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RESEARCH PAPER

Exploratory findings with virtual reality for phantom limb pain; from stump motion to agency and analgesia

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Abstract

Purpose. Phantom limb pain is chronic and intractable. Recently, virtual reality (VR) and motion capture technology has replicated the mirror box device of Ramachandran (Ramachandran et al. Nature 1995, 377, 489–490; Ramachandran and Rogers-Ramachandran Proc R Soc Biol Sci 1996, 263, 377–386) and led to reductions in this pain. We present results from a novel variation on this method which captures motion data directly from a patient's stump (rather than using the opposite remaining limb) and then transforms it into goal directed, virtual action enacted by an avatar in a VR environment.

Method. A sample of subjects with 'arm' ($n = 7$) and 'leg' ($n = 7$) amputations underwent trials of a virtual reality (VR) system, controlled by motion captured from their stump which was translated into movements of a virtual limb within the VR environment. Measures of pain in the phantom limb were elicited from patients before and during this exercise as they attempted to gain agency for the movement they saw, and feel embodied within the limb. After this each subject was interviewed about their experiences.

Results. Five subjects in each group felt the virtual limb to be moved by them and felt sensations of movement within it. With this they also reported reductions in their phantom limb pain greater than expected from distraction alone. No carry over effect was seen.

Conclusions. This technique, which has shown similar success rates to trials of a virtual mirror box, is relatively cheap and portable, and will allow further trials in a home environment.

Keywords: *Virtual reality, phantom limb pain, agency, analgesia*

Introduction

After losing a limb persistence of sensation of the limb, so called phantom limb sensation, either as a background awareness of that limb or more focussed sensations of position, shape and movement of the limb and of warmth or cold, is normal. The feelings are embodied, owned, and so vivid that occasionally people try to walk on their phantom leg [1].

Unfortunately it is also normal to have phantom limb pain (PLP). Since its earliest descriptions and naming [2], epidemiological studies taken from large samples have suggested that this pain occurs in around 60% of subjects [3]. More recent epidemiological studies have found similar or higher levels [4–6], with severe chronic pain being experienced in around one quarter of amputees. Descriptions of the pain are varied, from an unpleasant itching (which can, in extremis, be as unpleasant as pain itself), to severe burning or clenching. Some say it is like their fingers are being squeezed in a vice, or a nail being hammered through their hand or foot. The pain is felt most vividly in the feet, buttocks and hands/fingers, with fewer reports of the thigh or forearm being involved. Phantom limb pain is a form of a 'generic' pain which follows loss of a body part or functional disconnection of that body part with the brain.

A wide variety of therapies have been tried, including analgesic drugs, anticonvulsants,

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antidepressants, muscle relaxants, temporary anaesthetics, peripheral nerve blocks, dorsal column and deep brain stimulation, and more destructive surgery like DREZ (dorsal root entry zone lesions) lesions and cordotomy. Psychological treatments have included cognitive behaviour therapies and hypnosis, all with poor results on the whole [3]. Even the newer analgesics such as gabapentin have proved disappointing in severe PLP, though this remains controversial. One study suggested it was more effective than placebo [7] but another that any such difference did not reach statistical significance [8].

The cause(s) of PLP are unclear. A decade ago, Ramachandran introduced a novel suggestion and treatment [9]. Initially they were interested in the interactions of vision with phantom limb sensations by using a mirror.

> "A tall mirror was placed vertically on the table, perpendicular to the patient's chest, so that he could see the mirror reflection of his normal hand 'superimposed' on the phantom. As the normal hand was moved the phantom hand was seen moving and was also felt to move with 'vivid kinaesthetic sensation''. [9]

No one in their sample of nine had previously tried to move their phantoms. Five patients had painful, involuntary spasms which were relieved on looking into the mirror, moving the existing hand and making an effort to move the phantom limb too. The authors explained that 'when motor commands are sent from the premotor and motor cortex to clench the hand they are normally damped by error feedback, from proprioception. In a phantom such damping is not possible, so the motor output is amplified further and this outflow itself may be experienced as a painful spasm'.

In a further article, Ramachandran and Rogers-Ramachandran [10] described 10 patients and used a mirror box rather than a simple mirror alone with similar results on PLP. Subsequently other workers have used mirror boxes or similar devices with varying results. In one study of 22 patients with pain after leg amputation and which compared mirror therapy, motor imagery and a covered mirror condition, the mirror therapy was the only one effective, with a mean reduction in pain of 2.4 on a VAS scale [11]. In a larger scale study ($n = 80$), however, of mirror therapy for PLP in the leg no significant effect was seen [12], though analgesia effect was reported in a single case study [13].

In addition to these variable results, the mirror and mirror box techniques have some technical limitations. They require the arms and hands to move in mirror symmetry, and while this may be reasonable for the arm – since many movements of the arms are bilateral (though rarely mirrored or symmetrical), it is less natural to move the legs in such a way. The Dublin group, led by MacLachlan, also make the point that a patient's phantom limb does not appear like a normal limb; it is frequently irregularly shaped and may have a thin forearm and larger more elaborated hand and fingers [13].

In the light of these limitations, several groups have moved to replicating the mirror box effect using computer generated, virtual worlds. MacLachlan's group developed an environment they call augmented reality (AR) which presents the perceived phantom arm on a flat screen in 3D and which is controlled via a wireless data glove worn on the intact arm [13]. As the intact arm moves so the avatar follows with realistic finger and hand movements. This allows irregularly shaped phantom limbs to be represented and also allows the two arms to move both in the same direction as well as in mirror symmetrically. In control subjects, nearly 90% felt phantom sensation and when asked to compare AR with a mirror box, 44% found the former preferable (while 28% preferred the mirror box).

Murray and Pettifer's group [14–18] use a slightly different approach. They transpose movements made by amputees' remaining anatomical limb into movements of a virtual limb which is presented in the phenomenal space of their phantom limb. This allows for a visual representation of the amputee's whole body, including their phantom limb and, unlike the mirror box, also allows complex hand-eye coordination, and differing movements of the limbs, fingers and toes. Using such a system, users are able to perform tasks impossible in a mirror box, such as playing ball games. In five subjects they have found some reductions in pain over a 2.5 month period after weekly uses of the VR system for 30 min. However in the three patients who quantified their pain significant reductions were recorded only in two, whilst in one pain appeared to increase. For a review of work in this field see Cole [19].

The sense of active, intentional, initiation of action is often called the sense of agency. The mirror box effect seemed to require this sense of agency, and we suggest this may be a clue to the analgesic effect whether in the box or in immersive environments. Whilst some patients in Ramachandran's study [10] found an analgesic effect from illusory movement when they viewed the moving mirror-reversed arm of a control subject passively, most required a way of imagining their way into 'moving' both arms and seeing both hands move themselves. Current work in virtual environment systems also requires agency to be directed towards the phantom limb when intentional movement is also being applied to the remaining opposite one. This may be easier in tasks for the arms than for the leg.

Our own approach has been to develop a virtual system, as others have done, but to control it from the stump or proximal part of the affected arm or leg via a motion capture device. Subjects are asked to move their stumps and see an arm or leg in virtual space moving in a dynamically animated sequence. Their task is to gain agency for the virtually presented limb while effects on pain are monitored. The advantage of such a system is that bilateral movements are not required and that the movement of the virtual limb is driven from movement on the same side (and the correct side of the brain). Though there are disadvantages with such a system – finger movements are pre-animated and cannot be fashioned by the opposite hand as in a digital glove, it does have the advantage of being potentially cheap enough to mass produce, and so allow patients to use at home.

We report the preliminary results from this system in 14 subjects with PLP at the time of trial, seven with an arm amputation and seven a leg. We also report results from an additional nine leg amputees during trials when they were pain free.

Method

Patients were recruited through consultants in pain and prosthetics. They were instructed that the project was experimental, that if there was any effect on their pain it was likely to be temporary and that, though we hoped for an analgesic effect, the reverse could occur. We felt it necessary to inform subjects of the aim of the trial. Though aware of the possibility of so influencing the results, we felt that this unlikely. Firstly, given the severity of pain and their previous exposure to various medical interventions without success, any placebo response to medical intervention was likely to be small. Secondly, we also mentioned the possibility of the trial worsening their pain, so that any influence could have been in either direction. Experiments had Dorset Local and then National Research Ethics Committee approval and were performed in accordance with the Helsinki Protocol.

Patients' details for both the arm and leg trials are shown in Tables I and II. They were aged from 27 to 72, mean 49 years old, for subjects with amputations of the legs and 36–82, mean 56 years, for those with amputations of the arms. They were taking, or had taken, a variety of analgesics including paracetamol, amitryptiline, non-steroidal anti-inflammatory drugs, morphine, gabapentin and tramadol. Some had also tried acupuncture, hypnosis and CBT pain management, acupuncture. No changes in medication were made for the trials.

Amputees had had from 5 months to 10 years since losing their limbs. This was considered a preliminary trial of the technique and therefore our inclusion criteria were relatively wide. Those with arm amputations had more severe and constant pain than those with leg amputation. In addition we also saw a further group of nine patients with leg amputations and intermittent PLP with no pain at the time of testing. These will be dealt with separately. They were aged 29–78, mean age 64 years old. Those with arm amputations were seen twice several weeks apart; those with legs were seen once except for one person who returned for a

Table I. Subjects with amputation of the arm; details for the trial.

Patient, sex and age	Injury type and duration of pain	VAS pain, maximum and minimum	MPQ rank and (weighted)	VA	VS	Pain relief, VAS/%
F, 83	Rt forequarter amputation: pain 11 years	8 to 2, half day each	46, (47.9)	Yes	Yes	8 to 4.5/43%
M, 37	Rt C6-T1 root avulsion: pain 7 years	7–8 2 hours per day, 2–3 rest	46, (57.0)	No	No	No
M, 69	Lt brachial plexopathy: pain 9.5 years	8–9 to 3–4 round half time each	44, (49.2)	Yes	Yes	7–8 to 1–2/80%
M, 36	Rt forequarter amputation: pain 11 years	9 to 4. Severe most of the time.	41, (46.6)	Yes	Yes	8–9 to 2/76%
M, 72	Rt mid-humerus amputation: pain 12 years	4 to 1–2 (less than half the time)	16, (17)	Yes	Yes	4 to 0/100%
F, 61	Lt forequarter amputation (after plexopathy. pain emerged): pain 12 years	5 rarely only	11, (11.2)	No	Yes	No
F, 39	Lt forearm amputation: pain 12 years	9 constant	15, (18.45)	Yes	Yes	9 to 7/22%

PLP, phantom limb pain; VAS, visual analogue scale; MPQ, McGill Pain Questionnaire score; VA and VS, virtual agency and virtual sensation.
The VAS numbers in column 3 refer to maximum and minimum pain on a 10 point scale during a typical day. The VAS number in column 7 are the pain at the time of the trial starting and then during immersion.

Table II. Subjects with amputation of the leg; details for the trial.

Patient, sex and age	Injury and duration of pain	VAS pain, maximum and average	MPQ rank and (weighted)	VA	VS	Pain relief, VAS/%
M, 72	Below knee, post Ischaemia: pain 4 years	7–9 spasms	12 (13.3)	No	No	No
M, 54	Above knee post ischaemia: pain 6 months	6	16 (17.05)	(Knee not Foot)	No	Yes – slight
M, 37	RTA below knee: pain 3 months	6 foot pain 8 ankle spasm	10 (11.6)	Yes	Yes	Yes 7 to 2/71
F, 48	Osteomyelitis: pain 2 years	9	18 (21.4)	No	No	No
M, 66	Pathological fracture femur: pain 7 years	7 spasms, 1–2 Foot pain	12 (13.2)	Yes	Yes	Yes 7 to 0/100
M, 27	Electrocution: pain 4 months	5	11 (11.55)	Yes	Yes	5–6 to 1–2/72
M, 41	Diabetic ischaemia: pain 4 months	7–8 severe, 4 average	16 (21.68)	Yes	Yes	4 to 0/100

PLP, phantom limb pain; VAS, visual analogue scale; MPQ, McGill Pain Questionnaire score; VA and VS – virtual agency and virtual sensation.
The VAS numbers in column 3 refer to maximum and average pain on a 10 point scale during a typical day. The VAS number in column 7 are the pain at the time of the trial starting and then during immersion.

further trial. Our observations on agency and analgesia were reproducible in all subjects, though on their second visit some found agency and analgesia more easily and quickly.

Our studies were conducted in a clinical setting, within a low light environment, so that subjects' focus was maximised on the display. Session times were variable, depending on subject fatigue, but typically lasted 60–90 min. Two prototype virtual environments were developed for use with a domestic PC and a motion capture device (a 'Nest of Birds' box, produced by Ascension Technologies). The prototype systems respond to motion data captured from electro-magnetic sensors attached to either the arm or the leg of the user. Before beginning a goal directed activity, the user was asked to perform a series of physical actions with their stump to calibrate the state-based gesture system. Once the system was calibrated, subsequent motions were interpreted as physical expressions of a modelled gesture and evaluated probabilistically.

The first prototype interpreted motion for a missing arm. Here, the goal was to grasp an apple on surface of a table. Enactment of this goal included actions to reach, grasp, retrieve and replace the apple (see Figure 1).

In the second prototype, to support those with leg amputation, the user was presented with a bass drum as they might perceive it whilst sitting on a chair. The goal related actions were in four phases: raising the leg, a forward, pressing action of the foot on the pedal, releasing the pedal, and returning to a rest position (see Figure 2). The interpretation system was designed to be dynamically recalibrated to adjust for changes in physical performance.

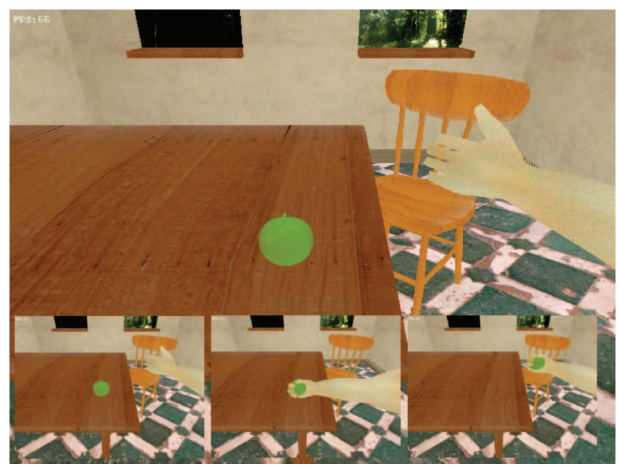

Figure 1. Virtual arm prototype (operational examples in-set).

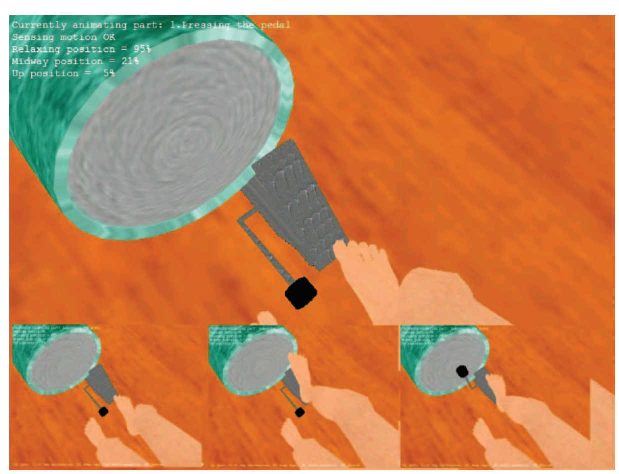

Figure 2. Virtual leg prototype (operational examples in-set).

Before beginning the session proper, a clinical history was taken in each patient as well as a McGill Pain Questionnaire [20], Visual Analogue Scale (VAS), drug history and recent pain history. The VAS was a 10 point scale with 0 being no pain and 10 the worst pain imaginable. The scale was used to assess maximum and minimum pain that people with arm amputations, and the maximum and average pain subjects with leg amputations, lived with during a typical day, and these figures are given in Tables I and II in column 3. If pain did not vary then one figure is given. In addition, during the trials the VAS figure given in column 7 of the tables refers to the pain intensity at the trial's start and then, subsequently, during immersion with agency. Experience with the McGill Pain Questionnaire has found pain levels of around 16–20 after sprains, cuts and toothache, while PLP is typically given levels of 25–26 on a VAS scale, alongside chronic back pain and non-terminal cancer pain. The subjects in the present trial with amputations of part of their arm therefore had more severe pain than seen typically, whilst those seen after amputation of a leg, or part of it, were experiencing moderate pain (see [20]).

They were then acquainted with the apparatus and the motion capture device taped lightly to the skin overlying a suitable area of their stump. Each subject was invited to use the VR system, with our initially prompting that they might try relatively slow and deliberate movements. During this time, the system was calibrated such that the best possible analogous motion was rendered on screen. We then allowed them time to find suitable and comfortable actions and left them alone for periods of 10–15 min, or up to half an hour. For many, the procedure was tiring and so scheduled breaks for rest and refreshments were included.

We deliberately did not keep interrupting the trial since this disrupted their concentration and so broke their sense of agency towards the VR limb – which then required further effort to recapture. During interruptions, and at the end of each trial, we would ask about agency, sensation and pain using a semi-structured interview. As a preliminary trial of the technique, we were concerned primarily with the subjective experience of patients; the focus of the interviews was therefore on the experience and effort involved in agency, the presence or absence of sensation and the experience of pain during the VR immersion.

Results of the arm prototype

Five out of seven subjects with arm amputations gained a sense of agency for the virtual arm, usually within half an hour (see Table I). They volunteered a difference between just seeing the avatar move as they moved their stumps, and intending movement of the virtual arm and hand as their own, in terms of both the mental effort involved and the subsequent perception. 'It is much heavier and needs more effort to move the virtual arm than just to move the avatar from the shoulder alone'. This return of intention did not always involve the whole arm at once. One who could move his arm but not all his fingers remarked, 'When trying to move the hand the fingers are stiff and seem to resist movement'. With time, minutes to an hour or so, most 'picked up' most parts of their arm and hand.

With this sense of agency also came distinct perceptions. One man, with severe PLP in fingers 3–5 and the elbow, described a novel, 'buzzing' feeling in his first two fingers as he controlled the avatar when he made a grasp movement. Another could feel touch sensation when he picked up the apple. The sensations felt were, therefore, not only in relation to movement but also of exteroceptive touch. As the experience of a sense of virtual agency and sensation emerged, pain reduced. One remarked, 'Now, when I move the fingers there is still pressure but there is no pain, they are not being ripped off or squashed'. Another suggested, 'When I move and feel the arm, it does not tingle; pain disappears into the background and merges into the movement sensation'.

Another subject developed agency soon after the trial. With that her fingers, which had been clawed, became more open and the sensation of pain was reduced. This was a greater reduction in pain than in her previously used mirror box. Interestingly, she felt this system was more immersive and also less emotional than her similar experiences with the mirror box: seeing her right arm as her missing left so clearly in the mirror box had been difficult emotionally. Her clawing pain was reduced though the burning pain was less affected. She could feel her fingers moving and touching the apple but, curiously, when gripping the apple she had occasional short spasms of pain. She had a mismatch between what she saw and felt. She did not really feel that her fingers were opened widely enough to grasp the apple, even though she moved them and saw them doing so. Her concentration levels with the system and the mirror box were similar to that of the mirror box, she reported, and like that, after a while she felt she could no longer concentrate. On giving up, the pain returned.

With the development of agency and sensation came reductions in pain. One subject with a VAS of 8 at the beginning of the trial achieved agency for his fingers within 10 min and then, after 30 min, felt the wrist and arm move. His VAS scale fell to 6. After a break he tried again and was able to pick up the arm and move it more easily; then his VAS fell from 8 to 2. After a week he returned and within 20 min had agency and sensation for the hand and fingers and his pain had reduced from 9 to 2–3. He commented on the balance between mental concentration on agency and analgesia. At the end of trials his concentration fell and the pain recommenced.

Another subject, with an initial VAS pain scale of 4, had a feeling of moving the arm, though the hand was still clenched, after 10 min. After 20 minutes he could feel and move the phantom arm and the pain had disappeared into background (VAS 0). This was reproducible across several trials over the day. At one point he felt his hand, joints and knuckles and the skin in the hand when grasping, 'the arm is now a gentle presence'. With less pain and a secure virtual limb this subject was the only one with a carry over effect; he was able to move his phantom and was pain free for the rest of the day, even at home. Unfortunately he was lost to follow up for medical reasons.

Two subjects had no sense of agency, embodiment or pain relief despite good trials. One had multiple complete root avulsions, from C6 to T1, with a subsequent elective amputation of the arm. His root avulsions precluded controlled movement of his stump, but he had also not moved the limb for 5 years before it was amputated. The second patient had not moved her arm for 18 years before her amputation. Interestingly she felt her phantom arm move in a mirror-box, and being touched by her other one in the mirror. Her phantom also moved, from lap to mirror. But this movement remained passive; she did not develop a sense of agency either in the mirror or from our virtual system. The other subject had no effect in the mirror-box. We did not formally test use of a mirror box in the other subjects, though as detailed above, one subject had used it before our trial of the VR system.

Results of the leg prototype

The subjects with leg amputation had less severe pain than those following arm amputations and many had spasms of pain rather than continuous pain. Interestingly five out of seven also had developed an ability to move their phantom themselves, something those who had lost their arm did not volunteer. Of the seven patients in this study, five experienced a sense of immersion during their interaction; and with this four had a significant reduction in pain, see Table II. Their experiences varied from obtaining little more than good sense of control over the virtual leg to strong changes in the sensation of physical location, orientation and touch in the phantom. Two of the subjects were imbued with enough confidence in their immersion that they were able to 'perform' the task, they said, with eyes shut.

One subject suggested that, 'I can feel the movement in the missing leg and maybe feel touch too. Once I am on the pedal I relax and feel my foot coming off it. It is second nature as though moving my full leg. The prosthesis is always a prosthesis; this is different. Here I am moving the foot. And at the moment the toes have sensation and though there is slight cramping in the toes there is no pain'. (Pain went from VAS 7 to 0).

It was a not uncommon but surprising experience that subjects were so immersed that they did not realise their pain had gone. 'Until you mentioned it I had not realised it was gone. One minute it was there and then, concentrating on the task, I did not realise it was gone'. (Pain VAS from 4 to 0)

Another subject reported that being in the virtual environment 'lightens the pain, from VAS 5–6 to 2 or even 1. It is no longer a constant throbbing, it is weird. I know it is not my leg and yet it feels as though it is. When I stop moving the pain returns within a second or two, but equally when I move and feel it is me, the pain reduces'. He saw the top of the leg and felt it was his, but had a less secure adoption below the knee. He asked for something for his stump to touch at the bottom of the movement and this was arranged, (an upturned bucket on some books). Then, when he pushed down, touch on the stump was felt as being in the foot and the pain was more clearly reduced (from 5 to 1). 'It is boring to do the test, but nice to feel I have a leg again. Before I felt the foot was not there because there was no feeling (he does feel foot fall through the stump with his prosthesis), but now I feel the stump touch as being on the foot'.

A further subject found, after gaining a significant sense of agency, that he felt the touch of the drum pedal (see Figure 3) on his phantom foot. Two others asked that the avatar be re-oriented to represent their seated position more accurately; they had a 'misalignment' in the experience of their phantom leg relative to their physical body so that the phantom aligned itself to the orientation of the virtual leg.

Two subjects with pain at the time of testing failed to engage with the system, despite having relatively good physical control and articulation of their stump. These subjects had not had a long term paralysed leg, and could not see the point of the interaction. They also found problems with the image and motion fidelity during interaction.

The system was also used in a further nine subjects with leg amputations who did not have pain at the time of the trial. Their pains were intermittent spasms from 2 to 30 min per day or so, but were otherwise unpredictable. None of these subjects felt

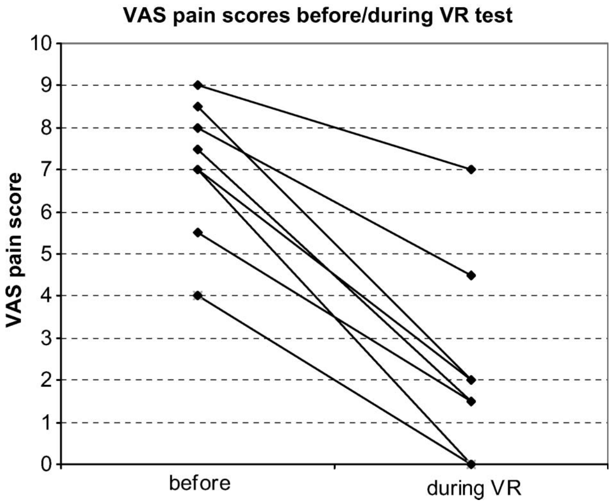

Figure 3. VAS pain scores before/during VR test.

sympathetic with the experiment once it was explained and none entered the trial sufficiently to have agency or sensation from the virtual limb. For these reasons, we do not expect the laboratory based application of our method to necessarily be effective for individuals without pain at the time of testing.

Summary of results

Figure 3 shows the maximum reductions in pain during trials of virtual agency, where the effect was quantifiable. The percentage reductions were 22–100% (with a mean of 64%). This is above the 30% some suggest is useful [21] and above a similar boundary others have suggested might be achieved by distraction alone [22]. Use of the VR system without a feeling of agency and sensation did not lead to any pain reduction, and pain reduction followed and did not precede the restoration of agency. More results are required before the statistical significance of this finding can be ascertained.

In post-trial interviews, patients suggested improvements, mainly in relation to environmental cues within the VE. Some asked for more realistic visual environments while others asked for additional haptic feedback, for instance appropriately timed physical touch to their stump during reaching or insufficient. Timed auditory feedback might be useful in immersion too. Subjects also suggested a wide variety of ideas to improve the task, from simple, rapid motions (such as kicking a ball) to small scale, gentle motions (in the case of the leg patients, this might include movement of the ankle) that would require some finesse. All agreed that incorporating game play into the system would promote continuous engagement. Work by Murray's group [14,15] already includes such features.

Discussion

Agency and analgesia

The use of a visual avatar, moved via motion captured from the subjects' movement of their remaining stump or even chest wall, allowed a returned sense of agency within the virtual limb for most of these patients. With this subjects also felt sensation in relation to intention. This supports the theory that this perception is taken from internally generated, predictive, forward models of movement rather than from peripheral feedback (albeit forward models working with visual feedback) [23]. But perception was not only of motion of the limb but also of touch, a virtual-visual cross-modal perception, [24].

Several subjects with partial leg amputations contrasted this system with use of their prosthesis, finding the virtual system more enabling of agency, despite them walking with and on the prosthesis. One must not forget how heavy a prosthesis feels and that for that reason it is rarely fully assimilated into a person's body image. Though VR induced agency and embodiment in the virtual limb was not effortless, when successful it was so assimilated into subjects' body image.

Once a sense of agency had been re-established subjects' pain was reduced. This does not appear to be solely due to a distraction effect, as has been used to good effect during medical procedures, [25,26]. The analgesic effect was also greater than usually ascribed to distraction [22] and of a degree considered clinically useful [21]. Subjects also remarked on the subjective difference between 'just' watching the avatar move from movement of their shoulder, and the mental effort of moving their virtual limb. Pain relief followed the latter only. In two patients, as their concentration tired, virtual agency faded and the pain returned.

Attitudes towards the use of the VR system were varied and these individual responses are not irrelevant to pain control. Patients less open to the technology and approach performed less well during interaction. Those patients without pain at the time of the trial, after leg amputation, did not engage with the virtual system. Patients with intermittent spasms of pain may not be helped by our present system, though they might by a system they can use at home, in their own time and in relation to their pain.

The mechanism of this analgesic effect is unclear. PLP may be of more than one type and involve both peripheral and central mechanisms [27]. Reduction in PLP has followed increasing attention to sensation from the remaining stump, through sensory discrimination training [28], or use of a myoelectric prosthesis [29]. Such effects are compatible with partial reversal of central plastic change associated with loss of sensory input. Work with mirror boxes suggests that PLP may result from a mismatch between motor intention and sensory return, leading to pain associated with internal forward models unrestrained by peripheral feedback [9,30]. Giraux and Sirigu trained patients with PLP over weeks to superimpose their own volition onto a movement of an arm displayed to them on a screen in a homologous position to their own arms, and found that this had an effect on PLP [31]. They commented that this allowed them a restoration of a coherent body image. Wall suggested that pain might not be simply a sensation but be a need state, like thirst or hunger [32]. Perhaps the need, in part, is for action. More recently Craig has developed these ideas independently, suggesting that pain is both a sensation and a motivation akin to other homeostatic drives like itch, hunger and thirst, which all reflect adverse conditions in and of the body requiring behavioural responses [33]. Just as PLP may be multi-factorial, so there may need to be more than one approach to treatment.

The absence of an effect in those two patients without movement of their arm for long periods before the trial suggests a decay in the mechanisms of intention with time, first described by Ramachandran as 'learned paralysis', [34]. Interestingly one of these patients felt her phantom arm move in a mirror-box, but this movement remained passive. Analgesia following restoration of agency and after passive observation of a mirrored limb may have differing mechanisms.

VR development

Factors which determined successful immersion, agency and analgesia may involve motivation; those without pain or with intermittent spasms, not surprisingly, found little purpose in the procedure. We had anticipated that older people might find this more problematic, but rather than age it seemed that attitude to a new technology was more important. Though initially sceptical, several older subjects found their way to agency and analgesia. Time since amputation may be relevant; the more successful at recovering agency were those with a shorter time without their limbs.

Enhancing embodiment may be possible by more immersive and creative environments and tasks. More playful games may reduce the effort involved and increase time spent immersed. Multiple sensory modalities may also be important with haptic touch of the stump during the task and auditory feedback useful. During the drum tapping a simple drum beat was included during one phase of development. Applied research in this area suggests that 'sound events' play an important role in engendering a feeling of immersion [35].

The success of the prototype system seemed dependent on the range of stump movement possible and the level of user engagement. In the most successful case, the seen VR movement approximated to the motion of the user so well that they performed the gesture with skill and control. Performance was less stable with users who had limited physical motion or were unable (or disinclined) towards the trial. In the former case, motion capture data were not of a sufficiently wide range for the inference engine to discriminate changes in gesture states; this translation of stump movement to VR motion seems a crucial area to improve.

It is also important to recognise that other factors may have had an effect on the 'positive' reports made by patients during the trial. In particular, some care should be taken with the verbal reports of patients as they relate their phenomenological experiences of the phantom in a clinical setting. Some patients may wish to cast their experiences in the best possible light, given the context of the early, exploratory nature of the investigation. A placebo effect may also have been operating, although the reported changes in VAS score are larger than usually ascribed to such a mechanism alone.

Comparison with other VR systems

Our results appear similar to those of previous workers, either using a mirror box or a virtual environment, [10,13,15] and better, in short term experiments than the single larger scale trial of mirror therapy in leg amputees [12]. These results suggest that our approach of employing the remaining stump to drive virtual limb motion is of similar utility to mirror and virtual mirror techniques. The system is complex to develop but has some advantages over a mirror box, particularly perhaps in those with leg amputation. Mirror symmetrical movements of the legs are rare in life, outside a swimming pool, and so this system may allow easier and longer immersion. It also has the advantage over virtual mirror systems in that it is potentially cheap and so patients may be allowed home with systems to try.

It is only when patients undertake trials over longer periods at home, with pain diaries and more sophisticated measurement of mood, emotional state and sleep for instance, that the utility of this system will become apparent. Such longer trials may also determine whether there is any carry over effect of either agency or analgesia. Better environments and tasks may allow easier and deeper immersion. Lastly, subjects seen sooner after amputation and the development of PLP may gain agency and analgesia more easily.

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