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Immersive Virtual Reality as a Rehabilitative Technology for Phantom Limb Experience

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Abstract

This paper describes the theory underpinning, as well as the design and implementation of a study to investigate the use of immersive virtual reality as a treatment for amputees’ phantom limb pain. The authors’ work builds upon prior research which has used simple devices such as the mirror box (where the amputee sees a mirror image of their remaining anatomical limb in the phenomenal space of their amputated limb) to induce vivid sensations of movement originating from the muscles and joints of their phantom limb. The present project transposes movements of amputees’ anatomical limbs into movements of a virtual limb which is presented in the phenomenal space of their phantom limb. It is anticipated that the protocol described here will help reduce phantom limb pain.

Key words

Amputee, Immersive Virtual Reality, Phantom Limb Pain

Introduction

According to the National Amputee Statistical Database, each year there are around 5,500 new referrals to prosthetic service centres in the United Kingdom, with a total number of prosthesis users in the UK in the region of 62,000 (NASDAB, 2002). A salient feature of amputation is the experience of phantom limbs. Many people who undergo an amputation experience a phantom limb, which is the experience of the amputated limb as still intact, often resembling the pre-amputated limb (see Murray 2004). Usually, phantom sensations and phantom pain occur soon following amputation and as many as 70% of phantoms remain painful even 25 years after the loss of a limb (Ramachandran and Hirstein, 1998).

Jensen, Krebs, Nielsen, and Rasmussen (1983) reported the frequency of phantom limb pain and phantom sensation following amputation as between 65 per cent and 85 per cent. The relationship between phantom limb pain (PLP), prosthesis use and psychological well-being is an intimate one. For instance, significant correlations have been observed between adjustment to amputation and pain (Katz, 1992), with adjustment to amputation less likely as levels of pain increase. Amputees with PLP are less likely to use a prosthetic limb (Dolezal, Vernick, Khan, Lutz and Tindall, 1998). Non-prosthesis use often results in the restriction of normal activities (such as self-care, visiting friends and carrying out domestic work), and is associated with higher levels of depression (Williamson, Schulz, Bridges, and Behan, 1994; Murray, 2005). The problem of PLP then is large and pervasive in many amputees’ lives.

While a range of pharmaceutical, surgical and psychological interventions are used to treat PLP, the success of these approaches is often limited and short-term. However, one promising development in
this regard was reported by Ramachandran and Rogers-Ramachandran (1996). They created a mirror box made by placing a vertical mirror inside a cardboard box with the top removed, in which the amputee places their remaining anatomical limb inside and views a reflection in the visual space occupied by their phantom limb. They report anecdotal evidence that the box was able to induce vivid sensations of movement originating from the muscles and joints of patients’ phantom limbs. For some patients their phantom limb pain was relieved and others were able to gain control over paralyzed phantoms (Ramachandran and Rogers-Ramachandran, 1996). The mirror box has also recently been used with similar success with lower-limb amputees, where viewing a reflection of an anatomical limb in the phenomenal space of a phantom limb resulted in amputees reporting a significantly greater number of movements of their phantom limb than with attempted movement alone (Brodie, Whyte and Waller, 2003).

There are, however, certain limitations imposed by the use of a mirror box. Focusing attention on one limb is the goal of the mirror box: the patient is asked to orient towards the mirror and focus on the reflection of their intact arm to allow the brain to receive visual feedback of limb movement in response to a motor command. However, it only takes a look at the intact arm providing the reflection to break this visual illusion: essentially, patients are given very few degrees of freedom with regard to movement of their body as a whole. They must remain in one place, next to the mirror, with their torso in a fixed position so as not to alter the reflection of their limb. Similarly, head movement is constrained by the need to focus towards the mirror, which makes the mirror box a fairly restrictive and tentative illusion.

The work on the mirror box is, however, greatly promising and suggests that other visual therapies that work in similar ways, whilst overcoming these drawbacks, may also relieve phantom limb pain as well as increasing volitional movement in phantom limbs. With a more robust visual therapy, the therapeutic benefits that Ramachandran observed could be improved upon. The benefits offered by virtual reality as a visual therapy for PLP have been noted by researchers such as Kuttuva, Burdea, Flint, and Craelius, (2005) who suggest that virtual reality visualisation of a phantom limb may help to relieve PLP. Similarly, an interesting extension of Ramachandran’s work was recently developed by O’Neill, DePaor, MacLachlan, and McDarby (2003). They created a non-immersive virtual mirror box whereby the mirror image of the arm was replaced by a virtual arm in augmented reality. This work was piloted on a group of able-bodied participants who deemed the virtual arm almost as satisfactory as the mirror image arm at generating the feeling of movement in response to a controlling arm.

The work of these authors gives promising indications for the development of a more sophisticated form of the mirror box where some of the drawbacks described above may be overcome. The use of immersive virtual reality (IVR) technology offers the opportunity to provide a visual representation of the amputees’ whole body, including their phantom limb. This is permitted by the combination of an immersive head-mounted display, instrumented peripheral devices and computer graphics (Murray and Sixsmith, 1999; Murray, 2000). The research project to be described here by the authors is intended to build upon the insights of Ramachandran’s mirror box by producing a similar phenomenon using IVR and to assess whether a more advanced medium such as this could be a promising new avenue for pain treatment in this field.

Our project uses IVR to fully transpose the movements made by an amputee’s remaining anatomical limb 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) 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. Considering the relatively nascent approach of using IVR to treat phantom limb pain, and the nature of pain treatment in general, a control group is necessary to assess the outcome of treatment over and above any placebo effects. Therefore, this transposition of movement does not take place for a control group: movements of the anatomical limb only generate movements in the virtual, corresponding limb.

It is envisaged that such virtual environments (VEs) will prove to be a therapeutic treatment for phantom limb pain, as well as aiding successful prosthesis use. In this way, the enhanced capabilities of IVR over the mirror box are anticipated to produce a similar reduction in phantom limb pain. In the following we outline the design of an experimental procedure to investigate this assumption.

**Aims and purpose of the investigation**

The objectives of the work are: to produce virtual faesimiles of amputees phantom limbs; to obtain appropriate measurements that enable conclusions to be reached about the efficacy of IVR in the treatment of phantom pain; and to obtain appropriate measurements that enable conclusions to be reached about the efficacy of IVR in decreasing body image dissatisfaction and encouraging and enabling successful prosthesis use.

**Study Design**

The study is a longitudinal one and has a between subjects design. There is one independent variable, as described above; namely whether participants use a pre-programmed virtual limb representation controlled by movements made by their opposite anatomical limb (group A), or a pre-programmed virtual representation of their intact limb controlled by movements made by the corresponding anatomical limb (group B). There are three main dependent variables, which are measures obtained on the McGill Pain Questionnaire (MPQ), the Trinity Amputee Prosthesis Experience Scale (TAPES), and the Amputee Body Image Scale (ABIS).

Participants also complete pain diaries and undergo brief semi-structured interviews throughout the course of the study, which allow a more qualitative analysis of the effect of treatment and a contextualised understanding of the quantitative scales implemented i.e. the MPQ, TAPES and ABIS, which measure changes in subjective phantom limb pain, adjustment to a prosthesis and body image satisfaction respectively.

It is hypothesised that group A will experience significant short-term and long term reductions in the frequency and severity of phantom limb pain (PLP), while group B will not, and that group A will experience significant positive changes in psychosocial issues, activity restriction, and satisfaction with a prosthesis, while group B will not.

**Participants**

Participants have been obtained from the regional Disablement Services Centre which has access to amputees across the Northwest of England. Participants are being contacted on a number of criteria: unilateral amputees having phantom limb pain, being suitable for being provided with a prosthesis limb; and being adults. Participants are a minimum 12 months post-amputation with no upper limit, and vary along such dimensions as age, sex, whether their missing limb is upper or lower limb, and the type of prosthesis used. No participants with serious visual or cognitive impairments are recruited.

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A target sample of 32 amputees (16 in each condition) with phantom limb pain are taking part in the study. Participants are recruited in pairs and randomly assigned to the experimental and control groups. Group A have a standardised visual representation of their phantom limb (e.g., all right lower-limb amputees experience the same visual representation of their phantom limb). As described above, the motor movements of their intact anatomical limb are transposed into movements on their virtual phantom limb. Group B have a standardised visual representation of their phantom limb, but the motor movements of their intact anatomical limb are transposed into movements on the corresponding virtual limb (e.g., movements of an intact anatomical right arm are transposed on to movements of their virtual right arm - not their virtual phantom limb).

Materials

A V6 virtual reality head-mounted display (HMD) is used to present the computer-generated environments to participants and to facilitate immersion. In order to monitor and represent participants’ arm/hand/fingers and leg/foot movements a 5DT-14 data glove and sensors are used for upper-limb amputees, while sensors are used for lower-limb amputees. Sensors are attached to the shoulder, elbow and wrist joints or the thigh, knee and ankle joints for upper- and lower-limb amputees respectively. A Polhemus Fastrak monitors head movements and arm/leg movements.

A minimal virtual environment (VE) represents the participant within a room, from an embodied point-of-view (see Figure 1). Participants are provided with a number of tasks in this virtual environment in order to provide opportunities for hand-eye and foot-eye coordination of their virtual limb. These tasks are similar to the physical therapy and functional rehabilitation exercises previously used in desk-top implementations of VEs (see Popescu, Burdea, Bouzit and Hentz, 2000) and are described below.

Calibration becomes an important issue establishing a link between the virtual and the real world. For example, when using extra-corporeal objects like the dance mat (which is part of one of the actual tasks) the area of the dance mat in the virtual world (the one displayed on the HMD) should match exactly the area of the dance mat in the real world. Calibration is achieved in the software, using some known correspondences between the real and the virtual world. In a calibration step, the sensors are placed consecutively at a series of known locations. The program then records their locations as given by the Polhemus Fastrak, and computes the correspondence function. Other locations are interpolated, which means that the matching between real and virtual world could not be equally accurate everywhere.

Assuming that the positions of the sensors are now accurate and stable, these sensors are used to control a model of the human body. Placing constraints on the joint angles allows impossible poses to be avoided. However, human kinematics is very complex, and a complete description of morphological constraints would require a much more complex model than used at present. Avoiding inter-penetration of body parts is a problem that is avoided by testing collisions between the sensors’ positions and the mesh of the body.

Transferring a movement from a limb to another is possible due to the joint angles parameterization. For example, once the joint angles are recovered from the right arm through inverse kinematics, applying these joint angles to the left arm results in mirroring the movement. This method of transferral as well as other implemented software generates responsive, fluent, real-time motion, allowing virtual limbs to
move in synchrony with anatomical limbs, whether it be the opposite or corresponding virtual limb (Group A and B conditions respectively)

The appearance of the body is modelled by a polygonal mesh, attached onto the underlying kinematic model. At each frame, the coordinates of the polygons constituting the mesh are then updated to reflect the movements of the kinematic model. In order to model properly deformable joints, the skin mesh cannot be rigid, but has to be deformable and influenced by more than one joint. We use a technique called "Mesh-Skinning", which allows a vertex of the skin mesh to be influenced by an arbitrary number of kinematic joints. The position and the normal of a given vertex are then computed as a weighted sum of their values as if it was attached solely to one kinematic joint at a time. This technique is sufficiently simple for real-time computations, but nonetheless gives realistic results.

Whilst the mesh-skinning gives realistic results at a gross level, there are certain constraints imposed on the level of detail at which the virtual limb can be presented. For example, features such as fingernails, fine joint creases and muscle tone are omitted from the virtual body, as can be seen in Figure 1. Experiments such as the Rubber Hand Illusion (Botvinik and Cohen, 1998) show how an alien object, such as a rubber glove, can be incorporated into the body image in the absence of visual feedback from an actual limb. The success of this illusion seems to be that the tactile stimulus to the glove is applied in perfect synchrony with the tactile stimulation to the hand, rather than the glove looking at all human-like. This is especially the case when non-corporeal objects are used as extensions of the body, such as tables and chairs. These experiments lead us to infer that real-time response of the virtual limbs is more important than exact replication of the limb. Hence, the sacrifice of this fine-level detail in the virtual limb was deemed worthwhile to allow responsive, fluent motion. However, in an attempt to reduce discrepancy, the interface on start-up does allow the colour of skin and clothes to be altered to approximate those of the participant.

Shadows are important for realism and the sense of immersion, but also because they give a good sense of depth that is not always obvious, even with 3-D rendering. The distance between a foot and the floor is easier to evaluate if the shadow of the foot is cast on the floor. Casting shadows is a standard computer graphics problem. Fortunately, recent graphic cards incorporate some routines to help implement shadows in an efficient manner. Our implementation uses the "Shadow-Map" facility.

**Experimental Measures**

Each of the below measures are completed by participants a total of two times: one week prior to using the virtual environment and once on completion of involvement with the study.

1. The McGill Pain Questionnaire (MPQ) (Melzack, 1975) is administered in order to indicate participants’ subjective phantom pain experience. This allows comparisons to be made over time on participants’ global pain experience and to assess whether the trials have any lasting therapeutic benefit.

2. The Amputee Body Image Scale (ABIS) (Breakey, 1997) is comprised of 20 items that assess how an amputee perceives and feels about his or her body experience. This scale produces scores that range from 20 to 100, with high scores indicating high body image disturbance (BID).

3. The Trinity Amputation and Prosthesis Experience Scales (TAPES) (Gallagher and MacLachlan, 2000) is a multidimensional self-report instrument designed to help understand adjustment to an
artificial limb (prosthesis). It consists of three sections: psychosocial issues, activity restriction, and satisfaction with prosthesis.

A Short-form of the MPQ is administered at the end of each IVR session in order to give a continuous assessment of pain levels and pain diaries are completed by participants throughout the course of the study to allow a more contextualised analysis of participant’s phantom pain experience. A measure of participants’ ability to visualise movement in their phantom limb during IVR sessions will also be explored using a recently developed Vividness of Imagery Scale which is administered after each IVR session.

It is also important to build a more qualitative understanding of participant’s phantom limb experience given that it is often highly unique and subjective. To enable this, participants are given a semi-structured interview before using the IVR equipment to establish the phenomenology and the nature of their phantom limb. A similar interview is carried out on completion of involvement with the study to determine whether any significant changes in participant’s phantom limb experience have occurred. It is envisaged that by combining data from qualitative and quantitative measures, exploratory analysis will inform the best protocol for future research.

**Procedure**

Over a ten-week period, each participant uses the IVR equipment every two weeks for a period of 30 minutes. Upper-limb amputees complete four tasks (in repetitions): placing their virtual phantom hand on tiles which light up in a random sequence, completing a virtual jigsaw; completing a game which requires selecting shapes and placing them in the appropriate holes; and directing a virtual ball towards a target. While seated lower limb amputees complete three tasks: kicking a virtual football against a virtual wall; raising and bending their virtual phantom limb in response to being asked to follow the trajectory of a moving stimulus; and placing their virtual phantom limb on tiles on a dance mat which light up in a random sequence. Group B complete the same tasks as group A, but with the movements of their physical limbs being transposed onto the movements of their corresponding virtual limb rather than their virtual phantom limb.

**Data Collection and Analysis**

Participants’ scores obtained on the MPQ, ABIS, and TAPES are compared over the study period and between the two IVR conditions. This data analysis allows judgements to be made regarding the short and long-term therapeutic benefit of IVR for phantom pain relief, body image disturbance and prosthesis satisfaction. Moreover, it enables comparisons to be made on these three measures over time, allowing a judgement to be made as to whether IVR therapy is an effective treatment for phantom limb experience.

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

References


Multimedia Links for Murray et al.: