitations of the headset, it will not render more than requested. Since this limitation would have affected the measuring of the actual performance of our simulation, we also conducted the tests by changing the headset's target refresh rate to 90Hz and 120Hz to retrieve the actual performance of the simulator. By using three different target refresh rates, we aim to depict the performance and stability of our simulation under different target hardware conditions. While changing the target refresh rate, we kept the render resolution the same for a fair comparison. The render resolution was set to 4128 x 2096. Another limitation we encountered during the performance tests was Asynchronous Reprojection, Asynchronous Spacewarp (ASW) [24], as called by Oculus. Reprojection is an algorithm to fill the missing frames by synthetically generating the frames by guessing from the previous frames. With Oculus ASW enabled, if the computer is not fast enough to provide the frames requested by the headset for the given refresh rate, the program is forced to run half of the target framerate, and then the headset tries to fill the gaps by itself. To measure the actual performance of our simulator, we disabled these features that might force our framerate to stay at a fixed point during the tests.

3 RESULTS

3.1 Simulation Performance Results

We used three different configurations for testing, as seen in Table 1. Each configuration has a different generation Graphics Processing Unit (GPU). Quadro P2000 has GDDR5 [25] memory, the oldest generation among the test configurations. Also, this GPU card is not a VR-Ready card, which does not meet the Oculus Quest 2's recommended minimum system specifications. We used this configuration to see how our simulation performs on the lowest end of the hardware.

Table 1. Test Hardware Specifications

GPU	CPU	GPU Memory
Quadro P2000	Xeon(R) E-2144G	5 GB GDDR5
RTX 3070	i7-11800H	8 GB GDDR6
RTX 3080	i7-12700KF	12 GB GDDR6X

On the contrary, the two other systems have better specs and are VR-ready cards. The configuration with the GPU card RTX 3080 has the most recent GPU memory generation called GDDR6X [26] and can be considered as the highest end of the hardware among our devices. With this system, we mainly aimed to see if our simulation could run stable on higher refresh rates such as 120Hz. Our other test hardware, RTX 3070, represents the middle-end and has GDDR6 [25] generation GPU memory, which outperforms GDDR5 but can't reach the performance of the GDDR6X. With this hardware, we aimed to see the performance of the simulation on average configuration.

Since the most performance-intensive features included in the simulation are a) cloth simulation, b) advanced lighting, and c) mirrors, the performance calculations have been measured with these features on or off. With these different versions, we can determine whether these features can reduce the frame rate below the refresh rate of the headset at any point. This data also shows if specific interactions cause sudden drops in performance or freezes. These tests are split into four different trials, which are listed below:

- High fidelity version with the mirrors, the advanced lighting, and the cloth simulation
- No Advanced Lighting
- No Mirrors
- No Cloth Simulation

We performed the donning and doffing scenario and recorded the frame rate. We ran the same scenarios for each hardware and each refresh rate of the headset (72Hz, 90Hz, 120Hz). The measurements are taken from the start of the simulation until the time the application is closed. This results in unequal results between the simulations, but computationally heavy actions typically show spikes in performance or locally varied frame rates. The time taken to perform each scenario also varies between recordings. Figure 9 shows the performance results of each test scenario for all target refresh rates.

Overall, the performance data show that even when computationally heavy physics features such as advanced lighting, mirrors, and cloth simulation are active, the high-fidelity version of the simulator can run smoothly with a consistent framerate. For a satisfying experience, the simulation should run at least at real-time fps, which is standardized as 24 fps [27], [28]. For the 72Hz refresh rate, even with the hardware specifications that do not meet the recommended minimum requirements of the VR headset, in our case, Quadro P2000, the simulator can still run at a real-time framerate. For the refresh rates of 90Hz and 120Hz, we observed that P2000 runs slightly under 24fps. The reason for that is when the computer cannot render at the speed of the requested refresh rate, the overhead of waiting for the frame also increases due to the headset requesting more frames and waiting for more frames. On the other hand, systems with decent hardware can get a stable gaming experience of at least a 90Hz refresh rate.

When the computer can render with the frequency of the refresh rate of the headset, the data points are densely packed around the average. RTX 3070 and RTX 3080 systems tend to stay around 72 fps and 90 fps for target refresh rates of 72Hz and 90Hz, regardless of which heavy physics features are active. The RTX 3080 system can also achieve 120 fps for a 120Hz refresh rate. However, the RTX 3070 system is not good enough to render 120 fps, and test results vary from 90 to 110 fps. The Quadro P2000 system is barely capable of running VR applications, and it shows the same consistent results from 22 to 29 fps for all target refresh rates.

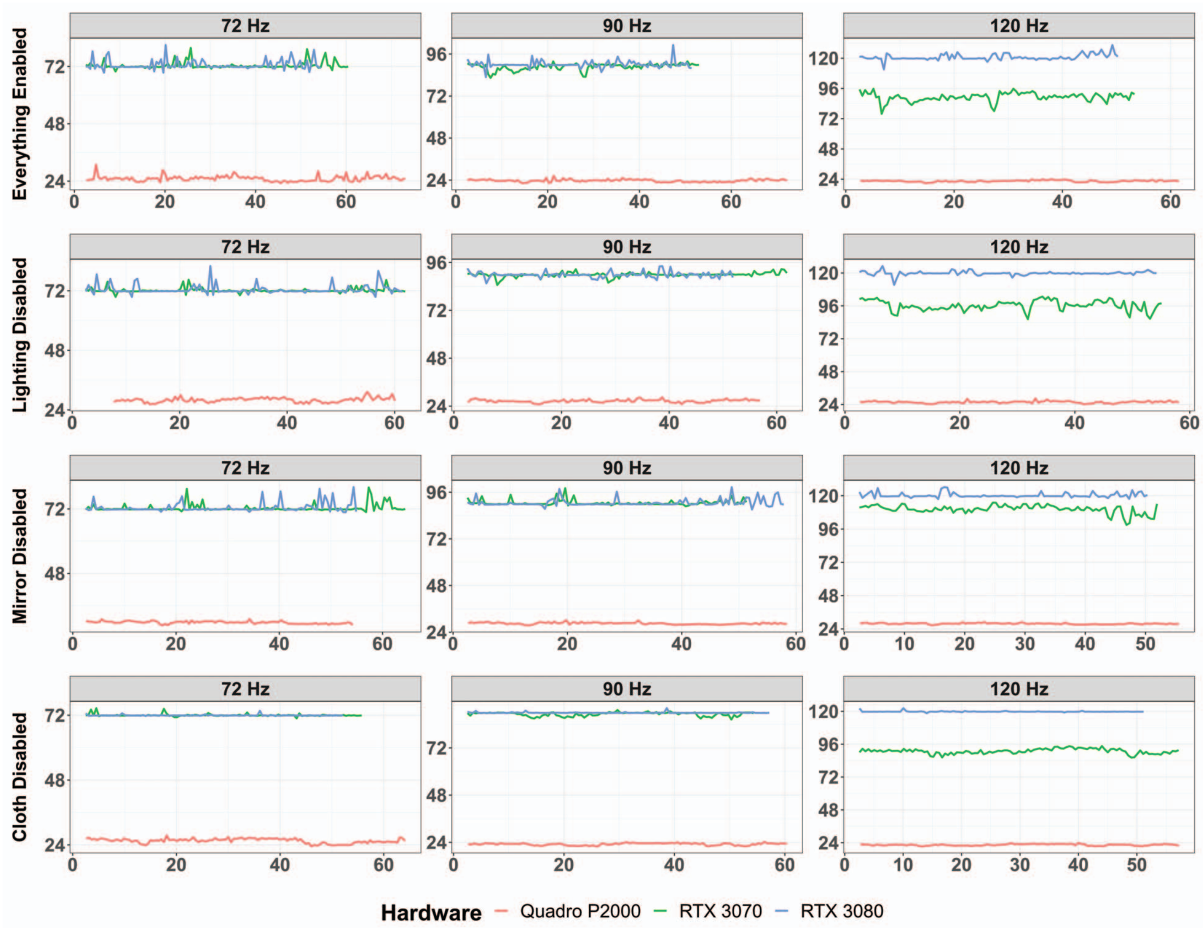

Figure 9: Performance Test Results (x-axis: Time (second), y-axis: Frames per second).

3.2 User Study VR Results

For the VR group, we tracked users' movements by recording the transformation data of their HMD and controllers throughout the simulation. The VR users were categorized based on their VR experience level, with individuals with more than three years of experience considered as experienced participants in this study. Comparing users according to their VR familiarity offers valuable insights into how previous experience affects accuracy, efficiency, and control in VR simulations. This exploration unveils potential learning curves and highlights how experience influences task performance. To assess the accuracy of the users' performance in terms of correctly following the sequence of donning and doffing, we used the Levenshtein distance [29] analysis and compared the results obtained from the post-questionnaire.

Levenshtein distance is a metric used to quantify the difference or similarity between two strings, in our case, the sequence of PPE donned or doffed. It measures the minimum number of operations (insertions, deletions, substitutions) required to transform one sequence into another. Consequently, a lower Levenshtein distance implies greater accuracy in the results. By utilizing the Levenshtein distance, we were able to compare the anticipated sequence with the sequence provided by participants through the post-questionnaire.

Regarding the donning task, the average Levenshtein distance for experienced VR users was 3, whereas, for non-experienced users, it was 4.5, representing a difference of 33.33%. In the doffing task, the average Levenshtein distance for the experienced VR users was 2, whereas for the non-experienced users, it was 5.53, indicating a difference of 63.83%. These results highlight the higher accuracy of experienced VR users in correctly performing the tasks compared to their non-experienced counterparts. The mean Levenshtein distance between experienced and non-experienced users within the VR group can be seen in Figure 10.

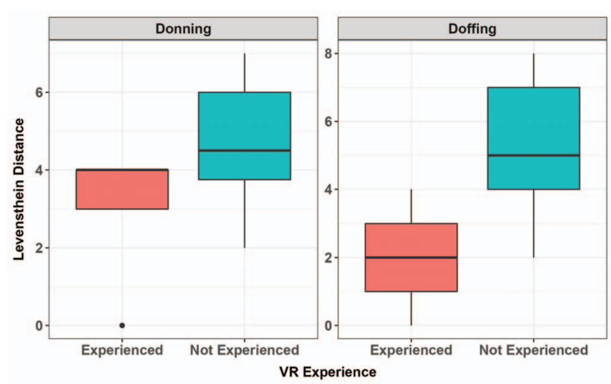

Figure 10: Levenshtein distance for VR group (Experienced vs. not experienced) for donning and doffing.

Additionally, we compared the mean velocity, acceleration, jerk, path length, and total time taken to complete the simulation. For experienced VR users, as shown in Figure 11, the mean velocity showed a 34% decrease, the mean acceleration was 36.30% lower, and the mean jerk was 36.66% less. Moreover, the experienced VR users had 42.39% shorter mean path length and 24.89% faster completion time than their non-experienced counterparts. These findings demonstrate that non-experienced VR users exhibited higher values for these measures, indicating less efficiency and control in their movements during the simulation when compared to experienced VR users. In the post-questionnaire, the VR group rated the realism and effectiveness of the simulator on a scale of five. The average scores for realism and effectiveness were 4.13 and 4.47, respectively.

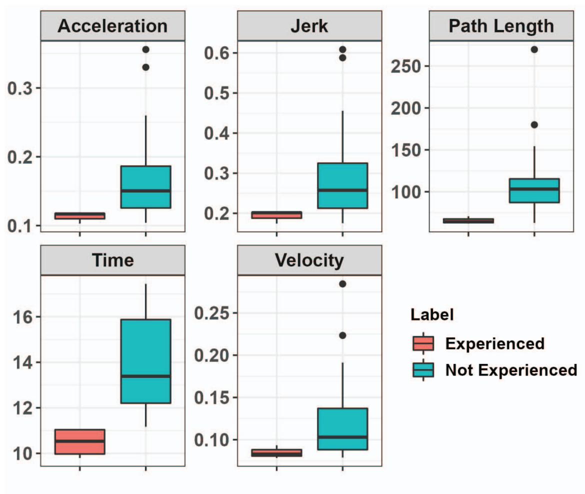

Figure 11: Performance metrics comparison within the VR group.

3.3 User Study VR and non-VR Comparison

We conducted Levenshtein distance analysis for the donning and doffing comparison for VR and non-VR groups. We used an unpaired two-tailed Welch t-test to analyze the results. For the donning task, the mean Levenshtein distance for the VR group was 3.4, while for the non-VR group, the mean was 4.65, a difference of 26.88%. For the doffing task, the mean Levenshtein distance for the VR group was 3.5, while for the non-VR group, the mean was 4.74, a difference of 26.16%, as seen in Figure 12. The t-test results for the donning and doffing tasks can be seen in Table 2.

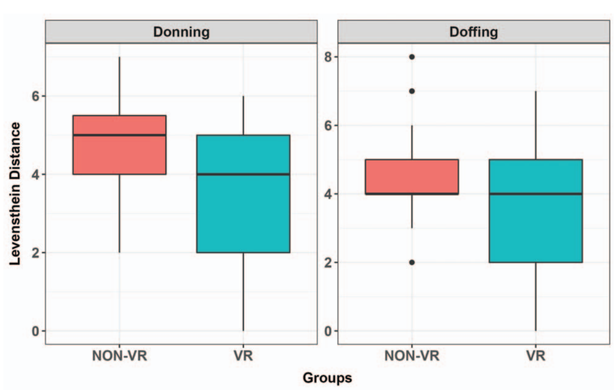

Figure 12: Levenshtein distance for test groups (Non-VR vs. VR) for donning and doffing.

Table 2. Donning and doffing tasks t-test results for VR-group

	t value	p-value	Degrees of Freedom	Critical Value
Donning Task	-2.63	0.013	37	2.03
Doffing Task	-2.66	0.012	38	2.02

4 Discussion and Limitations

Regarding the performance of the simulation, to reveal which features consume the most resources, the data of the Quadro P2000 for all refresh rates and the data of the RTX 3070 for 120Hz can be examined. We cannot use the RTX 3080 system for this comparison because it is powerful enough to render at maximum frame rate for all refresh rates, and its actual performance is limited and relative to the headset. By comparing the test results with every feature on and the other tests with deactivated features (Advanced Lighting Off, Mirrors Off, Cloth Simulation Off), it is observable that the mirror feature is the most expensive. The performance increased approximately by 20% and 10% for the tests with no mirror and no advanced lighting, respectively. Also, we can say that the cloth simulation almost does not affect the average framerate scores.

The performance effects of the mirror are reasonable. In the high-fidelity version of the simulator, there are two mirrors, therefore, there are two more cameras besides the avatar camera. Hence, in each frame, three cameras render every mesh in the scene, which adds overhead to the program. The second most costly feature is the advanced lighting. It also has performance effects due to the operations such as advanced shadowing, reflections, and lighting techniques. Despite the intense physics computations of the cloth simulation, we observed that it has almost no effect on the average performance score. This result shows that the optimization we carried out for the cloth simulation (pausing the system when no camera renders the object at that moment and enabling the system only when the object is being grabbed) works as intended and prevents unnecessary overheads. Therefore, the fidelity and immersion are increased by adding the deformable cloth simulation to the scene without compromising the overall performance.

Our user study started with 46 participants, but data from three participants were excluded due to those three participants not completely watching the video explaining the donning and doffing tasks. All participants reported that they do not have any experience with how to don and doff the PPE.

Our findings show that the VR group outperformed the non-VR group. Furthermore, within the VR group, participants with prior VR experience achieved even better results compared to those without such experience. The results of a t-test conducted between the VR and non-VR groups revealed significant differences in terms of the mean scores of Levenshtein distance, with p-values below the significance level of 0.05.

The analysis of other features such as velocity, acceleration, jerk, path length, and time indicates that users with prior VR experience move more gently in the simulator and accomplish tasks more quickly and efficiently. Higher velocity, acceleration, and jerk for less experienced VR users indicate that they made more abrupt movements. Consequently, experienced VR users had a more stable gaming experience during the simulation. Results concerning the total distance covered and duration demonstrate that experienced VR users exercised greater control over tasks and the virtual environment, completing the same tasks with fewer movements and less time.

Among the respondents in the user study for the VR-based simulation, the majority (18 out of 23 participants) reported no symptoms of motion sickness. However, a subset encountered mild discomfort: three participants experienced slight nausea due to locomotion, one reported slight dizziness, and another felt disoriented initially while adjusting the HMD. All participants who felt motion sickness reported in the pre-questionnaire about their previous discomfort in using VR. Furthermore, a few participants expressed difficulty donning face shields and doffing shoe covers, which were perceived as more challenging than other PPE tasks. This issue primarily stemmed from the limitations of the HMD used in the study.

One limitation of our study is that the non-VR (control) group did not receive real-world practice. The main reasons for this were the constraints of conducting the study in a university setting and the unavailability of the required PPE for participants. Procuring the necessary PPE would have been costly, and during the early days of the COVID-19 pandemic, the limited supply had to be preserved for patient care. As a result, we had to resort to alternative methods, such as video reviews and checklists, to provide training on the proper steps in a real-world setting. This approach is common, especially in low-resource settings with insufficient PPE for hands-on training and patient care. Another limitation of the study is that the final test was a written test rather than an expert-scored demonstration of donning and doffing by each trainee. However, given the study setting, we could not provide appropriate PPE to the participants to demonstrate hands-on skills.

Despite the limitations, our study suggests that VR-based practice is valuable, especially in settings where hands-on training might not be feasible. It demonstrated that VR-based training did not effectively compromise the participant's ability to recall the donning and doffing steps. Although the results may have been more convincing with hands-on practice for the non-VR group, we still consider the findings to be generally useful for various scenarios where real-world training is not possible.

5 Conclusion and Future Work

We have developed a VR-based donning and doffing simulation as an alternative or replacement for conventional training methods. This simulation tests the trainee's skills and requires them to don and doff PPE based on their memory. We followed the donning and doffing procedure used in medical work to ensure the accuracy of the training. Several existing technologies have been utilized with our newly developed functionality to create a virtual environment that aims to simulate reality. These developed features also help the user feel a presence within the scene, as they can visualize how they are moving and what they have done. The performance results showed that the high-fidelity version of the simulator with cloth simulation, advanced lighting, and mirror features can be run at a given target refresh rate of 72Hz and 90Hz by a system with average specs, 120Hz by a system with high specs, and real-time 24 fps by a system with low specs.

Also, we performed a user study involving a total of 43 participants, intending to assess the effectiveness of the VR simulator in comparison to traditional training methods. Furthermore, several aspects were evaluated within the VR group study. Users with VR experience had 42.39% shorter path length, 24.89% faster completion time, 34% reduced velocity, 36.66% lower jerk, and 36.30% reduced acceleration compared to non-experienced users. Also, results that emerged from our study indicated that participants who engaged with the VR simulator achieved significantly higher scores on the assigned tasks compared to those who merely watched tutorial videos, with 26.88% ($p = 0.013$) for the donning task and 26.16% ($p = 0.012$) for the doffing task.

As part of future work, the proposed VR training environment seeks to extend its uses beyond the procedure of donning and doffing PPE. This training model has the potential to greatly enhance medical training by offering adaptable educational tools for various scenarios.

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