POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Hololimb

A Portable Mixed Reality Application for Phantom Limb Pain Management

Authors:
Xin Ye, Matteo Civitillo, Mattia Vicenzotto, Dario Jauregui Lankenau

Course: Advanced User Interfaces
Professor: Franca Garzotto
Tutors: Giulia Valcamonica, Francesco Vona, Daniele Luigi Romano
Academic Year: 2024-25
Emails: xin.ye@mail.polimi.it, matteo.civitillo@mail.polimi.it,
mattia.vicenzotto@mail.polimi.it, dario.jauregui@mail.polimi.it

I. Abstract

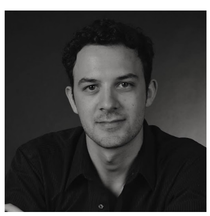
Hololimb is a portable mixed reality application designed to assist single arm amputation patients in the management of phantom limb pain (PLP). Using the Meta Quest 3 platform, it facilitates therapy engagement in any location, offering flexibility that extends beyond the confines of clinical settings. The system offers a variety of therapy modes, including static visualization and mirror therapy, enabling users to anchor a virtual phantom limb to their shoulder, adjust its opacity, and engage in movement-based or static focus sessions, both in a real and a virtual world. Its intuitive interface ensures accessibility for first-time MR users. Hololimb's portability, accessibility, and adaptability deliver a non-pharmacological, immersive PLP management tool, empowering users to control their therapy anytime, anywhere. Optimized for domestic use, Hololimb is designed for brief, focused therapy sessions ranging from 10 to 30 minutes, facilitating easy integration into daily routines without the need for clinical supervision.

II. Team Members

Xin Ye

Matteo Civitillo

Mattia Vicenzotto



Dario Jauregui Lankenau

III. Members Contributions

Members involved	**Activity**
Everyone	Project Requirements
Everyone	UNG Model
Everyone	State of the Art
Everyone	UX Design
Dario, Mattia	Mirror Mode
Matteo, Xin	Static Mode
Dario	Arm tracking
Mattia	Opacity
Xin, Matteo	Menu, Tutorial and Environment
Matteo, Xin	Project Documentation
Mattia	Validation Process Document
Everyone	Video and Presentation

CONTENTS

IV. Executive Summary

A. Main Problem and Requirements

Phantom Limb Pain (PLP) is a debilitating condition that affects individuals who have undergone upper-limb amputations. Conventional treatment options, such as medication or physical therapy, are often inaccessible due to cost, limited availability, or the need for continuous clinical supervision. To address this gap in the literature, we have identified key requirements for a solution that includes:

- **Non-invasive therapy** as an alternative to medication.
- **User-friendly interface** for first-time Mixed Reality (MR) users.
- **Portability and adaptability** to enable therapy outside clinical environments.
- **Personalization** to accommodate individual therapeutic needs.

B. Proposed Solution: UX and Technology

Hololimb is a Mixed Reality application designed for **Meta Quest 3**, providing a customizable and immersive therapy experience for PLP management. The **user experience (UX)** is designed to balance simplicity and flexibility, ensuring accessibility for new users while offering advanced features for personalized therapy. The application has key features, such as:

- **Arm Anchoring and Customization**: The phantom limb is automatically anchored based on the user's shoulder position. Users can modify the limb's opacity for optimal visualization.
- **Therapy Modes**: Hololimb supports **static and movement-based therapy**, enabling users to perform simple motions or complex exercises. The system encourages mental reconnection with the phantom limb through immersive sessions and virtual objects to interact with.
- **Flexible Session Design**: Sessions are designed to be **short and manageable (10–30 minutes)**, fitting easily into users' daily routines without requiring continuous professional supervision.

C. Value Proposition

Hololimb offers a **portable, adaptable, and non-pharmacological solution** for managing PLP. It combines advanced MR technology with a user-friendly interface to deliver an effective and customizable therapy experience. By enabling users to take control of their therapy anytime and anywhere, Hololimb promotes autonomy and improves quality of life. Its **scalable design and integration of home-based therapy** make it a unique tool in the field of digital health, offering a new standard for self-guided PLP management.

V. Requirements

A. Stakeholders

- **Primary User**: Person with a single-arm amputation experiencing PLP
- **Secondary User**: Therapists
- **Indirect Stakeholder**: Medical and Rehabilitation Community
- **Tertiary User**: User's Family and Caregivers

B. Needs

- **Improving the effectiveness and portability of PLP Relief Sessions**: Need for independent use and possibly more effective solutions than common methods of attacking PLP.
- **Non-pharma PLP Pain Relief**: The need for an effective way to provide pain relief for phantom limb pain (PLP) by helping users manage their discomfort through immersive experiences, aiming to improve their quality of life.
- **Ease of Use, Relaxed and Enjoyable Experience**: An intuitive user interface (UI) and experience (UX), with minimal learning curve, so users of varying technological skills can operate it effectively.
- **Innovative Tool for PLP Pain Relief Therapy**: The need for healthcare professionals to enhance phantom limb pain (PLP) relief therapy sessions for a more effective and innovative treatment approach.

C. Context

- **Organizational**: Family or Caregivers support in its use, especially in the initial stages. Therapist Guidance if needed.
- **Physical**: At-home indoor use.
- **Temporal**: At-Home Use. Varying lengths of time based on their needs and comfort level. (10 to 30 min)

D. Constraints

- **User**: Currently designed exclusively for a single user, who are single-arm amputees, whether left or right and with different levels of amputation. Patients with hemineglect or visual impairments are most likely unable to complete this form of treatment.
- **Physical**: Adequate space for VR use and limited interference to accurately track arm movements (e.g., good lightning, 2m x 2m). Users should have comfortable seating or standing options, as extended sessions may require a relaxed posture.
- **Hardware and Tech**: Meta Quest 3; hardware must support high-fidelity tracking and rendering of the phantom limb to ensure a realistic and effective therapy experience.
- **Time and Session Limits**: Ideal session duration may need to be defined to maximize efficacy without causing fatigue, especially for users new to VR. (Suggested 10 to 30 min).
- **Human/Resource**: Limited development capacity (4 students working on the project).

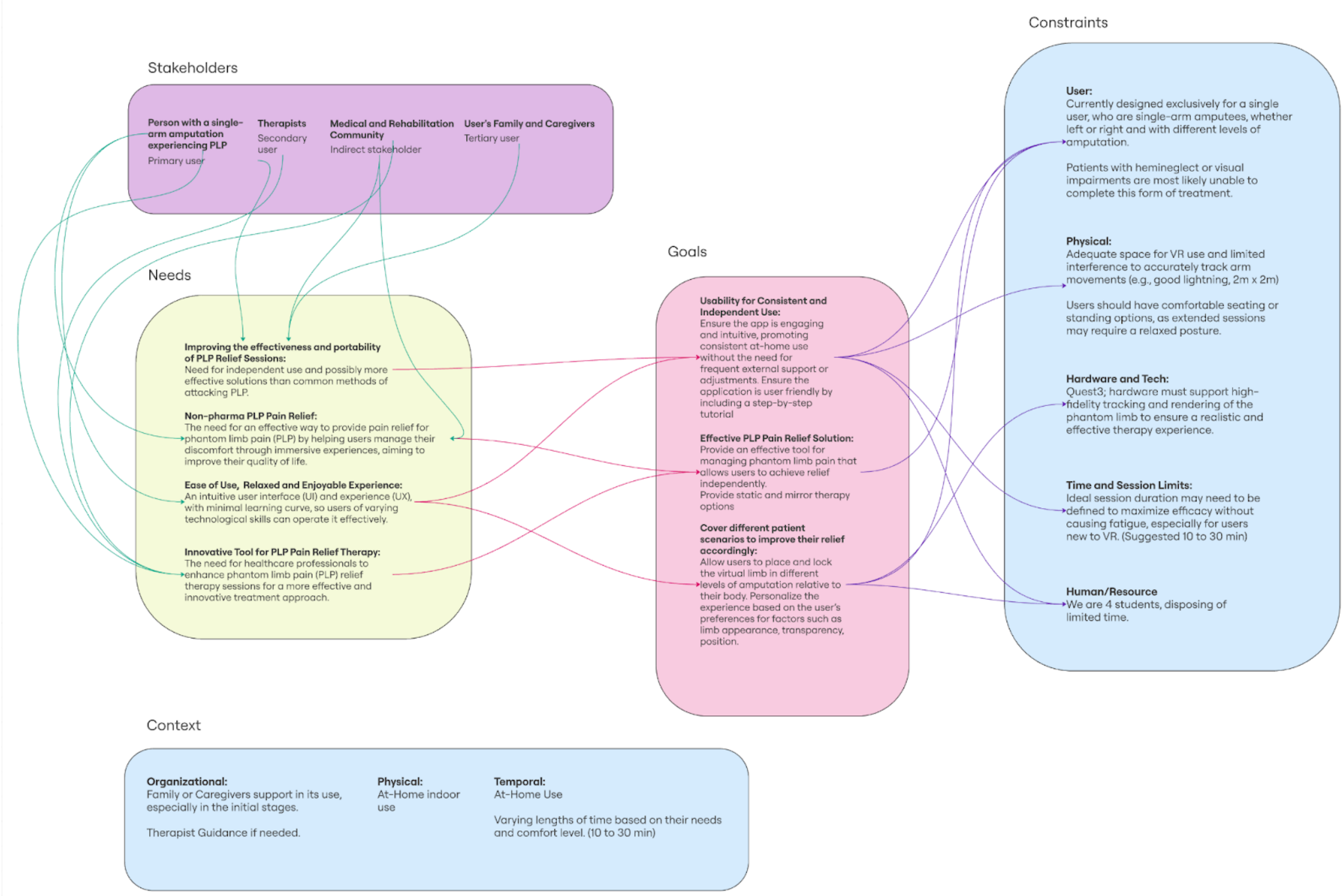


Fig. 1: UNG Model

E. Goals

- **Usability for Consistent and Independent Use**: Ensure the app is engaging and intuitive, promoting consistent at-home use without the need for frequent external support or adjustments. Ensure the application is user friendly by including a step-by-step tutorial.
- **Effective PLP Pain Relief Solution**: Provide an effective tool for managing phantom limb pain that allows users to achieve relief independently. Provide static and mirror therapy options.
- **Cover Different Patient Scenarios to Improve Relief**: Allow users to place and lock the virtual limb in different levels of amputation relative to their body. Personalize the experience based on the user's preferences for factors such as limb appearance, transparency, position.

VI. State of the Art

Mixed Reality (MR) and Virtual Reality (VR) technologies have shown significant potential in therapeutic applications, particularly for chronic pain management and cognitive rehabilitation. Over the last decade, research has highlighted the advantages of these technologies in modulating sensory experiences and supporting physical and psychological therapy.

One prominent example is the **Hololimb** past project, which goal was to use MR to treat phantom limb pain (PLP) by superimposing a customizable virtual limb on the user's phantom limb. That project aimed to reduce pain through sensory stimulation and brain plasticity, adjusting the virtual limb's attributes such as size, position, and transparency to fit the patient's needs, but during the project implementation, the team did not manage to produce a viable product or demo with all these features or realistic scenarios, and was only developed for Microsoft HoloLens 2[1].This approach builds on the established effectiveness of mirror therapy and extends it into MR, providing a more immersive and adaptable environment compared to traditional techniques[2].

In addition, other projects like **HoloLearn** explore the use of MR for cognitive rehabilitation. HoloLearn combines MR with speech-based virtual assistants to help individuals with cognitive disabilities improve their autonomy and learn daily tasks. The integration of virtual assistants in MR has been shown to enhance user engagement and performance by providing clear guidance and real-time feedback[3].

Several research efforts support the application of MR for pain management and cognitive rehabilitation. Studies have demonstrated that MR can effectively reduce chronic pain by fostering cortical reorganization, particularly when compared to fully immersive VR, which may disconnect users from their real environment[4]. MR systems like ”magic mirror” rehabilitation setups have also proven more comfortable for extended use, addressing issues such as VR-induced motion sickness[5].

These advancements underline the growing relevance of MR technologies in healthcare, particularly for home-based and portable solutions. Systems like Hololimb are designed for home environments, offering patients an accessible and non-invasive method to manage chronic conditions while maintaining a connection with their physical surroundings[1].

In summary, the combined use of MR and tailored virtual interventions is paving the way for innovative approaches in healthcare, reducing the need for pharmacological treatments and empowering patients with more autonomy and control over their therapy sessions[6].

VII. Solution – UX Design

A. General Approach

The platform leverages **wearable VR interfaces, full-body tracking**, and **multimodal feedback** (visual cues, interaction hints, and guided instructions) through an intuitive **GUI**.

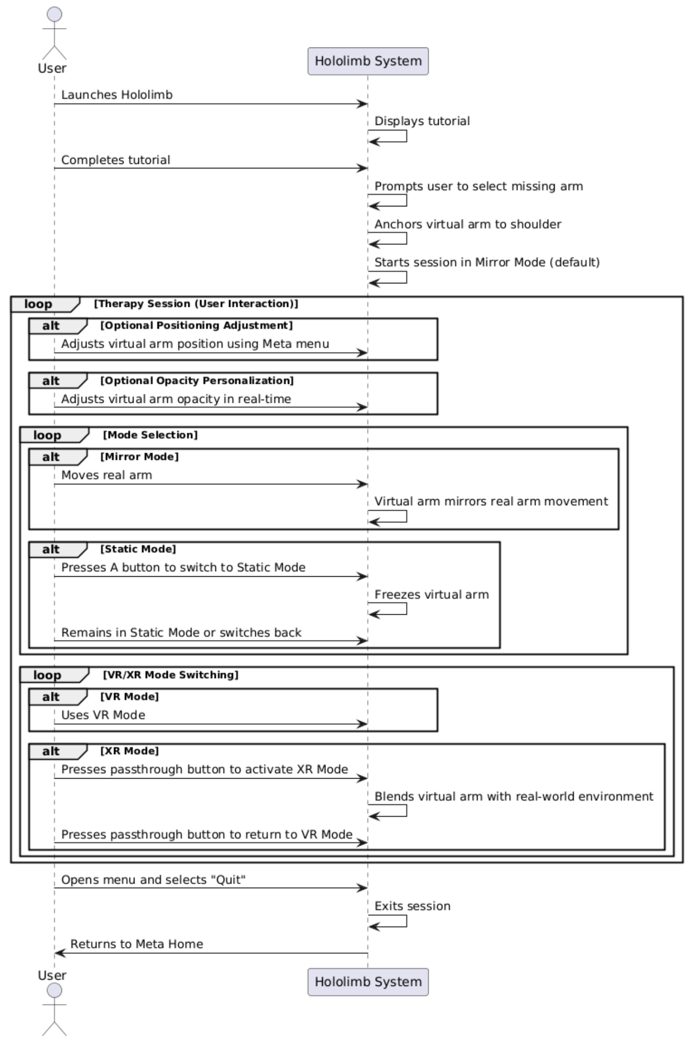


Fig. 2: User Workflow

B. User Workflow and Scenarios

1) Scenario 1: First-Time Use

Mattia selects his missing arm, completes the tutorial, and starts in Mirror Mode. He adjusts the virtual limb's opacity and easily interacts with virtual objects in the scene, tracking his progress with the session timer.

Fig. 3: Selection of missing arm

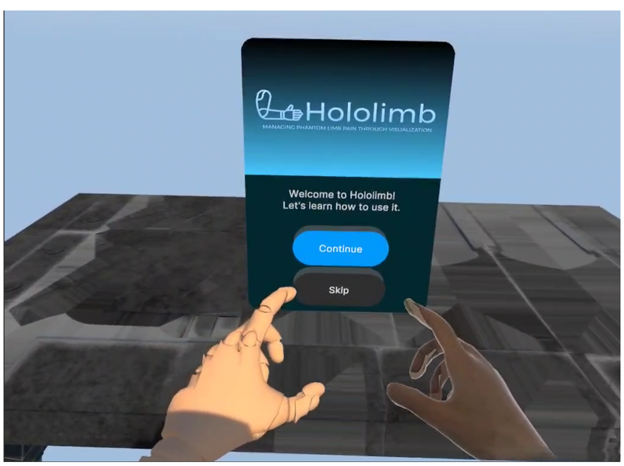


Fig. 4: Tutorial

2) Scenario 2: Switching from Mirror to Static Mode

Xin switches from Mirror Mode to Static Mode by pressing the B/Y button on the controllers. The virtual arm freezes to the position she selects, helping her focus on visualization.

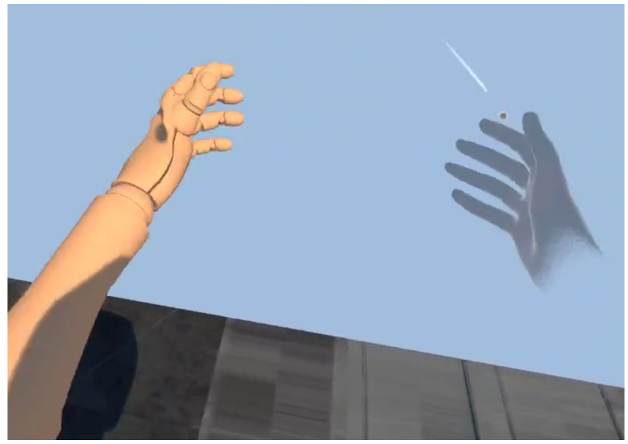


Fig. 5: Mirror Mode

Fig. 6: Static Mode

3) Scenario 3: Using Pass-trough Mode

Matteo activates Pass-trough Mode with the pass-through feature. He blends the virtual arm with his real-world surroundings, adjusts its position, and switches back to VR Mode for full immersion.

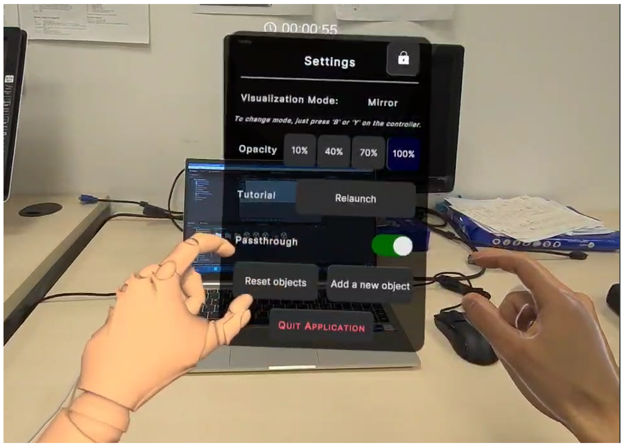


Fig. 7: Pass-through Mode

Fig. 8: VR Mode

VIII. Solution – Implementation

The **hardware architecture** of Hololimb is centered on the Meta Quest 3 headset, a standalone mixed reality device that provides immersive virtual and mixed reality experiences.

The **software architecture** leverages Unity 6 (Editor version 6000.0.27f1) as the main development platform, ensuring seamless integration with the Meta Quest SDK for building interactive experiences. The application is built for Android, development scripts are written in C#, using Visual Studio Code (Version: 1.97.1) for scripting, deployment, and debugging.

Collaborative development is managed through GitHub, enabling efficient tracking of changes and teamwork. The functional architecture follows a modular structure, separating key components such as tracking management cameras and objects, environment, MR interaction setup and user interaction management, ensuring scalability and maintainability throughout the development process.

The main implementation phases encountered were:

- **Unity trials**: to get more familiar with Unity platform, there were many initial trials of a broad range of template scenes, from VR and MR, to understand how elements in scenes works and how to develop working components.
- **Arm tracking**: after many attempts and research, the most accurate tool found was a Body Tracking Sample from Oculus Samples Github repo, from Meta. Unity-Movement is a package that uses OpenXR's tracking layer APIs to expose Meta Quest Pro's Body Tracking (BT), Eye Tracking (ET), and Face Tracking (FT) capabilities, with High Fidelity. The scene features a blue robot standing in front of a mirrored version, allowing you to see your body movements animate in real time. The sample was integrated and adapted to Hololimb's focus on one-arm amputees, by positioning the mannequin to match the user's posture and adjusting the body's alpha value, ensuring that only the relevant arm was visible. The avatar was then personalized for a more realistic representation.
- **Mirror Mode implementation**: the platform starts in default in Mirror Mode, when entering the scene, it automatically position the virtual arm based on the position of the real arm. It's possible to recenter the virtual arm, if the positioning was not accurate, using the Meta menu. In Mirror Mode, the virtual arm tracks the user's movements in high fidelity and represents the actions.
- **Static Mode implementation**: by pressing the buttons Y or B in the controllers, the user can easily switch from Mirror Mode to Static Mode (and vice versa), being able to choose the exact position they want to achieve in the Static Mode. The program keeps tracking the movements of the real arm, but stops representing the changes in the virtual arm, through a script that manages this interaction.
- **Opacity implementation**: the personalization of the arm is one of the core feature of the project, in particular from the Settings menu, the user can select at any time the % of the opacity of the virtual arm, handled by a script that modifies in runtime the alpha value.
- **UI implementation**: the user can interact with both the CoachingUI menu, which serves as a tutorial explaining how to use the program, and the Settings menu, which allows for the modification of various parameters such as arm opacity and Passthrough mode. In all cases, the interaction buttons have been designed with a large layout to enhance usability, providing visual feedback through color changes, sounds and animations. Additionally, proper spacing between interactive objects has been maintained to ensure smooth and precise interaction. By default, the Settings menu follows the user's head movements but can also be pinned to one side if preferred. Meanwhile, the CoachingUI can be launched from the Settings menu whenever clarification is needed, or skipped entirely if the user prefers.
- **Environment implementation**: Starting from the SampleScene of Unity's Mixed Reality (MR) Template, a table and a chair were added to enhance the user's spatial orientation within the virtual environment. Additionally, a ball, along with the option to generate multiple ones, was introduced to provide interactive and engaging elements for user entertainment.
- **Passthrough implementation**: the feature allows the user to switch from virtual environment to augumented reality, where only the virtual arm, timer and UI are visualized. This feature is managed by a script that fades the environment objects (e.g. table, chair, virtual ball, background environment), changing the alpha value of the components.

IX. Empirical Evaluation

The empirical evaluation of Hololimb is planned to take place after the submission deadline of the course project, in collaboration with specialized therapists and healthcare professionals. This evaluation will assess both the system's effectiveness in reducing phantom limb pain (PLP) and its usability in real-life settings. A detailed plan is included in the accompanying documentation deliverables.

The evaluation approach draws inspiration from established methodologies in prior studies on mirror therapy and mixed reality for PLP management. For instance, randomized clinical trials have demonstrated significant pain reduction through structured therapy sessions for upper-limb amputees[7]. Additionally, preventive applications of mirror therapy have shown positive effects in reducing PLP intensity and occurrence in lower-limb amputees[8].

The planned procedure will involve:

- **Preliminary Usability Testing**: Users will participate in initial sessions and complete standardized usability questionnaires, focusing on comfort, navigation, and overall user experience.
- **Longitudinal Assessment**: Multiple therapy sessions will be monitored over time, gathering quantitative and qual-

itative data on engagement, perceived comfort, and pain reduction.
- **Expert Feedback**: Clinicians and therapists will provide ongoing input to refine and optimize therapy modes, ensuring alignment with clinical practice standards.

The outcomes of this evaluation will help validate Hololimb as a non-pharmacological, immersive tool for PLP management, informing future development and clinical integration.

X. Value Proposition

Hololimb is an innovative mixed reality (MR) application designed to help individuals with single-arm amputation manage phantom limb pain (PLP) effectively through immersive, non-pharmacological therapy. By offering a customizable and intuitive experience, Hololimb addresses critical challenges faced in traditional PLP treatments, bringing advanced therapeutic solutions into the user's home. Running on the portable Meta Quest 3, the application combines real-time personalization, seamless integration of mixed reality, and an accessible interface to provide a powerful tool for pain management that can be used anywhere and anytime.

Hololimb distinguishes itself in the current landscape of virtual rehabilitation technologies. Existing solutions often rely on virtual reality (VR) alone, limiting users to fully virtual environments[7]. In contrast, Hololimb leverages mixed reality to offer a more contextually aware and comfortable experience by blending virtual and real-world elements. This MR approach enhances the user's spatial awareness and body perception, improving proprioceptive alignment and embodiment—key factors in effective PLP reduction[8]. Additionally, the ability to switch seamlessly between mirror and static modes, customize limb opacity, and toggle between VR and XR sessions in real time provides users with unparalleled control over their therapy experience.

Despite the presence of competitors in the field of PLP therapy, such as MR-based and immersive VR solutions, Hololimb offers distinct advantages[3]. Its home-based accessibility reduces the need for frequent clinical visits, encouraging more consistent use and fostering long-term therapeutic benefits. Unlike most existing systems, Hololimb is designed for continuous and independent use, empowering users to take an active role in their therapy. The application's unique combination of mixed reality, portability, and real-time customization, positions it as a promising and practical solution for improving the quality of life for individuals with phantom limb pain. Hololimb is not only a technical innovation but also a valuable tool for clinicians and patients seeking a personalized, effective, and user-friendly therapy experience.

XI. Discussion and Future Work

A. Challenges and Critical Aspects

The development of Hololimb presented several challenges, primarily due to the team's lack of experience with the technologies required. The project involved developing software in Unity, an unfamiliar engine, and optimizing it for the Meta Quest 3, a device with which the team had no prior experience.

Another major limitation was the inability to collaborate on the project simultaneously. It caused many inefficiencies in the workflow management, such as many hours of debugging process and conflicts in the progress of the work. This problem stemmed from the limited availability of headsets and the lack of a free, integrated version control system that would allow multiple developers to work efficiently within the same Unity scene.

A critical aspect of this project was ensuring that the application effectively addressed the needs of single arm amputees. A thorough understanding of traditional mirror therapy techniques and the specific challenges faced by users was essential to the development process. Without this foundation, the application risked failing to deliver the intended therapeutic benefits.

B. Potential Impact

The primary benefit of Hololimb is its accessibility and portability. By allowing users to perform mirror therapy from home, the application facilitates more frequent and convenient rehabilitation sessions. This increased accessibility has the potential to improve the effectiveness of the therapy while providing a viable alternative for individuals who may have difficulty attending in-person sessions.

C. Future Directions

Due to time constraints, certain features have been omitted from this version of Hololimb. These include:

- Personalization options, such as customizable arm colors.
- A more realistic virtual arm, as no suitable high quality 3D models were available that would fit seamlessly into the application.
- Complex exercises and gamification elements.

In the medium term, improvements to the virtual environment are planned, including the addition of interactive elements to enhance immersion. While the current version includes some interactive components, a more dynamic and engaging environment could further enrich the user experience.

In the long term, Hololimb is envisioned to incorporate guided therapy exercises. This feature would include step-by-step movement instructions and object interaction exercises to assist users in performing therapy more effectively. By providing a structured rehabilitation framework, this enhancement could significantly improve the therapeutic impact of the application.

XII. Business Perspectives

The Hololimb platform is at the forefront of innovation in the field of phantom limb pain management, utilising cutting-edge mixed reality technology to address this prevalent issue. The platform not only provides a solution to the pain management challenges but also opens doors to significant opportunities for external funding and strategic collaborations.

In the current landscape of digital health, where there is an increasing demand for non-pharmacological therapies, Hololimb is strategically positioned to secure grants from governmental bodies and research institutions that are at the forefront of supporting healthcare innovations. These grants can provide essential capital to fund further clinical trials, refine user-centred features, and accelerate product validation, thereby mitigating financial risk and expediting market adoption.

The formation of strategic partnerships with hospitals and private therapy centres is also critical. By integrating Hololimb into established clinical settings, hospitals can offer a modern, cost-effective solution to improve patient outcomes, while private centres can leverage the technology to enhance their service offerings and differentiate themselves in a competitive market. These collaborations facilitate pilot programmes, enable bulk licensing agreements, and generate real-world efficacy data that bolster clinical credibility.

Robust grant support and strong institutional partnerships form the backbone of a sustainable revenue model, ensuring that Hololimb not only meets an urgent medical need but also thrives as a commercially viable and scalable solution in the evolving landscape of digital healthcare.

XIII. Bibliography

1) Vona, F., Romano, D., Pieri, L., Maravita, A., & Garzotto, F. (2024). Hololimb: Mixed reality to alleviate phantom upper limb pain. In J. L. Pons, J. Tornero, & M. Akay (Eds.), *Converging clinical and engineering research on neurorehabilitation V: Biosystems & biorobotics* (Vol. 32). Springer, Cham. https://doi.org/10.1007/978-3-031-77584-0_51
2) Horner, K. (2022). Virtual therapy shows real promise for managing phantom limb pain. Retrieved from https://news.utdallas.edu/health-medicine/virtual-reality-phantom-limb-pain-2022/
3) Vona, F., Torelli, E., Beccaluva, E., & Garzotto, F. (2020). Exploring the potential of speech-based virtual assistants in mixed reality applications for people with cognitive disabilities. In *Proceedings of the 2020 International Conference on Advanced Visual Interfaces (AVI '20)* (Article 21, 1–9). Association for Computing Machinery. https://doi.org/10.1145/3399715.3399845
4) Prahm, C., Eckstein, K., Bressler, M., Wang, Z., Li, X., Suzuki, T., Daigeler, A., Kolbenschlag, J., & Kuzuoka, H. (2025). PhantomAR: Gamified mixed reality system for alleviating phantom limb pain in upper limb amputees—Design, implementation, and clinical usability evaluation. *Journal of NeuroEngineering and Rehabilitation, 22*(1), 21. https://doi.org/10.1186/s12984-025-01554-7
5) Hali, K., Manzo, M. A., Koucheki, R., Wunder, J. S., Jenkinson, R. J., Mayo, A. L., Ferguson, P. C., & Lex, J. R. (2024). Use of virtual reality for the management of phantom limb pain: A systematic review. *Disability and Rehabilitation, 46*(4), 629–636. https://doi.org/10.1080/09638288.2023.2172222
6) NY Post. (2024, December 21). Israel's war with Hamas leads to medical innovation. Retrieved from https://nypost.com/2024/12/21/world-news/israels-war-with-hamas-has-led-to-amazing-medical-innovation/
7) Finn, S. B., Perry, B. N., Clasing, J. E., Walters, L. S., Jarzombek, S. L., Curran, S., Rouhanian, M., Keszler, M. S., Hussey-Andersen, L. K., Weeks, S. R., Pasquina, P. F., & Tsao, J. W. (2017). A randomized, controlled trial of mirror therapy for upper extremity phantom limb pain in male amputees. *Frontiers in Neurology, 8*, 267. https://doi.org/10.3389/fneur.2017.00267
8) Purushothaman, S., Kundra, P., Senthilnathan, M., Sistla, S. C., & Kumar, S. (2023). Assessment of efficiency of mirror therapy in preventing phantom limb pain in patients undergoing below-knee amputation surgery—a randomized clinical trial. *Journal of Anesthesia, 37*(3), 387–393. https://doi.org/10.1007/s00540-023-03173-9