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Enhancing Upper Limb Prosthetic Embodiment through Virtual Reality with Eye-Tracking and Vibrotactile Feedback*

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Abstract—The advances in bionic prosthetics yearly show impressive achievements in the effort to improve the motor capabilities and the quality of life of people facing the difficulties due to a limb amputation or agenesis. However, aligning the actual and the desired experience of using an artificial limb in daily activities constitutes an additional challenge. Indeed, several prosthetic users tend to abandon their bionic limbs because of (for instance) their lack of reliability and sensory feedback. Consequently, strategies for increasing the prosthetic technology acceptance are explored in literature, often referring to the phenomenon of the embodiment: the incorporation of an external object in the individual body scheme (the neurocognitive representation of one's body). Among the solutions for stimulating the prosthetic embodiment, the literature offers heterogeneous interactive trainings, often based on Virtual Reality (VR) settings. By exploiting the capability of digital environments to engage the user in repetitive exercises (as in the exergames) and to accurately elicit expected reactions (like the ones of the Rubber Hand Illusion, RHI), the study presented in this paper explores the use of immersive VR to enhance the sense of embodiment, focusing on one of its components, the body ownership - the sensation of owning the external object. The VR application developed for accomplishing this study includes a vibro-tactile feedback to increase the sensory engagement and facilitate the integration of a bionic upper limb - in this case the “Hannes” hand. In particular, the experiment compares two conditions: in one, the users (healthy subjects) use their gaze for attaching components of the digital limb after a certain dwell time, and evoking the vibro-tactile feedback; in the other condition, they must press a button with the other hand for completing the task without any dwell time. The two conditions are assessed using measures of body ownership, such as the proprioceptive drift (estimating the real hand position after a session for triggering the RHI for the actual prosthesis). The findings suggest that immersive VR can improve the acceptance and integration of prosthetic limbs, especially without fully entrusting the gaze

control for the interaction: probably, this condition misdirected the cognitive resources for evoking the illusion of owning the digital hand, apparently a requirement for “embodying” the actual prosthesis. Preliminary results show this approach could help the bionic limb users with a novel tool to improve their prosthetic technology acceptance.

Index Terms—embodiment, virtual reality, prosthetics, training

I. INTRODUCTION

Bionic prosthetics research brings innovations devised for improving the motor skills and, consequently, the quality of life of people dealing with difficulties caused by limb amputations or agenesis, especially considering the activities of daily living (ADLs). Despite the advances in this domain, the risk of abandonment for artificial limbs is high: for instance, if the user feels they are not immediately responding in a reliable and intuitive way, they could decide to switch to use a cosmetic solution just mimicking the morphology of the limb. This can also happen because of the usual lack of sensory feedback, impairing the user's capability to perceive the consequences of their actions through the limb. To address this challenge, literature also explores strategies focusing on enhancing the prosthetic embodiment — the neurocognitive integration of an external object, in this case a prosthetic limb, into the user's body scheme (the mental representation of the individual body). In this context, eXtended Reality (XR) technologies like Virtual, Augmented, and Mixed Reality (VR, AR, MR) play a pivotal role. Research shows that XR is highly effective across various rehabilitation settings [1], [2], allowing users to immerse themselves more deeply in therapeutic activities [3], [4] and enhancing the overall recovery experience [2]. VR, in particular, has been highly successful in boosting motivation, increasing engagement, and enabling the practice of movements in a safe and controlled environment [5]. In rehabilitation settings, where fostering prosthetic embodiment is essential, a variety of interactive VR training tools have been developed to support this process. Immersive Virtual Environments (VEs) enable users to engage in repetitive exercises that can evoke anticipatory reactions, similar to those observed in the Rubber Hand Illusion (RHI). Despite its potential, a gap remains in research on using VR to enhance prosthetic embodiment, particularly in relation to

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body ownership, the feeling that an external object becomes part of one's body [6].

In response to this challenge, this study presents a potential solution for enhancing the prosthetic embodiment - specifically its body ownership component - through an interactive VR application, in line with a growing literature on the usage of digital systems in motor recovery [7]. The proposed application integrates vibro-tactile feedback to deepen sensory engagement and improve the integration of an artificial limb, creating a virtual limb illusion that transfers to the physical counterpart, i.e., the "Hannes" hand prosthesis¹, 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).

The application was designed to stimulate the sense of embodiment, specifically body ownership. Through the use of an Head-Mounted Display (HMD), users are immersed in a virtual experience where they assemble a prosthetic arm by positioning components solely through eye movement. Each successful placement is confirmed by vibro-tactile feedback. Two interaction modes were provided. In the first mode, which employs a visual-attention-driven interaction paradigm, the user's gaze, tracked by eye-tracking sensors, is used to select and interact with the virtual prosthesis. Interaction with virtual elements is achieved by maintaining the gaze on a component for a certain amount of time, triggering vibro-tactile feedback through a device on the biological limb. In the second, non-visual-attention-driven mode, the process is similar in terms of gaze-based selection and vibro-tactile feedback. However, instead of triggering the interaction via gaze, the assembly is initiated by pressing a button on a hand controller with the subject's other hand.

The two interaction modes were assessed through subjective questionnaires, measuring relevant aspects such as embodiment, user experience, task load, and preference, as well as through objective measures, like behavioral measures (i.e., proprioceptive drift, which evaluates the perceived alignment between the real and artificial limbs [8]), and task completion time. Results highlight that the carefully designed VR application can effectively stimulate a high degree of prosthetic embodiment, with both interaction modes showing significant user engagement. Moreover, the visual-attention based one appears to be more time-efficient, though it may slightly diminish the perception of the artificial limb as part of the body. These insights offer valuable guidance for optimizing user experience in future prosthetic technologies.

This work has been carried out as part of a collaboration between the Politecnico di Torino, the IIT, and INAIL, aiming to integrate scientific and technological expertise to enhance the quality of life for patients. Initial testing has involved participants without amputations or limb agenesis, serving as a preliminary study before trials with prosthetic users. The paper is structured as follows: the background section

reviews relevant studies on promoting prosthetic technology acceptance, particularly through device embodiment. The immersive VR application section details the proposed scenario, including design choices and components. The experiment section describes the user study, focusing on two interaction modalities. The Results section presents both objective and subjective findings, while the discussion and Conclusion section interprets the results and summarizes the work.

II. BACKGROUND

As introduced above, several studies to promote the prosthetic technology acceptance focus on the embodiment of the devices [9]. Such studies are aligned with the efforts of research in human-machine interaction from the perspective of human factors, especially cognitive ergonomics and neuroergonomics, aiming at improvements in user experience and system performance. In the literature, several studies on the embodiment intertwine engineering and psychology, developing devices able to stimulate separately or jointly the three components of this process [10]–[13]: the self-location, the feeling of being where the external object is; the ownership, the feeling that an external object is part of the individual body; the agency, the feeling of controlling the external object itself. In particular, the body ownership is extensively explored by behavioral approaches like the ones offered by the RHI paradigms, based on the co-occurrence of visual and tactile stimulations (watching the artificial limb touched by a stick while the biological one, hidden, is actually touched) that summon the sense of ownership for an artificial hand [14], [15]. Such a phenomenon, often estimated in terms of body ownership through protocols of proprioceptive drift (asking the person to point at the position of the actual limb), is also explored in VEs, especially for testing concepts that can be transferred into trainings for stimulating the embodiment of the digital version of a prosthesis even before approaching the actual one [8], [16]–[18].

The RHI paradigm demonstrates the malleability of body ownership, but its scope is generally limited to single-limb experiments and constrained by the physical and sensory limitations of the real-world setup. Aldhous et al. [19] and Kocur et al. [20] demonstrated that the RHI paradigm can be replicated, maintaining its validity in detecting embodiment development and indeed be enhanced in digital settings. XR, in this context, is an exceptional tool for directly studying the incorporation of objects and tools into our body representations as virtual body parts and bodies can be manipulated differently than in other non-VR experimental setups [21], [22]. XR technologies offer the possibility to maintain a first-person (egocentric) perspective. Studies have shown that embodiment is strongly influenced by the visual alignment of the virtual body or limb with the real body, and an egocentric viewpoint is critical in maintaining the sense of spatial coherence between the self and the virtual limb [23]. Furthermore, multi-sensor integration [24], [25] provided by digital technologies enhances the capability offered by traditional paradigms such as RHI by providing active control capabilities [26], [27], possibility to provide

¹Hannes hand prosthesis - Rehab Technologies - INAIL - IIT Lab - IIT:
<https://rehab.iit.it/hannes>

real-time feedback to the user and to control the virtual elements, facilitate the prototyping of control techniques and drives research into defining the factors that influence the modification of our body schema or body image [21]. To the best of the authors' knowledge, there is a significant gap in the literature regarding the application of VR to enhance body ownership in the context of prosthetic embodiment. To address this, an immersive VR application was developed, comparing two distinct interaction modes to evaluate the role of visual attention. By comparing a visual attention-driven interaction with a physical-driven one, this study aims to expand the understanding of how different sensory engagement modes affect the embodiment of virtual limbs.

III. IMMERSIVE VR APPLICATION

This section outlines the VR application designed to enhance the sense of embodiment in users of artificial limbs (Fig. 1). A video recording of the execution of the experience in VR is available for download².

The application, developed in Unity 2021.3 using OpenXR, relies on the Unity XR Interaction Toolkit to manage interactions within the VE. The experience was specifically designed to mimic the conditions of the traditional RHI. In particular, the experience was designed to be performed while seated in front of a physical table (Fig. 1b), aligned with a virtual replica of it, and maintaining a body stance similar to the one employed in RHI setups (with the primary arm resting on the table, the secondary arm kept still, while minimizing user movement). On the virtual table, aligned with the user's real primary arm, a 3D model of the Hannes prosthesis is displayed, while the rest of the body is covered by a cloth, leaving only the prosthesis exposed, as typically happens during real RHI experiments (Fig. 1a).

A. Virtual Environment

The VE was designed to simulate a realistic context for assembling the virtual prosthetic arm, resembling a garage setting that provides users with a familiar and relatable backdrop. For the purpose, the Simple Garage³ Unity asset, previously utilized in other VR assembly-related studies [28], was selected. This VE, displayed in Fig. 2, served as the basis for the virtual space where additional essential elements, such as the virtual table, were incorporated to facilitate the task. Additionally, the color scheme and certain design elements introduce a subtle medical feel, blending the familiarity of a garage with a clinical atmosphere to enhance immersion and deepen user engagement in the task.

The alignment between the real arm and the virtual prosthesis (Fig. 1c) is not accomplished through real-time tracking, but by physically positioning the user's arm and chest at specific points on the real table. This method is used both because the experience does not require arm movement and because the system is designed to accommodate amputee users, where

real-time tracking is not feasible. The alignment between the real and the virtual tables is achieved using one of the two controllers (the one corresponding to the primary limb, which is not used during the experience). This controller is placed inside a custom 3D-printed shell, namely the *Calibrator*, and used during an initial calibration phase of the scene. By placing the Calibrator at a predefined spot on the real table and pressing the trigger button on the controller inside it, the virtual table is aligned with the real one. Once the reference system is calibrated, the alignment remains consistent throughout the entire session, allowing the Calibrator to be set aside.

B. Selected Task

The task was designed to provide vibro-tactile stimulation at a frequency as close as possible to that generated by the brush during a real RHI, occurring when the user is actively engaged in its execution. The task itself consists of a relatively simple and repetitive routine, allowing users to quickly internalize the core mechanics and complete the task with minimal cognitive and emotional stress. Specifically, users are required to assemble the upper limb prosthesis piece by piece. The individual pieces of the prosthesis are placed in a box on the virtual table. Once the prosthesis is fully assembled, users must clean and polish the individual parts. For this, two additional props (a brush and a cloth), are used. These three interactive elements are positioned close to the user to be easily visible. Interacting with the box triggers an animation that brings the next prosthetic component out of the box and positions it in front of the user, potentially scaled up for better visibility (in the case of small parts like screws or washers). Simultaneously, a semitransparent copy of the component is displayed in its position on the already partially assembled stump. This copy serves as a target for eye-tracking interaction and changes color based on its state, as shown in the Fig.3. Additionally, various sound effects are employed to guide the experience, for example, to indicate or attachment of a piece, the extraction of the next one from the box, as well as the execution of cleaning and polishing (for these two actions, sound is the only feedback provided). In general, the selection of virtual objects for interaction is controlled via eye-tracking, while the actual triggering of the interaction is managed in two distinct modes, as described below.

C. Interaction Modes

To interact within the VR application, two different modes were considered, both based on eye-tracking. This choice aligns with the conditions of a real RHI, where the user is kept almost completely still. The first mode employs a visual-attention-driven interaction paradigm, in which the user's gaze, tracked via eye-tracking sensors, is used to select and interact with virtual elements. This is achieved by focusing the gaze on a component for a predefined period, triggering vibro-tactile feedback through a device attached to the biological limb. The second mode does not rely solely on visual attention. While the gaze-based selection and vibro-tactile feedback remain similar, interaction is initiated by pressing a button on

²VR Application Execution Footage: <https://tinyurl.com/yeyvu59y>

³Simple Garage: <https://assetstore.unity.com/packages/3d/props/interior/simple-garage-197251>

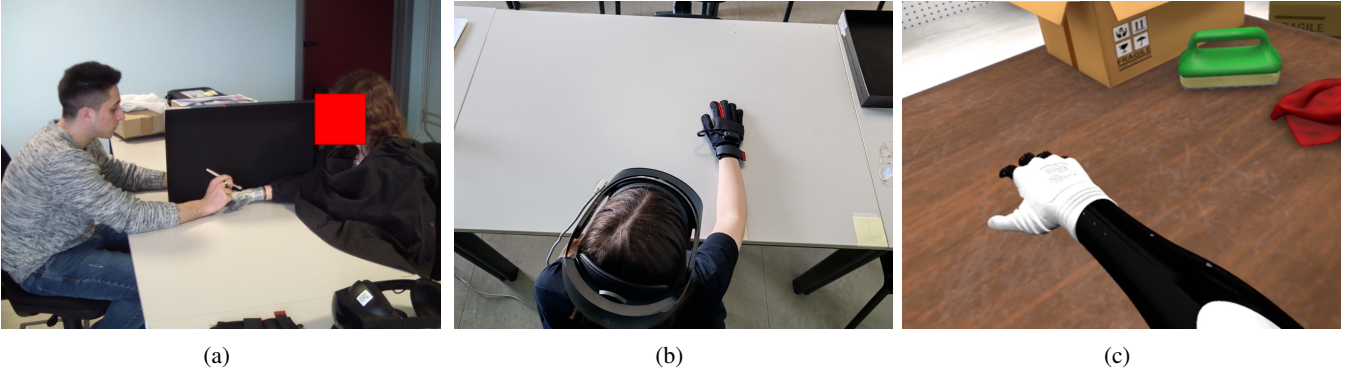


Fig. 1: The Rubber Hand Illusion (RHI), used as the basis for the application’s design as well as for the experimental activity (a), and the VR application, shown from an external view (b) and from the user’s perspective through the HMD (c).



Fig. 2: The VE used as setting for the VR application.

a hand controller operated by the user’s other hand, rather than through sustained gaze alone. The gaze-only method is expected to provide greater efficiency due to its hands-free nature, allowing users to complete tasks more quickly [29], [30], particularly in repetitive scenarios. However, this approach may also introduce a higher risk of unintentional triggers, especially in situations requiring precise selection or in environments with numerous interactive elements [31]. On the other hand, combining eye-tracking with a physical button for confirmation should reduce selection errors by offering more explicit control over interactions. Although this

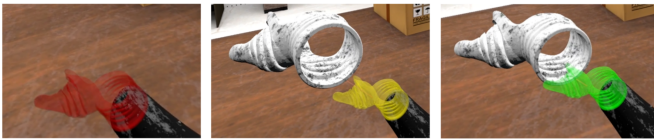


Fig. 3: Color feedback used to guide the user during the assembly of the prosthetic limb. Red color (left) indicates that no action is available, prompting the user to move their gaze away. Yellow (center) signals that the interaction is available, and green (right) confirms that the interaction is being executed.

method might be slightly slower due to the added step, it is likely to improve accuracy and provide users with a stronger sense of control and intentionality in their actions [32]. These two modes are considered sufficient for the experiment as they represent a clear contrast between implicit and explicit interaction mechanisms, offering valuable insight into their effectiveness in the considered VR context.

D. Vibro-tactile Stimulation

For vibro-tactile stimulation, in principle, any actuator that can be precisely positioned on the user’s limb can be employed. In the case of healthy users, it is sufficient to decide how many devices are required and where to place them on the limb, taking into account the areas where virtual stimulation needs to be felt on the real limb. This placement ensures that the user experiences the intended sensory feedback at the appropriate points, aligning the virtual and physical sensations for a more immersive and accurate interaction. For amputee users, however, it is necessary for medical personnel to first identify the spot on the residual limb where the vibration is perceived as originating from the desired location on the real arm, which can vary for each individual.

E. Logging and Performance Metrics

The application was equipped with logging capabilities, allowing the generation of a file for each session that contains the user ID, the selected interaction mode, and three performance metrics computed over the entire experience. The first metric, *Duration* (D), measures the total task execution time (t_e). The second metric, *GazeErrors* (GE), counts the number of times the user shifts their gaze away from the correct target. The third metric, *GazeAttentionIndex* (GAI), quantifies attention by calculating the average distance between where the user is looking and the correct target. It is defined as:

$$GAI = \frac{\sum_{f=1}^{N_f} G2Tdist_f}{N_f} \quad (1)$$

where $G2Tdist_f$ represents the distance between the 3D point actually focused on by the user (as tracked in the VE) and the target at frame f , and N_f is the total number of

frames in which the measure is recorded. The final metric, *GazeOnTargetTime* (GOTT), measures how much time the user spends focusing on the correct target:

$$GOTT = \frac{t_g}{t_e} \times 100 \quad (2)$$

where t_g is the time spent gazing at the correct target, and t_e is again the total execution time.

The correct target varies throughout the task based on the phase, and can be the box, the target position for the current prosthetic piece, the brush, or the cloth. These metrics have been then employed in the experiments described in Section IV.

F. Reference Implementation

The presented VR application is, in principle, compatible with any HMD equipped with eye-tracking capabilities and hand controllers. For the reference implementation, the Meta Quest Pro was selected as VR system. Thus, the 3D-printed shell for the Calibrator was modeled to fit the Oculus Touch Pro hand controller. For the vibro-tactile stimulation, it was decided to limit the setup to a single actuation point. Given that, in order to achieve easy integration with the application and allow for consistent positioning of the device across all users. This was achieved by using a haptic glove for VR. Specifically, a Manus VR development kit glove was used, worn only on the hand of the primary arm, and employed solely to deliver, through its SDK, vibro-tactile feedback to the back of the hand as needed. To ensure seamless integration of the Manus VR system, the application was deployed as a PCVR experience, allowing it to be played by connecting the headset to a PC equipped with the USB receiver for the haptic glove. The whole setup is shown in Fig. 4.

IV. EXPERIMENT

This section describes the study conducted on healthy subjects to evaluate the proposed VR application for enhancing prosthetic embodiment. The primary focus is on comparing the two considered interaction modalities. For this activity, the same hardware setup as the reference implementation was employed (i.e., Meta Quest Pro and Manus VR Development Kit). The Quest Pro was connected via Meta Quest Link to a notebook featuring an Intel Core i7-10750H, 32GB of RAM, and a GeForce RTX 2070 Super Max-Q.

A. Participants

A sample of 14 participants (7 males, 7 females) aged between 22 and 37 years ($M = 26.71$, $SD = 3.71$), recruited among the students and staff at the authors' university, with half of them wearing corrective eye-wear. 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).

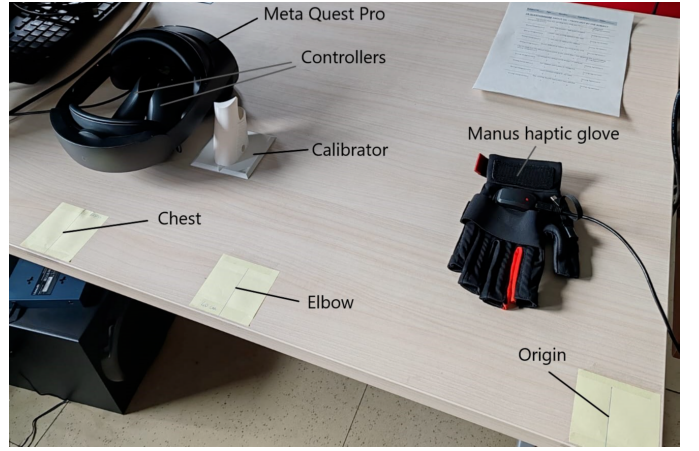


Fig. 4: Hardware setup required to run the VR application, also used in the experiment. One controller have to be placed inside a 3D-printed shell (Calibrator), while the other is either held or set aside depending on the interaction mode. The Manus glove is worn on the primary arm, and post-it notes mark positions for seating (Chest), arm placement (Elbow), and location for placing the calibrator (Origin) to perform the alignment with the virtual table.

B. Procedure

The experiment was designed as a within-subject user study, where each participant was tested in two conditions, presented using a Latin square order of exposure. The two conditions correspond to the interaction modalities being tested: the Visual-Attention (VA) driven mode, which relies solely on eye-tracking to trigger interactions, and the Non-Visual-Attention (NVA) driven mode, which requires an additional physical action, such as pressing a controller button, to confirm and complete the interaction.

The experimental procedure lasted one hour and consisted of multiple phases. After providing informed consent, participants completed a pre-experiment questionnaire to collect demographic information, such as age, gender, and the use of glasses or contact lenses. Following this initial phase, the experimental activities commenced. The first phase involved a traditional RHI induction session lasting five minutes (pre-RHI). During this phase, brushstrokes were synchronously applied to the real and artificial limbs. At the end of the session, participants were asked to close their eyes and use their unstimulated hand to indicate the perceived position of the index finger on the stimulated hand. The difference between the actual position and the perceived position of the finger was recorded as proprioceptive drift, which was used to assess baseline proprioceptive sensitivity [8]. In the second phase, participants engaged in the VR experience using one of two available interaction modes. Before starting, the experimenter conducted a calibration phase to ensure proper alignment. During this phase, the virtual limb was precisely aligned with the participant's real elbow, and the virtual table was adjusted to match the position of the real

table. The virtual experience lasted approximately six minutes, after which participants underwent a second RHI induction session, followed by another measurement of proprioceptive drift. Afterward, they completed a post-experience questionnaire to gather subjective evaluations. In the third phase, participants engaged in another virtual experience, this time using the second interaction mode, followed by a third RHI induction session (post-RHI), and completed a second post-experience questionnaire. At the conclusion of all test sessions, participants were asked to indicate their preference between the two conditions. The full questionnaire is available online⁴.

C. Measures

For the study, a combination of objective, subjective, and behavioral measures, was considered.

The objective measures included also the performance metrics captured by the VR application, detailed in Section III-E (task duration, gaze errors, GAI and GOTT), to evaluate the efficiency and accuracy of the two modalities. Subjective measures were collected through a post-experience questionnaire, obtained by adapting the one already used in [8]. The questionnaire is composed by three parts, administered after the RHI session conducted immediately following each VR experience. The first one focused on User Experience in VR (VR-UX), with a likert scale from 1 to 5, with 1 indicating strong disagreement and 5 indicating strong agreement with each statement in the questionnaire. The second one, based on the NASA-TLX [33] questionnaire, was aimed at collecting data on engagement and cognitive load. The third one (RHI), and it was used to subjectively assess the level of prosthetic embodiment experienced by the participants.

As previously mentioned, after each RHI session, the behavioral measure of proprioceptive drift was collected to assess the level of prosthetic embodiment [8]. This measure reflects the distance between where the user perceives a specific point on their limb (e.g., the fingertip) with their eyes closed and the actual position of that point on the real limb. The greater the drift toward the prosthetic limb, the stronger the user's sense of ownership over the device. Therefore, the difference between the post-RHI and pre-RHI drift values was used to quantify the positive impact of the VR experience on prosthetic embodiment [8].

Finally, the preference was measured using a 5-point Likert scale, where 1 indicated a strong preference for the first interaction modality experienced, and 5 indicated a strong preference for the second. Participants were also given the opportunity to provide additional comments.

V. RESULTS

The Shapiro-Wilk test was used to evaluate the normality of the data. Since the data were found to be non-normally distributed, the non-parametric Wilcoxon signed-rank test was performed, with a 5% significance threshold ($p\text{-value} < .05$).

Starting with the data analysis of the VR-UX questionnaire, shown in Figure 5, results indicated no significant differences

between the VA and NVA conditions for most of the items, with the exception of the item measuring the visual clarity of virtual elements, where the VA condition was perceived as slightly better than the NVA condition (4.64 vs 4.21, $p = .041$). This outcome may be related to the fact that, in the VA condition, participants were required to maintain their gaze on the virtual objects for a longer period, which likely resulted in increased attention to detail. This sustained focus may have enhanced their perception of the objects, making them appear more recognizable and visually distinct compared to NVA.

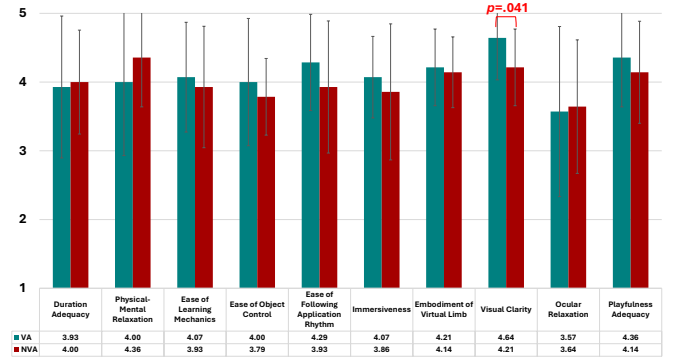


Fig. 5: Results for the VR-UX questionnaire [8] (the higher the better). Baffles are used to report significant differences ($p < .050$). Standard deviation is expressed through error bars.

No significant difference was found between the two conditions regarding the NASA-TLX part. However, optimal values below 10 were obtained for all items in both conditions, suggesting good usability of the application and a satisfactory user experience.

Similarly, the RHI questionnaire (Fig. 6) did not reveal any significant differences, achieving excellent results for both conditions, suggesting that both modalities can enable effective stimulation of prosthetic embodiment.

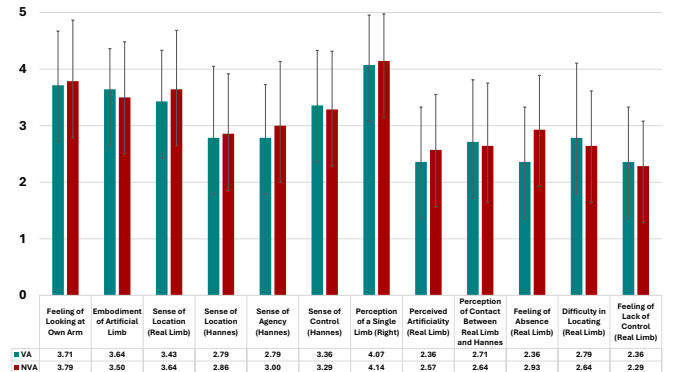


Fig. 6: Results for the RHI questionnaire [8] (the higher the better). Standard deviation is expressed through error bars.

Moving to the objective measurements, a pairwise t-test was performed to assess the performance metrics recorded during the two VR sessions, as the Shapiro-Wilk test confirmed the

⁴Questionnaire: <https://tinyurl.com/869m99mt>

normality of the data. The only metric showing a significant difference was D, measuring the total task duration, as reported in Fig. 7. In particular, results indicated that participants in the VA condition completed the required tasks significantly faster compared to those in the NVA condition. This suggests that the VA modality allowed for more efficient task performance in the VE (5.73 m vs 6.38 m, $p = .046$). This finding aligns with prior research [29], [30], which indicates that gaze-only interaction is generally more time-efficient compared to combined gaze and controller input. Furthermore, as no significant differences were observed in the other performance metrics (GE, GAI, and GOTT), it can be inferred that the advantage of VA does not compromise precision.

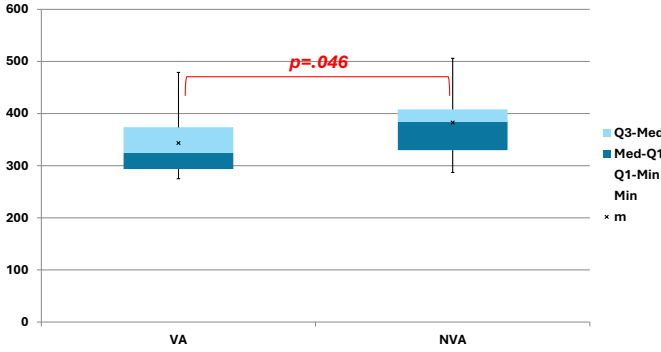


Fig. 7: Results for the task duration performance metric (in seconds, the lower the better). Baffles are used to report significant differences ($p < .050$).

Regarding proprioceptive drift, measured as the difference between the perceived position of the index finger and the actual position of the artificial hand, the results were normally distributed according to the Shapiro-Wilk test. A pairwise t-test revealed a significant difference between the two conditions. Specifically, participants exhibited a significantly higher average proprioceptive drift in the NVA condition compared to the VA condition (5.13 cm vs 3.06 cm, $p = .028$), as shown in Fig. 8. This suggests that excessive visual concentration in the VA condition may negatively impact the perception of the artificial limb as part of the body, leading to greater spatial distortion and reducing the overall effectiveness of the VR application in inducing prosthetic embodiment.

VI. DISCUSSION AND CONCLUSION

This study explored the use of immersive VR to enhance the sense of prosthetic embodiment, with a particular focus on body ownership, through a custom-developed VR application. The application integrates vibro-tactile feedback to boost sensory engagement and generate stimulation comparable to real RHI sessions. It offers two interaction modes based on eye-tracking, designed to minimize user movement, replicating conditions similar to real RHIs. The modes differ in how interactions are triggered: in the first, Visual Attention (VA) mode, interactions are initiated through eye-tracking alone, while the second mode (NVA) requires explicit confirmation

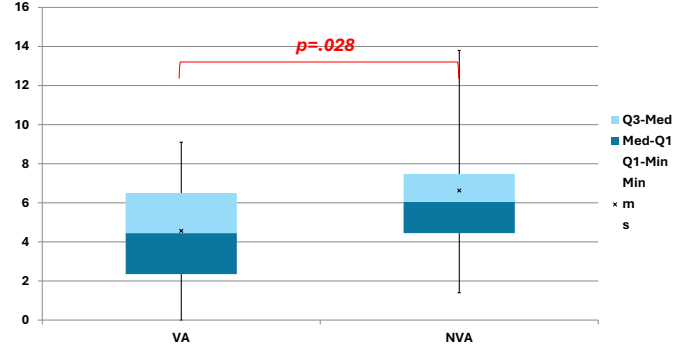


Fig. 8: Results for the proprioceptive drift difference (in centimeters), calculated as the difference between the value measured after the pre-RHI and the one measured after the post-RHI (the higher the better). Baffles are used to report significant differences ($p < .050$).

via a physical button press. The application, featuring both interaction modes, was tested in a preliminary user study involving healthy participants. The results highlight the application's effectiveness in fostering prosthetic embodiment across both modalities, while maintaining a low task load and high ease of use. When comparing the two modes, VA improved task efficiency and visual clarity, but it might divert cognitive resources from fostering a strong sense of body ownership, as suggested by the reduced proprioceptive drift, compared to the button-driven mode while NVA elicited a higher level of prosthetic embodiment, which is the primary objective of the application. Additional comments highlighting immersiveness, interactivity, and enjoyability provide further positive feedback, reinforcing the application's effectiveness. This suggests that it successfully balances engagement with therapeutic objectives.

One limitation of this study is that it was primarily conducted to explore potential effects of the two conditions presented above. A control group will be included in a subsequent investigation with a larger sample size to evaluate data from subjects who did not use the application. Another limitation is that only a single point of vibration application was used. Future developments will focus on increasing the number of these points by replacing the haptic glove with a custom-made device, equipped with multiple vibrating elements that can be positioned at various points along the limb. Moreover, despite the positive results of this study, its reliance on healthy participants poses a limitation, as their experiences may not fully represent those of actual prosthetic users.

Future research should include trials with individuals using bionic limbs to provide a more accurate understanding of how immersive VR can support prosthetic acceptance and integration into daily life. Additionally, exploring alternative sensory feedback mechanisms and interaction methods could offer deeper insights into improving embodiment and enhancing the overall user experience.

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