2023 IEEE International Conference on Systems, Man, and Cybernetics (SMC)
October 1-4, 2023, Oahu, Hawaii, USA

2023 IEEE International Conference on Systems, Man, and Cybernetics (SMC) | 979-8-3503-3702-0/23/$31.00 ©2023 IEEE | DOI: 10.1109/SMC53992.2023.10394286

Cognitive Workload and Usability of Virtual Reality Simulation for Prosthesis Training

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***Abstract*— Amputees use prosthetic devices to perform activities of daily living. However, some users reject their devices due to the lack of usability or high cognitive workload. Although virtual reality has been studied in this domain for training purposes, there has not been any investigation on usability and cognitive workload of using virtual reality simulations for training of prosthetic devices. The objective of this study was to compare cognitive workload and usability of using virtual reality-based simulation of electromyography based prosthetic devices and physical devices. The findings suggested that using virtual reality simulations were helpful in reducing cognitive workload and increasing perceived usability of prosthetic devices.**

Keywords—prosthesis, virtual reality, cognitive workload, usability, training

I. Introduction

More than 2.1 million amputees live in the U.S., and about 190,000 amputations occur yearly [1]. Prosthetic devices are essential for amputees to perform activities of daily living (ADLs) [2]. However, a lack of usability in these devices can lead to poor utilization and rejection by users [3]. Using prosthetic devices also requires substantial cognitive or mental resources, possibly leading to device rejection [4]. Previous studies found that devices that impose high cognitive workload (CW) can reduce task performance, resulting in user dissatisfaction, reduced device usability, frustration, and ultimately device rejection [5].

Virtual reality (VR) provides the capability to train individuals to deal with complex situations by immersing them in a virtual environment [6]. VR-based prostheses can be customized to fit the specific needs of the individual. This allows for personalized training programs that can be tailored to meet the user's unique needs and requirements [7]. VR-based training provides instant feedback on the user's movements and actions. This feedback allows the user to adjust their movements and improve their control of the prosthesis [8]. In addition, VR-based training allows users to repeat movements and exercises multiple times without the risk of injury. This repetition is essential for building muscle memory and improving control of the prosthesis [9]. VR-based prostheses can be used in a variety of settings, including at home. This makes them more accessible for individuals who may not have access to traditional prosthetic training programs [10].

A. Related Work

Some prior studies investigated the use of VR for the training of prosthetic devices compared to the physical device (PD) [11, 12]. It was found that using VR was cost-effective

NSF - No. IIS1856676/1856441/1900044

[12], easy [13, 14], had no negative effects on participants (e.g., simulation sickness) [11], and enabled skill transfer to the PD [10]. The ADLs used in these studies included target achievement task [12], box and block test [11], clothespin relocation test (CRT) [15], making foods [16], and grabbing/releasing objects [17]. However, these studies had some limitations. First, only one study compared the level of CW between PD and VR simulations. [13] measured CW with NASA-Task Load Index (TLX) [18] when 11 participants exerted force in both environments. The overall workload was greater in the VR setting. Using subjective methods for assessing the CW of prosthetic devices can be limited due to self-report or recall biases [19]. Instead, physiological measurement (e.g., pupil dilation) can provide objective outcomes with minimum intrusiveness for sound data collection. Second, no study assessed the usability of VR simulations in this domain. The usability of VR simulation should be measured to know the users' level of engagement with VR. If the VR simulation is not user-friendly or intuitive, it can be difficult for the user to engage with the training program. This can lead to decreased motivation and reduced effectiveness of the training [9]. The usability of the VR simulation can impact how effectively the user learns and retains new skills. A well-designed and user-friendly VR simulation can facilitate learning and improve the user's ability to transfer those skills to real-world situations [20]. Usability can also impact the efficiency of the training program. If the VR simulation is easy to use and navigate, the user can spend more time on the training and less time trying to figure out how to use the software [10]. A poorly designed VR simulation can also be dangerous for the users. If the simulation is difficult to use or confusing, the user may make mistakes that could result in injury [21]. Lastly, usability could also allow for greater personalization of the training program. By making the VR simulation user-friendly, the user can customize their experience to their unique needs and preferences [22].

B. Research Objective

Assessing the usability and CW of VR simulations is critical before suggesting these simulations to train amputees. Therefore, this study aimed to compare CW and usability of training with PD and VR simulations. To achieve this objective, pupillometry data, task performance, and subjective responses were collected when participants performed the ADLs.

II. METHOD

A. Participants

Forty able-bodied participants were recruited for the experiments. Twenty participants (Age: M=23 yrs., SD=2.22, Male=14, Female=6) were recruited to use the physical prosthetic device. The experiment was conducted at North Carolina State University. Twenty additional participants were recruited to use the VR version of the experiment (Age: M=26.85 yrs., SD=4.74, Male=13, Female=7). This experiment was conducted at Texas A&M University. All participants had 20/20 vision without prior experience participating in studies with prostheses or myoelectric exoskeletons for upper limbs. The Institutional Review Board (IRB) approved both studies.

B. Apparatus

Two EMG-based control schemes were used in this study, including direct control (DC) and pattern recognition (PR) [23]. The DC mode used two sensors on the flexor carpi radialis and extensor carpi radialis longus. In addition to those two, the PR mode used two sensors on the flexor digitorum and extensor digitorum muscles (Figure 2a). Detailed sensor placement and signal processing information is provided by [24].

A pupil-core eye-tracking system was used to capture pupillometry measures as a basis for measuring the CW of participants while using prosthetic devices and performing ADLs (Figure 1). The Pupil-core system consisted of two cameras and an infrared light-emitting pod. When reflected on the eyes, the light emitted from the pod is captured by the cameras and the pupil's outline. Eye movements were captured at a frequency of 120 Hz for each pupil with a gaze accuracy of 0.6°.

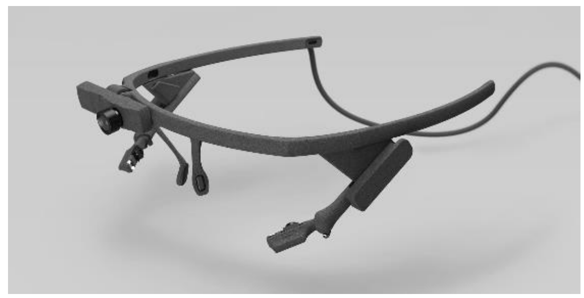

Fig. 1. Eye Tracking glasses (Pupil Core; Pupil Labs)

The experiment with the physical device was conducted with a commercial prosthetic hand (ETD, Motion Control Inc., USA), with 2-DOF of actuation in hand open/close and wrist pronation/supination, as shown in Figure 2 (b). The same EMG signals were collected and processed for the VR experiment with MATLAB, and the classified gestures were presented in the VR headset (i.e., HTC VIVE Pro Eye).

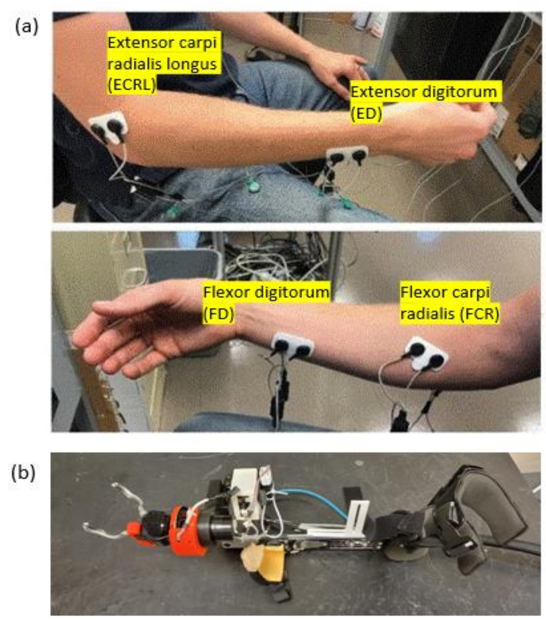

Fig. 2. EMG sensor placement (a), The physical prosthetic device (b)

C. Task

Two tasks were used in this study to assess the usability and CW of VR-based prostheses: CRT and Southampton Hand Assessment Process (SHAP)-door handle task. These tasks were identified as the most sensitive testbeds for usability assessment of upper-limb prosthetic devices from previous studies [25]. The CRT is a commonly applied ADL for assessing upper limb prostheses [23]. Participants had to move as many pins as possible from one bar to another within 2 minutes. The experiment included three trials. Between each trial, there was a 2-minute rest. The CRT workstation was mounted on a table and was adjusted to a comfortable height for the participant (Figure 3a). The SHAP-door handle task required participants to rotate the door handle using a power grip until it was fully open, then release the handle as quickly as possible (Figure 3b). The participants were asked to do this task five times as quickly as possible. Like the CRT, the experiment included three trials. Between each trial, there was a 2-minute rest. The virtual versions of these tasks were created using Unity platform (Figures 3c and 3d).

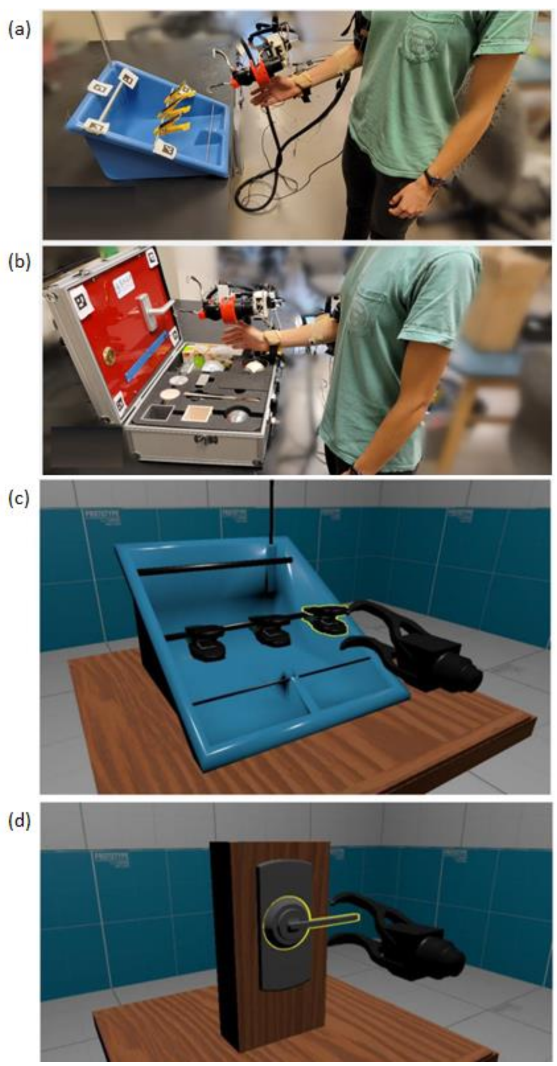

Fig. 3. Performing the CRT with physical device (a), Performing the SHAP-door handle task with the physical device (b), CRT in VR (c), and SHAP-door handle in VR (d)

D. Experimental Design

The experiment followed a mixed design with two between-subject factors (environment: VR vs. PD and configuration: DC vs. PR), and a within-subject factor (task: CRT and SHAP). Each participant was randomly assigned to one of two types of environments and device configuration. Upon being assigned to a specific type of prosthesis, all participants experienced two tasks (i.e., CRT and SHAP-door handle tasks), including three trials for each task.

E. Dependent Variables

Three dependent variables were measured in this study including: the percent change of pupil size (PCPS), task performance, subjective level of workload, and usability. PCPS and task performance were collected as objective measures of CW [19, 26]. Pupillometry data were collected using a Pupil-core eye tracking system (Pupil Labs, Germany). PCPS has been used in previous studies to assess the effect of device configurations on CW [27]. Usability of prosthetic devices was measured with two questionnaires. The first was the USE questionnaire (Usefulness, Satisfaction, and Ease of Use) [28], which measures the subjective usability of a product or service; thus, it can be applied not only to prosthetic devices but also to other domains. The second questionnaire was Quebec User Evaluation of Satisfaction with assistive Technology (QUEST 2.0) [29]. This questionnaire was designed for a person's evaluation of those distinct dimensions of the assistive device that are influenced by one's expectations, perceptions, attitudes, and personal values. Participants were asked to rate the device's usability after the last trial. NASA-TLX was used to measure subjective workload, as this measure has been used extensively in prior studies in the prosthesis device context [30]. Participants were asked to rate their perceived workload using the NASA-TLX questionnaire after each trial.

F. Data Analysis

An analysis of variance (ANOVA) was conducted. Diagnostics were conducted on all dependent variables to satisfy parametric test assumptions of normality and equal variance. Residual normality was assessed by inspection of normal probability plots, and Shapiro-Wilk's Goodness-of-Fit tests and variance homoscedasticity were checked using Bartlett's tests. The box-Cox transformation was used to transform the data in case of parametric assumption violations. All the statistical analyses were conducted using R 4.2.2.

G. Procedure

At first, participants signed the informed consent form, an informed consent form addendum for research during the COVID-19 pandemic, and a demographic questionnaire. After the participants signed all documents, they were asked to complete the Edinburgh Handedness Test [31] and the Purdue Pegboard Test [32, 5] to assess their handiness and dexterity.

Participants under physical environment task conditions donned the prosthetic adapter during the experiment, and EMG electrodes were placed on their skin based on the assigned control mode for all participants. Participants received training for their assigned control mode (i.e., DC or PR). The task-specific training assessed participant mastery of device handling and the respective control mode while completing the CRT. The training session for CRT required participants to use the prosthesis to move three clothespins from a horizontal bar at the base of the workstation to a vertical bar extending upward on the clothespin apparatus. They began with the movement of the rightmost clothespin and completed all pins as quickly as possible. An experimenter recorded the time to move the three consecutive clothespins. If the average task completion time of three sequential trials was within 15–25s for the PR and 20–35s for the DC, the participant passed the training and proceeded to the experimental trials. The training session for the SHAP – door handle task required the participants to rotate the handle clockwise for a minimum of 90° and then return to 0° before being released. The participants could do this training several times until they felt comfortable. Upon completion of the training trials, the eye-tracking system was calibrated for the participants, and they could begin the experiment trials after having 5 minutes of rest.

Participants were provided instructions on completing the two experimental trial tasks. For CRT trials, the instruction included moving as many clothespins as possible from the horizontal rod to the vertical rod and back within 2 minutes. The number of successfully relocated clothespins was recorded at the end of each trial. For the SHAP–door handle, participants were instructed to rotate the handle five times as fast as possible. The participant's eyes were tracked throughout each trial. After all trials, they also filled out USE and QUEST 2.0 forms.

H. *Hypotheses*

Two hypotheses were formulated. We expected the use of VR to reduce CW (H1) and increase perceived usability (H2) as compared to the physical prosthetic device.

III. Results

The pupillometry responses suggested significant differences in CW between the VR and PD (Table 1). PCPS in VR-based training was significantly lower than that in the PD experiment. Reversely, the blink rate in VR was significantly higher than in PD. In addition, task performance in VR was significantly better than that of PD. There were significant interactions between the device configuration and environment for the PCPS ($F(1, 225) = 14.93$, $p < .001$) and NASA-TLX ($F(1, 228) = 5.42$, $p = .02$) responses. Participants who used the DC configuration exhibited significantly higher PCPS and reported more effort when using the PD than in the VR setting, while there were no significant differences between these two conditions for the PR configuration. For usability, QUEST 2.0 results suggested that the VR was significantly more usable than the PD in terms of the dimension, weight, ease of adjustment, and comfort of the device. However, the findings of USE survey did not indicate any significant differences in usability of VE and PD ($F(1, 34) = 1.12$, $p = .30$).

TABLE I. Summary of signficant findings

Category	Dependent variables	Results	Test statistic, *p*-value
Cognitive workload	PCPS	$PCPS_{VR} < PCPS_{PD}$	$F(1, 225) = 12.55$, $p < .001$
	Blink rate	$Blink\ rate_{VR} > Blink\ rate_{PD}$	$F(1, 226) = 23.05$, $p < .001$
	Task performance	$Performance_{VR} > Performance_{PD}$	$F(1, 224) = 4.79$, $p = .03$
	NASA-TLX (Weighted Average score)	$Overall\ workload_{VR} < Overall\ workload_{PD}$	$F(1, 228) = 9.31$, $p = .003$
	NASA-TLX (Mental demand)	$Mental\ demand_{VR} < Mental\ demand_{PD}$	$F(1, 228) = 9.14$, $p = .003$
	NASA-TLX (Temporal demand)	$Temporal\ demand_{VR} < Temporal\ demand_{PD}$	$F(1, 228) = 10.30$, $p = .002$
	NASA-TLX (Effort)	$Effort_{VR} < Effort_{PD}$	$F(1, 228) = 7.81$, $p = .007$
	NASA-TLX (Frustration)	$Frustration_{VR} < Frustration_{PD}$	$F(1, 228) = 12.09$, $p < .001$
Usability	QUEST 2.0 (Weight)	$Weight_{VR} < Weight_{PD}$	$F(1, 34) = 11.49$, $p = .002$
	QUEST 2.0 (Comfort)	$Comfort_{VR} > Comfort_{PD}$	$F(1, 34) = 7.14$, $p = .01$

IV. Discussion

Hypothesis 1 posited that using VR would reduce CW compared to using the PD. This hypothesis was supported based on the findings of pupillometry measures, NASA-TLX, and task performance. The average PCPS in VR was significantly smaller than that of PD. In the VR simulation, the participant controlled the hook in the virtual environment using the attached EMG sensors and did not have to wear the physical device. Participants reported that due to the weight and size of the physical device, they could not focus on learning how to control it and perform the ADL. This might be the main reason for higher CW in the PD condition. The difference in PCPS values in the PD vs. VR environment was more pronounced in the DC configuration. Prior studies found that able-bodied participants using EMG-based prostheses tended to focus on their hand, rather than on the objects [33-35], which might be another reason for increased PCPS in the PD environment than the VR because they could not see their hand in the VR (they could only see the hook). Since the PR configuration was more intuitive than DC [5, 23, 27] and required more natural hand gestures (i.e., open, close, supinate, pronate), this difference between the PCPS values was more pronounced in the DC configuration. The lighting condition can also affect pupil size. The change of light in VR headset could be less than the PD. The visual stimuli of VR experiment depended only on the graphics in the headset as the headset blocks external lights [36], while there could be other visual stimuli (e.g., reflected light from the prosthesis or hook) in the PD condition.

Task performance in VR was significantly better than that of PD. Some of the previous studies support this finding. They found that task performance in the VR was almost the same or better than in the PD [12]. However, task performance cannot solely be a determinant of CW because it lacks interpretability, scientific rigor, and apparent compensatory effect [19]. The subjective CW ratings also supported H1 specifically in dimensions including mental demand, temporal demand, effort, and frustration. Since we used an immersive VR headset, participants in VR could concentrate on the task. In contrast, participants with PD might have been distracted or overloaded by the physical device and surrounding environment, which could lead to exerting additional efforts. Regarding the frustration dimension, participants with the PD reported more frustrations because of the weight and dimension of the device. The short essay responses in the USE questionnaire supported this as many participants answered that the device was too heavy, bulky, and sometimes it blocked their view of the task station, which could increase their frustration.

The findings of this study were not in line with [13] results that found workload was higher in the virtual condition than in the physical condition. However, it is important to note that this difference might have been due to the type of task. This study used ADL tasks, which did not require maximum or extreme forces. However, the tasks in [13] required participants to exert high levels of force. The participants in [13] were asked to grasp and lift similar physical and virtual objects of various weights. Second, it was not clear from [13] how the participants were trained on using the virtual environment, which might have affected CW of users.

The findings of QUEST 2.0 revealed that participants perceived the usability of the VR to be better than the PD (supporting H2) specifically in aspects such as the weight of the device and comfort. However, there was no significant usability difference between the VR and PD based on the USE questionnaire. This might have been due to the fact that the USE questionnaire was designed for general products or websites, not specifically for prostheses [28]. The QUEST 2.0 and USE finding could provide two insights to prosthetic users, clinicians, or designers. First, prostheses users can have better or at least similar levels of usability to what they had with physical prostheses while interacting with virtual prostheses. However, this cannot guarantee better functional outcomes in the real world [37]. Second, although further investigations are required to see the transfer effect from virtual to physical prostheses in the long term, clinicians and prosthetic device designers can test the usability of new prostheses in VR in early stages of the design and development process and before they give any recommendations to users or the physical device developers [12, 16].

Overall, the findings of this study revealed that using VR for upper limb prosthetic devices could lead to lower CW and produce better usability than using the PD. This could give insights to prosthetic device developers when they would like to test or validate novel algorithms/devices [11] with human-subject experiments. In addition, clinicians could use VR when they need to find the most appropriate prosthesis for an amputee. However, to assess the long-term training effect with the VR, additional studies with longer duration are necessary to investigate retention [37].

The main limitation of this study was the recruitment of able-bodied participants instead of amputee patients. The decision to work with an able-bodied population was made due to the limited number of trans-radial amputees in the surrounding area. Future studies should address this limitation and explore potential differences in results, particularly considering the varying cognitive workload experienced by individuals with amputations. Furthermore, when including amputee patients in the experiment, it may be necessary to modify the protocol to account for potential differences in habituation time, as these may vary individually. This consideration is essential to ensure a more comprehensive understanding and enable meaningful comparisons, particularly when it comes to training purposes. Their inclusion would contribute to a better understanding of the topic, facilitate more accurate comparisons, and ultimately improve the applicability of the findings in training contexts.

V. Conclusion

The findings of this study revealed that participants who performed ADLs in the VR settings exhibited lower CW compared to those who used the physical prosthetic device. In addition, participants had more positive opinions regarding the usability of VR-based simulation than using the physical prosthetic device. Therefore, using VR simulations can be useful for prosthetic device developers, clinicians, and amputees for training purposes. However, tasks and experimental design should be carefully selected because they can impact the CW in VR-based trainings.

Acknowledgment

The funding for this study was provided by the National Science Foundation (No. IIS1856676/1856441/1900044).

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