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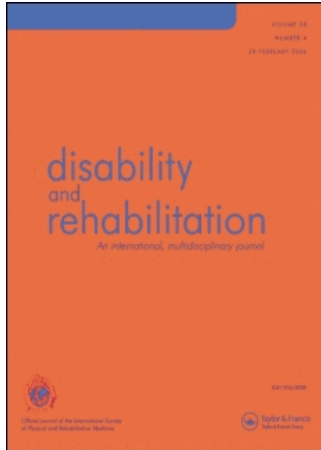
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CASE STUDIES

The treatment of phantom limb pain using immersive virtual reality: Three case studies

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Abstract

Purpose. This paper describes the design and implementation of a case study based investigation using immersive virtual reality as a treatment for phantom limb pain.

Method. Three participants who experienced phantom limb pain (two with an upper-limb amputation, and one with a lower-limb amputation) took part in between 2 and 5 immersive virtual reality (IVR) sessions over a 3-week period. The movements of participants' anatomical limbs were transposed into the movements of a virtual limb, presented in the phenomenal space of their phantom limb.

Results. Preliminary qualitative findings are reported here to assess proof of principle for this IVR equipment. All participants reported the transfer of sensations into the muscles and joints of the phantom limb, and all participants reported a decrease in phantom pain during at least one of the sessions.

Conclusion. The authors suggest the need for further research using control trials.

Keywords: *Phantom limb pain, amputee, immersive virtual reality*

Introduction

It is a common experience following amputation for the person to experience the amputated limb as still intact [1]. This experience of a 'phantom' limb is often painful and can have far-reaching implications for amputees' lives. For example, increased phantom limb pain (PLP) is negatively correlated adjustment to amputation [2]. Research on the relationship between PLP and prosthetic usage provides a mixed picture. While research with British [3] and American veterans [4] has found prosthetic usage unaffected by phantom pain experience, a later study of a geriatric population found amputees with PLP were less likely to use a prosthetic limb [5]. Non-prosthesis use often results in the restriction of normal activities and is associated with higher levels of depression [6,7].

The mirror box is a promising development in the treatment of PLP [8]. This device allows amputees to

view a reflection of their anatomical upper limb in the visual space occupied by their phantom limb. The box has been found to induce vivid sensations of movement originating from the muscles and joints of patients' phantom arms and to reduce phantom limb and/or gain control over a paralyzed phantom limb [8–10] although there is variation in its effectiveness [11]. The mirror box effect may work in some patients by providing a means to link the visual and motor systems to help them recreate a coherent body image and update internal models of motor control [12,13]. If this is the case, then other visual therapies which work in a similar way may also be of benefit in treating PLP.

A limitation of the mirror box is that it operates within a narrow spatial dimension, which requires the patient to remain in a fairly fixed position with the head oriented towards the mirror and the body held in mid-sagittal plane with the mirror [14]. It also requires that the user attempts to ignore the

intact limb providing the reflection in order to focus on the image of the phantom limb. These issues make the mirror box a fairly restrictive and tentative illusion. One potential solution to these problems is immersive virtual reality (IVR), which can be used in a similar way to the mirror box whilst allowing far more scope for changes in experimental paradigm [14–16].

The present study uses an IVR system which transposes movements of amputees' anatomical limbs into movements of a virtual limb in the phenomenal space occupied by their phantom limb. This gives a similar illusion to the mirror box without the confines imposed by reflection-based work: in the virtual environment (VE) only the virtual phantom limb moves in response to motion of the anatomical limb so the illusion is robust, independent of the orientation or focus of the patient. In the remainder of this paper we outline the preliminary observations of the technology in use and feedback from three participants regarding changes in the phenomenology of their phantom limb. The objectives of the present work are to show proof of principle for the development of this kind of technology for the treatment of phantom limb pain.

Methods

Description of the virtual environment and virtual tasks

A V6 (Virtual Research Systems Inc., CA, USA) virtual reality head-mounted display (HMD) was used to present the computer-generated environment to participants and to facilitate immersion. In order to monitor and represent participants' limb movements a 5DT-14 data glove (5th Dimension Technologies, California, USA) and sensors were used for upper-limb amputees, while sensors were used for lower-limb amputees. Sensors were attached to the elbow and wrist joints or the knee and ankle joints. A Fastrak (Polhemus, Vermont, USA) monitored head movements and arm and leg movements. A minimal virtual environment (VE) represented the participant within a room, from an embodied point-of-view (see Figure 1).

In the present study participants used the IVR system for a period of 30 min, completing four tasks in repetitions. A full virtual body representation was provided for participants. A virtual representation of the phantom limb was made available by transposing the movement of the participant's opposite anatomical limb (e.g., their physical left arm) into the phenomenal space of their phantom limb (e.g., their virtual right arm). The tasks were: placing the virtual representation of the phantom limb onto colored tiles which light up in sequence; batting or kicking a virtual ball; tracking the motion of a moving virtual

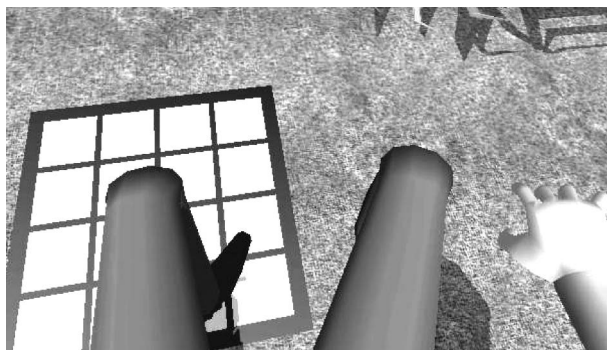


Figure 1. One possible view participants may see when taking part in the experiment.

stimulus; and directing a virtual stimulus towards a target.

Participants

Participants were recruited through collaboration with a sub-regional Disablement Services Centre (DSC) in Manchester, England, and contacted on the basis of a number of criteria: having phantom limb pain; being adults without any major visual or cognitive deficits; and being a minimum 12 months post-amputation. The DSC sent out letters inviting research participation from patients for whom phantom pain had been identified as particular problem for them. Ethical approval for the study was granted by the local NHS COREC. The intensity of the intervention was determined by how often the patients could come for testing since, due to the nature of the equipment, sessions were carried out only at the University of Manchester.

Data collection

In order to gain a full picture of patients' PLP over the course of the study a number of self-report measures were used. Participants completed The McGill Pain Questionnaire (MPQ) [17]. The Short-form MPQ was administered at each testing session and pain diaries were completed in between each visit to assess interim levels of pain and to place the data in a more contextualised analysis. The purpose of the present paper is to present preliminary qualitative findings on a small sample to assess proof of principle for this IVR equipment, and no statistical analyses are reported here.

In the present paper we emphasize the importance of achieving a qualitative understanding of patients' phantom limb experience, and of their experience of using the IVR system, in their own words. The broad approach here is a phenomenological one; with the aim of understanding patients' own embodied experiences [18]. This is achieved

through semi-structured interviews carried out at each session both before and after use of the virtual reality system (lasting about 15 min each). These interviews provide the core focal point for analysis in this paper, since the authors feel they highlight important aspects of the system which are not encapsulated by quantitative assessment. These interview data are supplemented in the findings reported here, where informative, by pain diaries completed by participants in the interim period between each trial.

Case Study One: PK

A 63-year-old male left upper-limb amputee (above elbow). He had been an amputee for 12 years and 10 months, as the result of a swimming accident, and he did not use a prosthetic limb. PK suffered with severe PLP 'twenty-four seven – I'm never ever out of pain'. His phantom limb was shorter than his anatomical limb in a fixed position with the elbow bent at roughly right angles and the fingers in a cupped position. PK suffered with intense flashes of pain attacks in his phantom which could be very severe; he would often find himself immobilized by the pain. Despite the severity of PK's condition, he insisted on keeping himself busy and, as such, PK came for five testing sessions over the 3-week period, with a maximum 5 days in between sessions.

Case Study Two: WW

A 60-year-old male right lower-limb amputee (below knee). He had been an amputee for 12 years and 3 months as the result of a work-related accident, and he used a prosthetic limb. His phantom pain was less severe than PK, but he was still constantly aware of it: 'it's always there, like a nagging sensation'. The most distressing part of the phantom pain was the intense flashes of pain he experienced in his phantom foot which felt 'as if someone's ramming a sharp knife into the sole'. These attacks varied in frequency but the severity often interfered with his sleep and his everyday life. WW attended three sessions over the course of 3 weeks. The second and third sessions were both carried out 2 days apart in the same week, 2 weeks after the first session.

Case Study Three: DT

DT was a 65-year-old female left upper-limb amputee (below elbow). She had been an amputee for 1 year, as the result of a fall, and used a prosthetic limb. The phantom pain DT experienced was mainly localized to her phantom hand; a constant pins and needles sensation which varied in severity. DT's phantom hand was immobile with the fingers in a

clenched position, and accompanied by a pain she described as in '... the palm because I think it's like the nails of my fingers digging into my palm'. The pain interfered with her sleep on a regular basis. DT attended two sessions in a 3-week period with 2 weeks in between trials.

Indicative results

During each period of IVR use PK reported a decrease in his phantom limb pain. However, he also reported that this would be accompanied by the pain coming back 'with a bit of a vengeance' within a few hours after completion of each testing session. He attributed this to the fact that the pain would be returning after a lull during the sessions which would make the comparative return of the pain seem more severe. During the third session, PK reported vivid sensations of movement in his phantom arm: 'During it, I actually felt as if it was my left arm that was doing the work and chasing the ball. My actual phantom arm rather than my right... and that was more like reality than virtual reality.' PK commented that 'If I could harness that (the movement in his phantom limb) maybe I could open my fingers and ease the cramping pain a little'. Interestingly, in the following week to this session, a pain diary measure showed an average rating of 6.8 (out of 10) over the following 3 days, which then increased to an average of 8.3 for the subsequent 3 days. Obviously, this improvement in PLP ratings is short-lived but given the relatively low frequency of testing sessions, this could be considered a promising result. Self-reported evidence from PK suggested a positive change in his sleep patterns after the first session of IVR which has continued throughout the 3-week period: 'I've actually been sleeping a little better over the last few days... I'm getting about 5–6 h of uninterrupted sleep as opposed to 2–3 h and I'm doing nothing else different in my life except coming here.'

WW's results indicate a more variable pattern than PK's. There were no consistent alterations in pain ratings during use of the IVR system for the first two sessions. It is worth mentioning however, that WW did suffer with simulator sickness which meant the first session had to be terminated early. At one point during the second session, his anatomical left leg collided with his stationary prosthetic leg. WW commented that this was an 'uneasy sensation... it looks on the thing (HMD) like it's not in the way but then you bang into it and it feels queer.' When asked to try and elaborate on this, WW mentioned his phantom pain had increased slightly during this period. This is consistent with research which sites sensory-motor incongruence as a possible source for painful sensations [19]. WW chose to remove his

prosthesis for the third session to avoid this situation and consequently, he engaged more in the third session and reported no feelings of nausea for the first time. Interestingly, his pain rating at the end of the session compared to the beginning showed a decrease of four points (from a 7 initially to a 3 on leaving). WW also commented that 'It feels as though I'm doing something with my right (phantom) leg... It's a queer sensation but it feels good that I'm achieving something with my right leg. That I'm doing the task with my right leg'.

DT has attended the fewest number of sessions out of all three participants but interestingly reported a drastic change in her phantom hand after just one session: '... it's funny... one of my fingers is coming out, sort of pointing out now'. When we consider that one of the vivid sensations experienced by DT was that of nails digging into her palm, if this phenomenological change continues, it has the potential to alleviate this pain. DT has also reported vivid sensations of her phantom hand carrying out the tasks and she unconsciously moves the stump of her left arm around whilst carrying out the tasks: 'My left arm felt if it was moving... which was quite an odd sensation'. She also reported she is tired after sessions and that her left (phantom) arm ached significantly more than her right (the labour intensive arm) after the IVR sessions.

Discussion

All participants made some reference to a transferral of sensations into the muscles and joints of the phantom limb. PK and DT support this more vividly than WW and this may indicate the system could potentially be of greater benefit to upper- than lower-limb amputees. This is a tentative claim, however it could be supported by the larger degree of movement afforded by the virtual hand over the virtual foot (i.e., all the fingers move separately whilst for the foot there are no toes – it is represented as if it is wearing a shoe).

DT reports the most drastic change in her phantom limb after just one session. This may indicate that this kind of treatment is more effective for more recent amputees. A speculative hypothesis could explain this in terms of a greater plasticity in the brain for recent amputees as it has had less time to re-define the internal model of the body.

All three participants report a decrease in phantom pain during at least one of the sessions. However, another common factor is that they all comment on how they are focused on the tasks which may suggest they are simply distracted from the pain. This evidence stresses the importance of further research using control trials to assess the efficacy of this system over and above any pain relief caused purely

by the novelty of the tasks and the concentration required. Such work would also be able to confirm or discount the possibility that the positive results found in the present study are the product of a placebo effect.

Most importantly, the results appear to highlight the necessity for a more intense intervention since the interim pain diaries suggest there is little effect of the sessions beyond a day or two. This is understandable, especially for PK and WW who have suffered with this pain for over 12 years: it would be unreasonable to expect any treatment to have a dramatic effect in such a short space of time.

Finally, all three patients involved in the present study had lost a limb due to an accident, rather than through disease. This is a factor which needs to be addressed in future work: in order to identify the characteristics of patients who might make receive the most benefit from this technology it is necessary to include of patients who have lost limbs through a variety of circumstances in further evaluative research.

The virtual reality system itself could also be improved before more detailed work is carried out. For example, as discussed earlier, some differences between calibrations between the virtual environment and the physical environment resulted in contact between WW's anatomical and prosthetic limb, when the image supplied by the virtual environment indicated they were not that close together. Although this was 'solved' by the participant's removal of their prosthetic limb, future software development work should focus on reducing such 'noise' as possible.

In conclusion, the authors contend that these preliminary qualitative findings show sufficient proof of principle to justify further testing with the IVR system using control trials, more intense intervention, a wider variety of circumstances leading to limb loss, and a greater number of participants.

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