Experiences of Treating Phantom Limb Pain using Immersive Virtual Reality

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ABSTRACT

Phantom limb pain (PLP) is a phenomenon that affects millions of amputees worldwide. Its causes are poorly understood, and traditional forms of pain relief are largely ineffective. For over a decade virtual reality (VR) has shown tantalising possibilities of treating or managing this debilitating condition. Until recently however, the cost, complexity and fragility of VR hardware made exploring this unorthodox approach at any meaningful scale challenging; patients have had to travel to the location of specialist equipment to participate in studies, and missed appointments, dropouts or broken hardware have hampered data-gathering. Improvements in 'consumer grade' VR headsets now makes larger trials of this visual approach to pain management viable. We describe a trial of a VR system for PLP reduction utilising lightweight, standalone and low-cost VR hardware suitable for independent home use.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; • **Applied computing → Life and medical sciences**; • **General and reference → Empirical studies**; **Experimentation**.

KEYWORDS

phantom limb pain, virtual reality, assistive technology, treatment

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1 BACKGROUND

A significant majority of limb amputees, somewhere between 50% and 80%, experience not only the presence of a 'phantom limb' in the place where their real limb used to be, but pain in that nonexistant limb [Richardson and Kulkarni 2017]. PLP manifests in a variety of different forms including uncomfortable clenching or contortion, burning, stabbing, itching, pins and needles and 'electric shocks'. Severe PLP has been shown to cause societal withdrawal for extended periods [Sherman et al. 1984] and depression [Murray 2005]. Amputees with PLP are also less likely to use a prosthetic limb [Raichle et al. 2008]. A recent comprehensive review of treatments for PLP found that there is no reliable first line treatment available [Richardson and Kulkarni 2017].

1.1 Visual Treatments

In the mid 1990s psychologist V.S. Ramachandran devised an experiment using a 'mirror box' that presented amputees with a reflection of their anatomical limb in the visual space occupied by their phantom limb [Ramachandran and Rogers-Ramachandran 1996]. It was reported that the mirror box induced vivid sensations of movements originating from patients' phantom limbs, and in some cases relieved their PLP. Since then, others have experimented with alternative visual therapies such as [Giraux and Sirigu 2003]'s use of video, [Soler et al. 2010]'s transcranial direct current stimulation and [Desmond et al. 2006]'s use of a 'data glove' to track anotomical hand movement and render a synthetic graphical representation of the phantom limb on a flat screen.

In their review [Richardson and Kulkarni 2017] state that "various mechanisms have been proposed for the effects of mirror therapy, including reversal of cortical reorganizations, relinking the visual and motor systems, activating mirror neurons in the contralateral brain, modulation of pain pathways, the reawakening of proprioceptive memories and the reversal of a potential neglect syndrome. [Casale et al. 2009; Hanling et al. 2010; Rothgangel et al. 2011; Weeks et al. 2010]" but that future "research needs to be refined to assist elucidation between these potential mechanisms."

2 OUR EARLIER WORK

Since 2005 we have been exploring whether VR could be used to alleviate PLP by tracking the movement of the anatomical limb and rendering a 3D computer-generated image of a virtual limb in place of the missing limb. Our first system [Murray et al. 2007] was a fully immersive environment, presented to the user via a tracked, head-mounted display. This system used our own research VR platforms (MAVERIK [Hubbold et al. 2001] and DEVA [Marsh et al. 2006]) and electromagnetic tracking with wired sensors attached the patient's head and anatomical limb. While providing reasonably accurate tracking, the system used cumbersome wiring and required complex manual calibration to compensate for distortion to the tracking space by metal objects. This severely limited the ability to move the equipment to new locations and thus required patients to visit our lab to take part in experiments. Equipping the patient with the sensors required specialist expertise, and patients needed careful supervision to avoid becoming entangled in the numerous cables.

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The bespoke headset, tracking equipment and graphics engine cost well in excess of $200,000.

Despite these restrictions, in a small-scale trial, five participants whose PLP had resisted all other forms of treatment used our system on a weekly basis: four reported a noticeable reduction in their pain levels; two found they gained some control over their phantom limb's position (being able to manoeuvre it into a more comfortable state); and one found that they were even able to exercise some control over the stump of their amputated limb which had previously been paralysed for over twelve years. Though participants requested access to the system post-trial, its cost and fragility made this impossible.

Building on this work we developed a new system [Pettifer et al. 2012] that exploited advances in consumer hardware. Instead of being encumbered with wired sensors, the patient wore an ordinary baseball cap instrumented with a lightweight wireless sensor utilising gyroscopes and accelerometers for tracking head movement. Under this the patient wore a consumer-targeted Vuzix VR920 headset to view the virtual environment immersively. The patient's anatomically intact limb was tracked using an Xbox 360 Kinect motion tracking device and the tracked movements were used to control a 3D representation of the phantom limb as before. For most of the participants in this trial it appeared that pain had reduced over time in relation to the number of sessions undertaken. Generally PLP would return relatively quickly after each session but often at a reduced level than before. Again there were requests for more sessions.

3 OUR CURRENT TRIAL

In 2018 the Oculus Go was released which made available an entirely self-contained 'untethered' 3D VR setup within a lightweight, high resolution headset for around $200. The device also included a hand held pointing device that communicates with the headset wirelessly. There are some limitations to this arrangement: the headset and pointing device are not tracked in space but instead just return an orientation. While not a critical issue for the headset (when the user is stationary), it provides a number of challenges when using the pointing device to track the position of an anatomical limb.

The Oculus Go's software partially addresses this by using a heuristic to provide an estimated pointer position based on orientation by assuming various factors such as the elbow being held by the side of the body, the wrist being held rigid, and so on. This estimated position is not intended for interactive hands-on tasks but is sufficient for pointing and interacting at a distance. To be able to use a device that is unable to detect movement without rotation for the PLP mirroring application therefore requires some creativity. It was observed in our previous trials that inaccuracies in tracking precision do not appear as critical as in many VR applications since there is no proprioceptive sensory feedback contradicting the rendered phantom limb. Instead, for the mirroring tasks it seems the user's sense of agency is more significant, which the low-latency updates and high frame rate of the Oculus Go assists with, especially in comparison with older generations of hardware.

We symmetrically mirror the estimated location of the controller provided by the Oculus Go's heuristic and extend it slightly forward relative to the body, using an inverse kinematics model to plausibly position and articulate a virtual arm. We previously observed that moving the mirrored hand in front of the face appears to enhance the feeling of direct control and so we exploit this in our activity: a simple sorting game involving picking up tokens, turning them over and looking at the underside to identify a symbol, and then dropping them on an appropriate target. (The task is contrived to not require reaching.) As the user becomes more skilled in manipulating the virtual arm they are able to achieve higher scores.

The low-cost and ease of setup of this virtual environment has enabled us to provide devices to patients to use in their own homes by working with the Specialised Ability Centre (Manchester) to distribute the hardware. No longer requiring patients to travel to a single location has significantly increased the scale of the trial and the final analysis will be based on a combination of per-session instrumentation and feedback questionnaires as well as 'exit interviews'.

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