Embodying the Phantom: A Low-Cost, Inclusive VR Mirror Therapy Driven by 2-Point Tracking

Jacob Loat[1], Andrea Aternali[2], Joel Katz[2], Sander L. Hitzig[3] & Lora Appel[1,4]

[1]Faculty of Health, School of Health Policy and Management, York University, Toronto, ON, Canada | [2]Faculty of Health, Department of Psychology, York University, Toronto, ON, Canada | [3]St. John's Rehab Research Program, Sunnybrook Research Institute, Sunnybrook Health Sciences Centre, ON, Canada | [4]OpenLab, KITE, University Health Network, Toronto, Ontario, Canada

[1]jacobloat@gmail.com

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Abstract

This paper presents a two-point torso prediction system designed for use in virtual reality (VR) mirror therapy apps for individuals living with phantom limb pain (PLP) following an upper-limb amputation. PLP affects up to 80% of individuals with limb loss, significantly impacting their quality of life and contributing to depression and anxiety. While traditional mirror therapy can be effective in treating pain, modern VR apps offer greater flexibility and customization. However, many existing VR interventions rely on expensive external sensors and complex hardware setups, creating societal and economic barriers that limit widespread and at-home accessibility. To address this, we developed a system that estimates torso orientation using a two-point tracking system (the head and one hand), utilizing only consumer VR devices. Operating at the engine level without relying on external sensors or custom simultaneous localization and mapping (SLAM) datasets, this hardware-agnostic, six degrees of freedom solution facilitates accessible room-scale VR development. This paper outlines the technical design of the system and introduces the upcoming usability trial designed to test its viability as an accessible, inclusive, and low-cost intervention.

1. Introduction

Phantom limb pain (PLP) is the experience of pain in a part of a limb that has been amputated, frequently persisting for years and significantly reducing a person's quality of life (Polat et al., 2021). Mirror therapy is a common treatment approach, using a mirror to reflect the intact limb to generate the visual illusion that the missing limb is present, thereby alleviating pain (Campo-Prieto & Rodríguez-Fuentes, 2022). Recently, virtual reality (VR) technology has been applied to simulate this illusion, supporting advanced customization and an immersive environment.

Despite the potential of VR, current interventions often present significant accessibility, societal and financial barriers. A review of recent VR PLP treatments (Farsi et al., 2025) highlights that the vast majority rely heavily on external electromyography (EMG) or optical sensors to control the virtual limb. The complexity and high cost of these sensor-dependent interventions limit their versatility for regular, inclusive, or at-home use.

This document describes a lightweight mirror-therapy VR tool (MTVR) designed to overcome these technological and accessibility barriers. The MTVR system utilizes the built-in capabilities of modern consumer Android-based VR devices, supporting full room-scale tracking without external trackers or custom simultaneous localization and mapping (SLAM) pipelines. By relying exclusively on a novel 2-point torso prediction system, this app allows patients to navigate and interact with their virtual environment freely, maintaining accurate representation of the phantom limb.

The design of this intervention is heavily influenced by research on homuncular flexibility and virtual embodiment (de Vignemont, 2017). Visuo-motor synchronicity is a critical influence on body ownership and agency in VR (Mottelson et al., 2023). By maintaining strict temporal synchronicity (the avatar moves in sync with the user) and mechanical consistency (each motion has a consistent, proportional, and reliable outcome), the system promotes a greater level of virtual embodiment and proprioceptive drift between the affected limb and the mirrored virtual limb (Steptoe et al., 2013, Ichinose et al., 2017). Crucially, doing so within a lightweight hardware footprint democratizes access to this therapy, removing the financial and spatial barriers typical of clinical-grade motion capture systems. This system is currently being prepared for an initial usability trial, paving the way for a future clinical study.

2. System design for inclusion and accessibility

2.1. Avatar, Environment, and Customization

To promote inclusion and self-location, MTVR features a highly customizable humanoid torso and arms. The legs of a traditional humanoid avatar have intentionally been omitted due to the inability of common consumer VR devices like the Meta Quest 2, 3, 3s, or Pico 4 Ultra to track leg movements without the use of peripheral tracking devices. Acknowledging the diverse backgrounds of patients, the avatar's skin tone and limb size can be personalized via an in-app slider (*figure 1, A*) and automatic calibration process. The experience takes place in a familiar, well-lit living room environment featuring interactable objects to promote user presence and agency and includes a television (which is used as a grounded method of administering instructions to the user) (*Figure 1, B*).

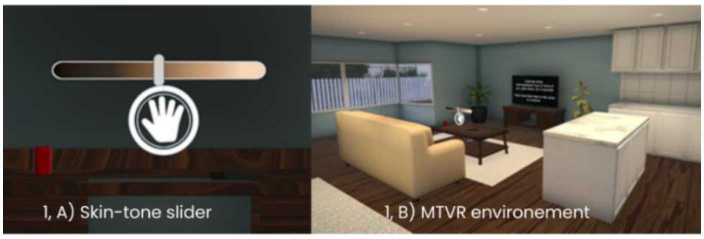

Figure 1: **A)** *The skin-tone customization slider and dominant hand selection tool for MTVR.* **B)** *MTVR environment, uses warm lighting and home-like features to feel familiar and comfortable to users.*

2.2. Mirroring and the Virtual Limb

Following calibration, the user is prompted to select their dominant hand by placing it within a glowing marker in the virtual space. The amputated limb in VR then mirrors the motion of the dominant limb using the forward direction of the avatar's torso as an axis of symmetry. Relying on the hand and finger tracking native to consumer VR devices, the mirrored limb reflects all 6 degrees of movement and individual finger bone rotation, allowing users to freely interact with objects using either limb.

2.3. Two-Point Torso Prediction

2.3.1. Tracked Variables

The two-point torso prediction system relies on six factors: the position of the users' head mounted display (HMD), the orientation of the HMD, the change in orientation of the HMD over time (0.5 seconds to reduce jitter), as well as the position of the users' dominant hand relative to the HMD measured in degrees (or the orbit of the hand), the orientation of the dominant hand, and the orbit of the hand over time (also 0.5 seconds). These six values are taken from three-dimensional space and projected onto the horizontal plane (the X and Z axes), as this is the plane of translation and rotation which influences the axis of symmetry of the mirrored limb.

2.3.2. Rotation and Translation Gates

As the position of the mirrored limb depends on the axis of symmetry bound to the users' torso, it cannot be allowed to move and adjust continuously as this would result in the unintended motion of the mirrored limb, breaking the rule of visuo-motor synchronicity. Instead, a minimum threshold is applied to both the translation and rotation of the HMD as these are found to be the strongest indicators of a users' intentional body movement. After some experimentation, those thresholds are set at 15° for rotation, and 5 cm for translation relative to an anchor point whose position and rotation are updated to the new position and orientation of the HMD each time these thresholds are passed. These values have shown to be small enough to offer a sensation of continuous movement for the user (maintaining visuo-motor synchronicity) while filtering out the noise of smaller movements and preventing the need to recalculate the transform of the torso every frame.

2.3.3. Torso Translation

The position of the torso is dependent only on the position of the HMD along the horizontal plane. In the event that the distance between the torso and the HMD on the horizontal plane (d) is greater than the translation threshold, the torso is set to follow the position of the HMD at a velocity of $3d$ m/s. This creates a smooth motion where the torso accelerates and smoothly slows to a stop based on d. Once the threshold is surpassed, the tracking of the HMD's position on the horizontal plane is continuous until d is 0.

2.3.4. Torso Rotation

Torso rotation prediction relies on a series of checks to determine whether there is intentional torso rotation or simply active head motion. First, a check is made as to whether the HMD is rotating and the dominant hand is orbiting meaningfully (at a rate above 15°/second for both) in the same direction. Should both tracking points be rotating in a relatively synchronous manner, it is a strong indication of intentional rotation. Second, as the rotation of the HMD passes the threshold, it is first determined whether the static hand position is within 30° of the forward direction of the HMD. If this arm threshold is surpassed, a calculation is made to determine whether the angular gap (difference in degrees between the orbit of the dominant hand in orientation of the HMD) is growing or shrinking. If the angular gap is greater than 30° and is currently shrinking at the time that the 15° base rotational threshold is passed, intentional torso rotation is detected. There is a third and final condition in which the HMD is not meaningfully rotating. This third condition is effectively the inverse of the second condition: first, the HMD must be greater than 15° from the current anchor orientation with a 30° angular gap to the orbit of the dominant hand. If these conditions are met, and the hand is shown to be orbiting towards the current forward direction of the HMD, it is taken to imply the intentional torso rotation towards the look direction of the headset. When intentional torso rotation is detected, the torso begins rotating smoothly in the forward direction of the HMD following the same principles outlined in section 3.3.3, wherein the speed of rotation is determined by the angle gap between the torso and HMD on the horizontal plane and torso rotation is continuous once triggered until that gap reaches 0°.

3. Integration into clinical care: Upcoming usability trial

To evaluate the therapeutic impact and accessibility of this system, MTVR is currently being deployed in a usability study at Sunnybrook Health Sciences Centre's St. John's Rehab program in Toronto, Canada. The study aims to recruit individuals with upper-limb amputations. Participants will utilize a Meta Quest 3 Head-Mounted Display integrated with the *caregiVR* platform (*caregiVR Inc., 2026*) to engage in a 30-minute session of guided standardized virtual arm exercises. To ensure the system is genuinely inclusive and user-friendly, the study will capture extensive usability and physiological metrics, including:

- **System Usability Scale (SUS):** To capture subjective perceptions of the system's ease of use and accessibility.
- **Prosthesis Embodiment Scale:** To evaluate feelings of ownership, agency, and the anatomical plausibility of the virtual mirrored arm.
- **Fast Motion Sickness Scale:** To continuously monitor for VR-induced sickness, ensuring the 2-point tracking system does not introduce disorienting latency or jitter.
- **Changes in PLP and Telescoping:** Evaluated pre- and post-session using a Numerical Rating Scale and an online app (https://demo.phantomlimbs.ca/).

Feedback from users with limb loss, as well as experts in rehabilitation, will directly inform iterative design improvements. The goal of this phase is to establish proof-of-concept for an accessible, low-cost VR program that can be widely distributed for at-home PLP treatment, paving the way for a clinical trial. Although pain relief outcomes have not yet been empirically established, the system shows promise for improving engagement and accessibility in rehabilitation through immersive, gamified experiences, potentially enhancing adherence for individuals with post-amputation pain.

4. Implications & applications

Future work will focus on continuing to refine the system outlined above to handle fringe conditions and a dynamic weighting system for the tracked variables. This app is currently being developed as part of an ongoing trial which will assess the usability and therapeutic impact of the intervention to influence future design decisions.

However, beyond clinical rehabilitation, this 2-point torso prediction algorithm presents significant opportunities for addressing physical diversity in general consumer VR. Traditional room-scale VR apps inherently design for three-point tracking (a headset and two hands), creating a systemic barrier that excludes individuals with upper-limb loss from fully participating in standard VR experiences. Because this novel system is computationally light and designed for the OpenXR standard, it can be easily implemented into most VR apps. By successfully providing a dynamic axis of symmetry using only the head and one hand, this hardware-agnostic tool offers new accessibility solutions for broader VR app design. Future applications of this algorithm could allow commercial developers to create inclusive virtual environments and games where users with unilateral mobility differences can stand, walk, and interact with the same agency and visuo-motor synchronicity as two-handed users.

5. Limitations

Prioritizing accessibility through two-point tracking on standalone consumer hardware (e.g., Meta Quest series, Pico 4 Ultra) sacrifices the exact spatial accuracy of clinical-grade motion capture and omits lower-body representation. Technically, the algorithm's static translation and rotation thresholds require refinement to incorporate dynamic parameter weighting. Finally, the system requires validation with the target population. Our ongoing trial will evaluate its real-world performance, assess its therapeutic impact on phantom limb pain, and ensure the tracking method avoids inducing VR-related motion sickness.

6. Conclusion

While clinical-grade VR therapies offer high accuracy, their reliance on complex hardware creates systemic barriers to access for the average patient. MTVR demonstrates that computationally light, hardware-agnostic solutions, like the 2-point torso prediction system, can offer comparable visuo-motor synchronicity and mechanical consistency on cheap, consumer-grade devices. By prioritizing inclusivity through customizable avatars and removing the need for external sensors, this system presents a scalable model for making advanced VR rehabilitation accessible to broader populations living with disabilities. We would like to acknowledge that the project was generously funded by The War Amps, an organization serving all Canadian amputees, including children.

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