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An Augmented and Diminished Reality Exergame for Investigating the Embodiment of a Prosthetic Limb

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ABSTRACT

Bionic limb prosthetics continue to face significant challenges in terms of artificial limb embodiment, often leading to prosthesis abandonment in patients. Following recent results in literature on digital trainings, this study investigates the impact of the visuo-attentive feedback of an Augmented/Diminished Reality (AR/DR) exergame on prosthetic embodiment. Two interaction paradigms were compared, i.e. a reference unrestricted interaction of a virtual prosthetic limb against a one in which the prosthesis and its interaction capability fades over time and requires the participant's visual-attention to reestablish it. Preliminary findings on non-amputees demonstrated hardship with the visuo-attentive approach which was associated with detrimental effects on the prosthesis embodiment, possibly because of the re-allocation of cognitive resources that are necessary to establish the process of body ownership.

Keywords: Embodiment, Augmented Reality, Diminished Reality, Prosthetics, Attentional Refocus

1 INTRODUCTION & BACKGROUND

Technology-aided healthcare aims to enhance accessibility, personalization, and treatment outcomes through innovative solutions [4, 30]. Within this field, significant attention is devoted to bionic prosthetics research, which seeks to improve motor skills and ultimately the quality of life for individuals coping with limb loss or agenesis, particularly in everyday activities [2, 6]. Despite advancements in this field, prosthetic abandonment remains a prevalent issue. In fact, users often find artificial limbs lack intuitive control, and reliable functionality [33]. Combined with the inability of these prosthetics to provide sensory feedback, this frequently leads them to opt for motionless cosmetic limbs instead [20].

One strategy to address these challenges focuses on fostering prosthetic embodiment, described in this context as the neurocognitive incorporation of a prosthetic limb into the user's body schema (the mental representation of the individual body), enabling it to be perceived as an integral part of its own body [8]. What is more, since it has been demonstrated that increased proshetic embodiment can reduce *phantom limb pain* [13] finding ways to ameliorate embodiment may also help in rehabilitation settings. Nonetheless, the cognitive and sensory factors influencing prosthesis embodiment are still debated and subject to investigations.

So far, embodiment has been extensively studied through the Rubber Hand Illusion (RHI) serving as a pivotal experimental paradigm. This approach demonstrates how visuo-tactile stimuli (synchronized between a virtual or a practical prosthesis and the actual subject's body) can facilitate prosthetic limb integration by boosting the replica's embodiment [5, 28]. Also, the RHI is especially useful as an evaluation means to extract proprioceptive sensitivity metrics like the proprioceptive drift [8, 27]. This methodology enables the use of non-amputee participants to gather preliminary data on approaches designed to enhance embodiment, benefiting from the lower inter-subject variability compared to actual patients [23].

In this regard, eXtended Reality (XR) technologies, such as Virtual (VR), Augmented (AR), and Diminished Reality (DR), have increasingly been adopted to allow replicating an amputee settings for healthy subjects. In fact, these technologies have already demonstrated their potential in enhancing the rehabilitation process by engaging the patient in exercises that increase the sense of ownership for the digital replica of the prosthetic limb, and at same time providing cost-effective platforms for its evaluation. Literature includes many notable examples of XR-based rehabilitation approaches, usually provided in the form of exergames, that take advantage of novel interaction paradigms and applying them to digitally improve the prosthetic embodiment [15, 16, 19, 29].

Nonetheless, vibro-tactile RHI methods seems to have reached a plateau since translating them into practical solutions for amputees is challenging due to limited tactile stimuli that can be provided [10]. Hence, the community speculates that efforts should prioritize approaches leveraging *visuo-motor* correlations to enhance embodiment in prosthetic use [13]. In this context, studies utilizing

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(a) (b)

Figure 1: (a) Minimum opacity of the hand. (b) Visual feedback upon reaching maximum charge.

XR-based exergames to investigate the role of biofeedback control—such as altering the visualization of a virtual prosthetic limb (e.g., making it appear or disappear) [3, 25]—indicate significant potential for this strategy in enhancing embodiment. However, it is in need of further clarification the impact of the attentional effort to focus on the artificial limb over the self-regulation of physiological variables cross-connected to the biofeedback-control. In this regard, recent investigations highlighted how splitting the mental focus (in terms of working memory, for instance) across dual tasks (e.g. fullfilling the main mechanic of the exergame while requiring and additional input to fed the rehabilitation paradigm) might have a detrimental effect on the artificial limb embodiment [21, 22].

With the aim to add to the understanding of the overlapping effects of visuo-attentional driven feedback, this work presents a preliminary study involving non-amputees using an AR exergame based on a pick-and-place task. In this study visuo-attentional focus does not involve the self-regulation of biosignals (the main feature of biofeedback protocols) as input for the exergame, as already considered in the previous research, hence removing this potential confounding factor. The visuo-attentional version, which has been compared against a ground-truth implementation, requires the participant to deliberately focus with his/her eye-gaze on a fading virtual prosthesis in order to regain control over it. To allow the healthy participants to see-through their real arm, DR techniques have been used to remove the limb.

2 MATERIALS AND METHODS

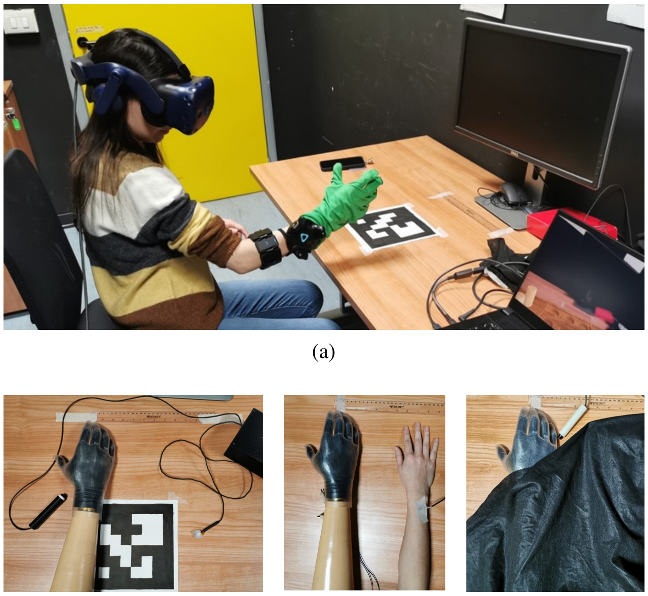
This section outlines the exergame devised for the study and presents a description of the system's implementation.

2.1 Exergame

The AR-DR exergame application was developed via the Unity game engine (v2021.3LTS) and the OpenXR framework using the HTC Vive Pro Eye[1] headset to deploy the experience.

2.1.1 Task

The exergame consisted of a repetitive pick-and-place task in an AR and DR environment, in which the participant is asked to place, one at a time, a set of cylindrical objects into randomly assigned socket-holes on a pegboard (Fig.1a). A new target hole is highlighted after each correct placement, and participants are required to complete at least 20 placements within a maximum time set at 300s. The pick-and-place task was chosen for two reasons: first, it is frequently used in the context of XR rehabilitation [12]; second, it encourages participants to look ahead of their hand during movement execution [9], thereby providing an opportunity to use hand-looking as an attentional refocusing task.



(a)

(b) (c) (d)

Figure 2: Configuration and Hardware of the (a) devised system for the exergame and (b-d) equipment used in the RHI induction.

2.1.2 Virtual Environment

The pegboard, the cylinders, and the virtual prosthetic hand are all digital AR artifacts, whereas the rest of the environment is real. The pegboard is virtually anchored to a real table placed in front of the seated participant using an ArUco [7, 24] marker[2] and the OpenCV plus Unity asset[3] for pose tracking and content registration. Participants can grab virtual objects with their hand via direct interaction. The hand tracking is enabled by tracking the position of the forearm using an HTC Vive Tracker (v2.0) strapped as far as possible from the wrist (to leave more room for the green glove required for segmentation, Sec.2.1.4), combined with the open/close gesture detected using the Myo electromyographic armband device (fist gesture detection of the SDK)[4]. Synchronized animation of the selected 3D model of the "Hannes[5]" hand prosthesis, developed by the Rehab Technologies Lab at the Italian Institute of Technology (IIT) in collaboration with the Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro (INAIL) is achieved exploiting the Unity AnimationRigging package. The user specific parameters were configured in the application during a manual calibration phase. Additionally, the Myo is used to provide vibro-tactile feedback upon object collision/interaction whereas audio feedback was provided to confirm successful placements. The system configuration is depicted in Fig.2a.

2.1.3 Conditions

For the sake of the experimental purpose the exergame task was declined in two different variants, both of interest to the research domain:

Unconstrained Execution (UE): the task was kept as already described hence the virtual prosthetic hand remained fully opaque throughout the entire task execution (whereby the participant's real arm is already removed via DR), so the interaction is unconstrained.

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[1] HTC Vive Pro Eye: `https://tinyurl.com/vive-pro-eye`

[2] ArUco: `https://tinyurl.com/3vjfc9sx`

[3] OpenCV plus Unity: `https://tinyurl.com/OpenCVPlusUnity`

[4] Myo: `https://github.com/thalmiclabs`

[5] Hannes: `https://rehab.iit.it/hannes`

Vanishing Interaction Execution (VIE): in this variant the interaction capability of the virtual prosthesis fades out linearly over time and can be restored by visual-attentional refocusing of the participant. The interaction capability was connected to the transparency of the virtual artifact and the interaction will be lost at 30% transparency (Fig.1a) which will progressively occur over a period of 30s. The capability can be restored by having the subject focus on the virtual prosthesis with eye-gaze for 5 seconds. Specifically, the prosthesis was considered "looked-at" if the distance between the eye-gaze ray and the centroid of the 3D prosthesis model (positioned in the palm) was equal to or less than 10 cm. This "re-charging" progress is signaled by increasing-pitch sound effect, visual effects and by the restoring of the virtual prosthesis opacity (Fig.1b). The eye-gaze input was enabled via the eye/facial tracking module[6] of the Vive OpenXR SDK.

2.1.4 Real Arm Removal

To enable the VIE variant for non-amputees, i.e. to be able to see-through their real arm when the transparency of the virtual prosthesis is reduced, it was necessary to leverage DR techniques in order to emulate the amputation by masking the limb. DR is usually implemented based on the following approaches: *diminution* (distorting or dispersing color), *see-through* (making objects behind an area visible) which can be declined in the form of *pre-observed background generation*, *replacement* (substituting real objects with virtual elements), and *inpainting* (filling parts of an image based on surrounding context) [11, 18].

In this work it was adopted the *pre-observed background generation* by means of a video see-through headset. For this approach video see-through displays have been preferred to optical see-through ones since it is easier to match the visual quality of the real world (captured from the headset cameras) and the pre-observer reconstruction of the real-environment sensed by the same headset.

The processing was performed as follows: (i) *Background Acquisition*: at application launch a 3D reconstruction of the room in which the experiment is executed is performed using the HTC Vive Pro Eye headset and the rigid reconstruction feature of the SRWorks SDK[7]. This will be used as background model behind the rendered stereo-camera feed; (ii) *Arm Segmentation*: the arm is segmented based exploiting the green glove via the chroma key masking [1]. Visual processing for masking calculation and its application to the stereo-camera feed was implemented with a custom compute shader, as the HSL thresholded mask was further processed using morphological operations to reduce noise, fill holes, and refine contours. A dilation operation and gaussian filter (15px kernel)[8] were then used to improve blending between the pass-through and background images hence reducing visual discontinuity of the seam.

Since the background model was generated with the headset's cameras in the same environment with unchanged light conditions, no color correction was required. The final result is shown in Fig.3b.

3 EXPERIMENT

This section describes the study conducted on non-amputee subjects to gather a preliminary observation of how the two conditions may affect the prosthetic embodiment.

3.1 Sample

Twelve participants (4 males and 8 females, aged $\bar{x} = 27.5 \pm 3.4$y.o.) were recruited among the students and staff at the authors' university. All the participants were right-handed. The procedure (starting with the informed consent request and signature) was defined by the IIT REHAB HT01 protocol (363/2022), approved by the Ethics Committee of the Liguria Region in Genoa (Italy).

(a) (b)

Figure 3: (a) Original Image from pass-through. (b) Result of limb removal using the Pre-Observed Background technique.

3.2 Procedure

The experiment followed a within-subjects design and order of exposure for the two conditions was fully counterbalanced. Prior to experience the conditions in the assigned order participants underwent a RHI induction session (pre-RHI). This session was required to measure a baseline proprioceptive sensitivity (see Sec.3.3). An additional post condition RHI induction session (post-RHI) was also administered after experiencing each condition in order to collect the aforementioned measure to compare with the baseline. Hence a participant experiences a total of three RHI sessions throughout the experiment. In order to minimize potential carry-over effects participants had to wait at least a 2h wash-out time after each RHI session (i.e. before experiencing each of the two conditions). It is here recalled that a calibration step was required before experiencing each condition (1-2minutes).

3.2.1 RHI Induction

During a RHI induction sessions haptic stimuli are synchronously applied to the real and an artificial limb. The equipment involved is depicted in Fig.2b and consisted of a real prosthesis, a ruler, a black blanket, and a haptic stimulator. The prosthesis was positioned perpendicularly to a ruler with the index finger pointing at 0cm on it, while the participant's right arm was placed beside of it (Fig.2c) and limb view is occluded by the blanket being then just the prosthetic hand visible (Fig.2d). Thus participant observed the prosthesis during 5 minutes of rhythmic haptic stimulation (exerted by a stimulator attached about 3cm below the wrist). A measure of *proprioceptive drift* is obtained by asking the participant to point with the unstimulated hand (left hand) and eye closed towards the perceived position of the index finger on the stimulated hand. The deviation between the actual and perceived position of the stimulated hand index finger is then noted as proprioceptive drift (the closer it was pointed towards the prosthesis the higher the value). An initial measure of proprioceptive drift is taken before the pre-RHI induction and excessive values (above 2cm absolute threshold) constitutes exclusion criteria from the experiment.

3.3 Metrics

Structured interviews were administered after each conditions (ACQ) and after the post-RHIs (ARQ) sessions to collect evaluation metrics. The questionnaire was made in total of 34 statements adopted from [14, 32], with constructs measuring: embodiment, usability and cognitive workload. Open feedback were also collected at the end.

Embodiment Was measured by 12 statements in the ARQ to evaluate ownership, body representation, and agency constructs. In addition, ownership was further evaluated by the *proprioceptive drift deviation (PDD)*. PDD is used to measure variations in the proprioceptive sensitivity [14, 27, 32].The PDD is the difference between the proprioceptive drift measured at the end of a post-RHI and the one measured after the pre-RHI. Higher positive values indicate a higher proclivity of the condition to induce sense of ownership of the prosthesis.

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[6] Facial Tracking Module: `https://tinyurl.com/36vye5bp`

[7] SRWorks SDK: `https://tinyurl.com/SRWorksSDK`

[8] Compute Shader Blur: `https://tinyurl.com/compShaderBlur`

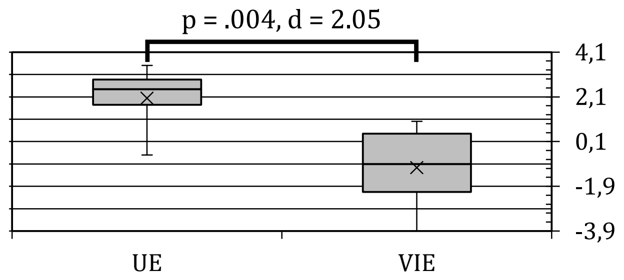

Figure 4: Results of the PDD [cm].

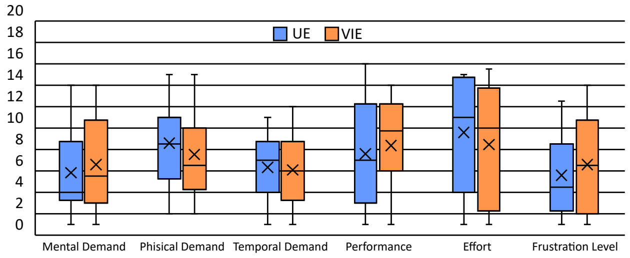

Figure 5: Results of the cognitive workload.

Usability It was measured with 15 statements to evaluate the constructs of stress, ease of use, learnability, input control, immersiveness, visual clarity, fatigue.

Cognitive Worklload Was measured by the 6 items in the ACQ originally borrowed from the raw NASA-TLX questionnaire. Construct measured are mental demand, physical demand, temporal demand, performance, effort, and frustration.

4 RESULTS AND DISCUSSION

Inferential statistics were computed using the Wilcoxon signed-rank test via microsoft excel with the real-statistics add-on (v9.3). Effect sizes are computed as adjusted Cohen's d to account for the small sample size. Statistical significance threshold was set at p-value $< .01$, which is more often used in medical research to reduce the risk of false positives [26], and more generally to enhance the reliability of findings [31].

Embodiment Regarding the PDD, a statistical significant advantage was found for the UE against VIE. As depicted in Fig.4, it appears that UE retains the ameliorating effects on embodiment already observed in the literature [14]. On the contrary, being the values associated to VIE even negative it seems to indicate that this condition had actually a detrimental effect on the embodiment process. In VIE, this can depend on the cognitive effort to focus on the visuo-spatial attention on the limb for making it appear with a minimal perception of the subject's agency. Indeed, the fading is commanded without any strong interoceptive connection with the breathing or the heart rate, probably producing an expected higher sense of control. However, this speculation will require further data to be substantiated as no significance has been found from the questionnaires in terms of agency. Another interpretation, supported by the open feedback, is that for a healthy subject the fact of observing their hand disappearing might have caused additional anxiety, thus reducing the sense of presence and suspension of disbelief, and a consequent unconscious rejection of the artificial limb. In contrast the UE environment is likely to offer a less conflicting experience as the not disappearing virtual prosthesis might be interpreted as potentially occluding the hand sight (as if it was a glove). These conjectures cannot be fully substantiated by questionnaires data as no significant differences were observed across any of the constructs from the ARQ, which can be justified by the limited sample size.

Usability In terms of usability, no significant difference was spotted for any of the constructs. It can be cautiously implied that the different interaction mechanic of the VIE was not perceived as misusability of the exergame. That's key especially for what it concerns input control construct, being then unlikely that results discussed for embodiment were affected by misjudgment in the application interaction mode.

Cognitive Workload Interestingly, performance, and effort construct were fairly high for both conditions indicating an adequate engagement and commitment of the participants in the task execution. However, no significant differences were found in terms of cognitive workload (Fig.5). This can be cautiously interpreted as if the workload among the two conditions is comparable and not influenced by differences in the conditions. Nonetheless, it might be argued that, in the VIE condition, the simultaneous management of the primary pick-and-place task and the requirement to observe-to-enable the virtual hand interaction has introduced a competition for attention. Hence at equal overall demand it is conceivable that a portion of cognitive resources have been splitted among the two tasks, then resulting in less attentive resources contributing to the embodiment, possibly influencing the perception of the prosthesis as a natural extension of the body. This interpretation further corroborates the results of the PDD and is in line with previous results on the visuo-attentive refocusing [14, 17, 21, 22].

5 LIMITATIONS AND REMARKS

Despite the contributions of this research, there are some limitations to consider. Firstly, the Myo armband may be difficult to include in future setup since it is no longer in production. Therefore future studies willing to reproduce or expand the finding of this work would require alternative EMG devices or adopt alternative approaches for the hand gesture detection (e.g. gloves with finger-tracking for experiments with non-amputees).

Secondly, the HTC Vive Pro Eye's video see-through capability is limited, highlighting the need for more advanced technologies. The Meta Quest 3, despite its superior video see-through quality, cannot be currently considered as a viable alternative due to Meta's API/SDK restrictions on accessing and processing the RGB video feed from HMD cameras. These limitations, implemented for privacy reasons[9], prevented its use for the real arm removal implementation (Section 2.1.4). Similar restrictions are also present in other consumer devices, such as the Apple Vision Pro[10]. An alternative that can be potentially included in future iterations of the experimental campaign that overcomes these limitations and offers improved visual clarity is the Varjo XR-3 HMD.

Lastly, the experiment was conducted with non-amputee participants, which naturally raises the prospect of future studies targeting amputees. Such studies could yield valuable insights: the exposure of amputees wearing prosthetics to the experiment and using DR to remove it, might offer key insights into the VIE condition. The fact that a prosthetic is not a biological limb may lead to distinct outcomes in terms of embodiment. However, future optimization of this paradigm for amputees will be necessary and rely on iterative co-design phases with clinicians and prosthetic specialists, leveraging their clinical expertise and deep understanding of patient needs.

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[9] Mixed Reality with Passthrough — Meta Horizon OS Developers: https://developers.meta.com/horizon/blog/mixed-reality-with-passthrough/

[10] Apple Vision Pro: https://www.apple.com/apple-vision-pro/

6 CONCLUSION

This work adds to the growing body of research on prosthetic embodiment by exploring the effects of visuo-attentive feedback mechanisms within an augmented and diminished reality exergame. By employing a deliberate gaze-driven interaction paradigm, this study removes the potentially confounding effects of biofeedback inputs and observes the effect of visuo-attentional strategies influencing the embodiment process.

The results show that the VIE condition, in which the virtual limb and its controls fades over time requiring visual-attention to restore it, negatively impacted embodiment. In contrast, the UE condition retained the expected embodiment improvements already reported in the literature. These results emphasize the challenges of designing strategies exploiting the visuo-motor correlations to enhance embodiment in prosthetic rehabilitation.

In this study, potential paradigms were explored to engage prosthetic users in embodiment training exercises while maintaining a view of real surroundings. The preliminary investigation with non-amputee participants provided a foundational basis for future clinical trials involving amputees, as the rendered virtual prosthesis corresponds to the prosthetic limb intended for real-world use. Future research will focus on testing improved visualization paradigms and incorporating exercises inspired by clinical training for upper limb rehabilitation. Additionally, the cognitive resource demands observed highlight the need for further studies to analyze mental workload during DR exercises, potentially using bio-signals as indicators of effort.

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