Virtual Reality combined with Robotic facilitated movements for pain management and sensory stimulation of the upper limb following a Brachial Plexus injury: A case study

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Abstract— **Brachial Plexus injuries are complex in nature caused in large by high impact traffic accidents which can lead to additional complications such as Complex Regional Pain Syndrome and even lead to amputation or the need for further surgical intervention. Treatment options to help repair the brachial plexus initially involve surgical intervention and post-surgery rehabilitation with medication to help with ongoing pain. Pain treatments used for these types of injuries are limited and differ in effectiveness. Paradigms utilising multimodal systems such as the one described in this paper based on virtual reality and robotics could yield results that are non-invasive and provide better rehabilitation outcomes for the sufferers. In this paper we present a single case study exploring whether Virtual Reality plus Haptic feedback have any practical potential for reducing upper limb pain and improving function in patients with brachial plexus injuries. The case study is presented with long standing complex combination of phantom limb and neuropathic pain. A decrease in perceived levels of pain was reported which amounts to a 50% reduction in pain from baseline and an improved range of motion. An examination of the sensory phantom map on the stump seems to indicate an early establishment of the thumb representation on the stump close to the area being stimulated with potential implications for prosthesis use.**

Keywords - Rehabilitation, Pain, Brachial Plexus, Rehabilitation Robotics, Haptics, Virtual Reality, Sensory Map

I. Introduction

Brachial plexus injury is devastating peripheral nerve trauma often because of vehicle (mainly motorcycle) accidents [1]. Most of these injuries occur in high velocity collisions in which the neck and head experience enough impact force and traction for the nerve roots to break or tear away from the spinal cord. The level of injury is factored through the specific roots and degree of injury to each root. The effects of a brachial plexus injury usually lead to paralysis, loss of sensation, and debilitating, often intractable pain, therefore causing severe physical, psychological, and socioeconomic disability [1]. The degree of disability is determined by the extent of injury to the nerve roots. Severely limited range of motion or even complete loss of function of affected arm and/or hand makes rehabilitation extremely challenging.

Treatment is multidisciplinary, longitudinal in nature and often involves primary explorative, reconstructive and further staging of secondary, even tertiary surgical procedures. This results in high cost of treatment and rehabilitation in this population group. Not to mention, the cost is further increased by the gross number of people not being able to rehabilitate and to achieve a reasonable quality of life due to severe pain in the affected limb.

Brachial plexus injuries commonly result in pain. It is reported in 67% to 78% of patients [2,3] with high prevalence of neuropathic pain, reported in up to 95%, especially in cases of nerve root avulsion [4,5]. In brachial plexus injury pain poses an additional negative factor further reducing the quality of life of the patient. Pain in these cases is multifactorial and difficult to manage. There are mainly two groups of pain: nociceptive and neuropathic. The former relates to direct musculoskeletal and soft tissue trauma resulting in a complex cascade of inflammatory reaction. The latter is associated with dysfunction of peripheral and, at a later stage, of the central nervous system [2,6]. These central neurophysiological and molecular changes are responsible for refractory neuropathic pain [7,8] and a phenomenon known as phantom limb pain. Therefore, the pain management is complex and sometimes ineffective. Additional injuries such as amputation at the time of brachial plexus injury or later, when amputation is a choice of treatment to alleviate mechanical strain of non-functional extremity, can present even more challenges in pain management.

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There are two major treatment options - conservative (pharmacological) and surgical. Conservative management aims to maintain as much function and range of movement as possible in the affected limb via strengthening existing functioning muscles whilst providing pain relief. Pharmacological treatment is combined to further manage the pain. Surgical interventions on the other hand aim to restore function of the injured arm which can in some cases reduce the pain [5].The goal of combining pharmacology, physiotherapy, and rehabilitation, which can include biofeedback, percutaneous nerve stimulation, hypnosis and similar procedures, is to strengthen residual function and reduce pain. While NSAIDs (Non-steroidal anti-inflammatory drugs) and opioids reduce nociceptive pain, neuropathic and phantom limb pain is harder to tackle, resorting to the use of antiepileptics and antidepressants. Moreover, only 30% of people with brachial plexus injury and neuropathic pain will have significant reduction in pain with drugs such as gabapentin, etc. [5]. There is a variety of surgical techniques used to treat brachial plexus injury [3]. Early exploration, repair, if possible, and nerve transfers have proven to be successful in improving functionality of the limb and recovery. Decompression of the lesion allows nerve recovery and improves pain. Even slight improvement in limb movement may reduce pain. However, cases exist in which surgery alone, and even paired with conservative management, does not provide acceptable levels of pain relief, leading to new treatment options being sought for to help the most severe cases. With incidences of traumatic brachial plexus injuries increasing coupled with the rehabilitation demands on already overloaded services to which incorrect efforts could lead to massive decreases in terms of quality of life for sufferers. Although surgical interventions are continually improving in techniques and outcomes, functionality still varies. Partly due to the complexities of such injuries, these effects can factor into the patient's ability to partake in rehabilitation. Therefore, a need to allow those who are most at risk due to severe lack of movement to take part in rehabilitation not only for function but also to manage pain is required.

Ongoing clinical trials conducted at the Royal National Orthopaedic Hospital, Stanmore have found significant reduction in phantom limb pain in amputees using virtual reality with robotic facilitated movements with over 64% pain reduction (3 out of 12 participants are pain free) sustained over 12 months post intervention [9]. The initial results in reducing neuropathic pain in amputees suggests that the treatment could also benefit those with neuropathic pain as a result of peripheral nerve injury due to the cortical reorganisation created through the intervention. The following sections of this paper detail an immersive virtual reality and haptic robotics system that allows individuals with traumatic brachial plexus injuries with severely limited range of movement, to undertake the same rehabilitation exercises as those with normal range of movement and explores its feasibility as a potential rehabilitation modality for brachial plexus injuries. We hypothesise that as the participant embodies the virtual limb their perceived pain areas will decrease, levels of embodiment will increase and as a result a more pronounced sensory map will be present on the participant's stump. This will be tested using the short McGill pain questionnaire as the primary measure and embodiment questionnaire along with sensory map data as the secondary measure.

II. Methods

A. Sensorimotor System

The sensorimotor training system consists of guided motor activities using our immersive haptic sensorimotor training system [9] that provides:

1. Direct physical contact to the haptic device,
2. Maps information from the device to the virtual representation of the physical limb,
3. Provides a series of engaging visualisation exercises within a 3D virtual environment.

As shown in Figure 1 (the system was originally designed for to alleviate Phantom Limb Pain in upper limb amputees), the participant is connected to the robot via an arm interface to a gimbal. The robot provides position information, and the gimbal provides orientation data of the connected limb. The robot serves two purposes; to allow accurate mapping of the limb from the real domain to the virtual, and to provide force feedback.

Figure 1 - Participant using the system. Showing the HapticMASTER robot, Oculus Rift and experimenter's screen.

The participant wears a VR headset (Oculus Rift CV1), which provides an immersive view of a human avatar. This acts as the visual side of the mirror box therapy (The use of a mirror to create a visual reflective version of an affected limb (upper or lower) from the non affected limb to attempt to correct the brain's representation of the affected limb), with muscle control from the limb connected to the robot providing one half of the sensory input (visual). The second half of the sensory input (tactile) will be provided by the robot

(HapticMASTER, Moog), which has been used in previous research on patients following a stroke.

Unreal Engine 4 was used as the primary engine to render the exercises and avatar along with custom software that synchronises the control loops mainly via the engine and HapticMASTER server along with communication with the different subsystems which make up the whole system. The participant is connected to the robot via a residual limb interface (gimbal), which provides limb tracking in 6- DOF (position and orientation) along with force feedback in 3-DOF. An Oculus Touch controller is attached to the participant's intact limb. This is to facilitate 6-DOF tracking of the intact limb in relation to the Oculus Rift headset. This set up allows easy tracking of both limbs in left and right sided amputation configuration with minimal physical changes between the two sides.

The position and orientation data from the HapticMASTER via the gimbal and the Oculus Touch controller is fed into a custom inverse kinematic solver within UE4, which results in correct anatomic position and orientation of the virtual limbs of the avatar being controlled by the participant. In addition to mapping arm movements of the affected limb, the robot outputs force (haptic) feedback when the participant interacts with the environment and tasks. These types of interactions include simulating the physical properties of virtual objects, such as a geometry, texture and weight, collisions with objects or to assist with arm movements [10].

The system therefore builds upon mirror box therapy with interplay from three main components (Figure 2). The participants **'see'** a virtual surrogate of their limb, they **'control'** the limb with their physical side as well as using classified EMG to allow the virtual hand to open and close. This enhances proprioception and the sense of embodiment and agency. The participant **'feels'** force feedback when interacting with virtual objects such as geometry, texture, weight and collisions. The aim of the system is to heighten the sense on embodiment and 'agency' as far as possible.

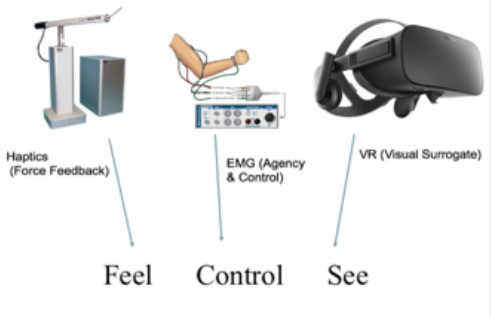

Figure 2- Feel-control-see concept for enhancing embodiment, proprioception (visual and proper) and agency through initiation and control of movement.

B. Case study clinical presentation

Participants are being recruited with NHS ethical approval (IRAS project ID: 179870. REC Reference: 15/WM/0147) and through the Royal National Orthopaedic Hospital NHS Trust's Surgical Innovation and Techniques and Technology committee.

Mr RB, a 52-year-old man sustained a left brachial plexus injury (BPI) in 1987 when he was involved in road traffic accident while riding a motorbike. He had full left arm paralysis at the scene. He was admitted to hospital and subsequently underwent left brachial plexus exploration that found pan - brachial plexus injury, meaning that all 5 nerve roots C5-T1 were affected. Suspected upper and lower trunk avulsions and middle trunk long traction injury (judging by clinical presentation as there are no records available).

Mr RB did not recover any movement or sensation after the first surgery. Further, another surgery was done using saphenous nerve graft in attempt to re-innervate shoulder muscles with poor functional outcome. At this point C5 and C7 nerve distribution sensation was recovering, there was recovery in triceps muscle. Also, some C6 sensorimotor function recovery was observed, however, not sufficient for functionality. In following years (1990) triceps to biceps muscle transfer was performed to augment elbow flexion. Some function was achieved. However, forearm and hand stayed unfunctional insensate, no motor activity and heavy. Mr RB was lost for follow-up. Eventually returned to Peripheral Nerve Injury unit and a wrist fusion with metal plate was done. Due to bone breakdown the metalwork was removed. After long discussions and considerations transradial amputation was performed in 2020.

Since injury Mr RB has had phantom limb pain (PLP) in the whole of his left arm. PLP was characterised as shooting electricity like pain radiating down his arm terminating in his hand and fingers. He also experienced burning, tingling and pins and needles kind of sensation throughout his left arm. With some early upper arm sensation and muscle recovery the shooting pain and overall pain decreased about 15%. Nevertheless, he reports persistent and constant phantom limb pain, this was accompanied with phantom limb pain and sensations in the lost limb after amputation was performed. On examination there is some muscle activity in supraspinatus, latissimus dorsi, pectoralis major, triceps and biceps. There is minimal shoulder abduction and adduction, there is no external rotation, there is reasonable elbow flexion powered partially by biceps and triceps. There is normal sensation in C5 and C7 distribution and present but reduced and altered sensation in medial cutaneous nerve of the arm and forearm.

During the first examination of the sensory system on the Mr RB's stump it was found that he does not have a definite phantom sensation unless the stump is touched. The phantom limb pain - buzzing, burning, tingling, however, is present as a background. When stump is touched (Figure 3), radiating tingling and pins and needles sensation is evoked in missing limb area without specific localisation. Mr RB has been treated by pain team. In the time since the accident, he has been taking many different combinations of pain medication to improve his phantom limb pain. Currently he is taking Codeine and Zopiclone at night. There is little effect and pain continues to be persistent, even waking him up early every morning. Mr RB reports considering invasive pain treatment methods like spinal cord stimulator or dorsal root entry zone lesioning.

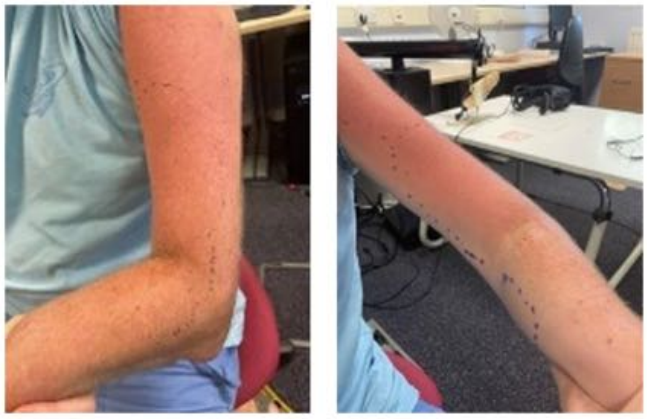

Figure 1 – Participant's phantom sensation area marked on the stump. (left) lateral aspect; (right) medial aspect

C. *Measures and data collection*

Motor control actions are picked up by a range of different biomechanical sensors (present in the haptic device), by the HMD (head tracking) and kinematic tracking of the limb(s). A series of outcome measures assessing changes in reported pain, embodiment kinematics features, documentation of sensory map changes and phantom map subjective linking to specific areas of lost limb as well as qualitative information in the form of a diary, were used to quantify therapy effectiveness.

Primary outcome measure

- McGill pain (short) questionnaire [11]: was used to measure perceived levels of pain experienced by the participant taken at the beginning of the study, at the end of each therapy session.

Secondary outcome measures

- Botvinick's embodiment questionnaire [12]: was used to measure perceived levels of embodiment (limb ownership) that the participant may experience, which is taken at the end of each session.
- Kinematic data: limb movement profiles were captured from the 3 degrees of freedom haptic device and through a tracking system. The data is used examine any effects relating to movement quality (e.g., smoothness, Range of movement).
- Sensory map data: sensory examination of stump prior to sensory stimulation in VR was done and photographically documented before each session.
- Sensory map random recognition data was collected, and consistency of map was analysed.

D. *Procedure*

The participant had his stump supported by the robot against gravity through an arm splint interface (Figure 1). The robot provides limb tracking in 6-dof (position and orientation) and force feedback in 3-dof. Position and orientation data from the robot interface is fed into a custom made inverse kinematic solver, which produces the correct anatomic position and orientation for a virtual avatar of the left upper limb being controlled by the participant's residual muscles. The benefit of an immersive VR approach is that the physical stump movements of the participant can be scaled so virtually it appears as if the participant is moving with full range of movement. The Oculus Rift HMD is used to provide a stereoscopic first-person view of the virtual environment collocated with an avatar head and body position (i.e., one-to-one mapping of the real-world). The participant is not only seeing (via the Oculus Rift HMD) the correct position and orientation of their limb (via the virtual limb), but that they are controlling the reaching and grasping movements and physically interacting with the virtual objects. Each session consisted of two phases:

Firstly, the participant engaged in a simple tabletop game of moving and stacking cubes using their left upper limb. Secondly, the participant observed his missing limb thumb and index finger being stroked with a brush in the VR environment while his stump was simultaneously stimulated at 2.5Hz for 2 minutes in each area with a real paintbrush in attempt to recreate the sensory phantom map of the missing hand on the stump. Questionnaires were taken after this stimulation in order to gauge perceived consistency of the sensory map along with marking on the participant's stump any changes were the participant felt the missing hand on the stump.

E. *Study Timeline*

The participant had an initial meeting in which the study was further explained, and consent was taken. This was followed later by a preparation session used to set up the sensors. An initial pain questionnaire was taken, and initial sensorimotor

examination was performed along with allocation of a pain diary. The intervention was delivered in nine sessions (one hour each, with two hours in total needed considering setting up, breaks and filling questionnaires) over three weeks on an outpatient basis. The McGill and Embodiment questionnaires were taken before and after each session. Sensory map recreation was started in 3rd session once the participant was comfortable with the VR setting and the tasks. Sensory examination was performed before each session and random sensory map recognition data was collected once it was evident that there was a specific sensory representation. All sensor kinematic/kinetic data was automatically collected during each session while performing the exercises. Upon completion of the VR and Robotic therapy sessions (week three), the participants was required to attend follow-ups at week 6 and 12, where the McGill pain questionnaire was repeated. Medication usage and any additional therapies were also be recorded at both 6 and 12 weeks follow ups, and participant was asked to keep a diary throughout the study until the final follow-up to record their subjective assessments. This allowed us to account for any observed variations between sessions and follow ups in terms of pain or additional observations.

III. Results

As shown in Figure 4, a decrease in perceived levels of pain was reported which amounts to a 50% reduction in pain from baseline to session 9 from a baseline score of 3 (out of 5) to 1.5. The participant's perceived pain levels post intervention went up to 2 at the first follow up session (FU1) and remained at that level until the final follow up session (FU2). One comment the participant stated in FU2 was that "(he) didn't think he gets many extremely painful spikes compared to before the intervention", however when pain spikes did occur the duration of the pain spikes were shorter than before. Minimum pain levels around 1-1.5 out of 5 were reported at the end of the intervention, much lower than before participating in the study.

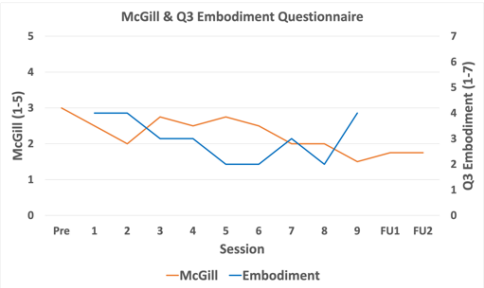

Figure 4 - McGill pain score and embodiment level for the participant

Embodiment fluctuated as did pain levels, with a jump in pain from session 2 to 3. As observed in Figure 4 pain levels did decrease steadily from session 3 to session 9, with a steeper decrease in pain from session 7 onwards. This is also when the participant's embodiment levels increased.

	Baseline - Session 9	Session 9 - Follow Up 1	FollowUp 1 - Follow Up 2
All	-55% (82%)	-7% (86%)	+7% (79%)
Group V	-35% (64%)	-11% (82%)	+15% (63%)
Group VH	-64% (111%)	-5% (89%)	-14% (99%)

Table I - Pre-existing data from Amputees clinical study (VH group received VR with force feedback, V group without force feedback). [N = 12] showing percentage changes from baseline to session 9 (intervention), session 9 to follow up 1 and follow up 1 to follow up 2 [9]. Relative standard deviation as expressed in percent in brackets.

Initial examination of the kinematic data (see Table II) showed that the participant's ROM increased in all axes (from baseline to study completion), transverse movement was not as affected pre study, however significant changes can be seen in ventral and vertical movement.

	Transverse (x)	Ventral (y)	Vertical (z)
Change (cm)	+ 3.8	+19.1	+15.1

Table II- Change in Range of Movement

Sensory phantom map recreation resulted in establishing early on the thumb representation on the stump close to the area being stimulated. The representation of other digits was inconsistent throughout the sessions (see Table III and Figure 5). Subjectively, the participant reported up to 60-70% of feeling resemblance of sensation in the missing thumb during the sensory stimulation sessions. There was marked decrease of thumb representation from 87.5% to 50% after the weekend interruption of sessions, however, it returned to 88% on the next session.

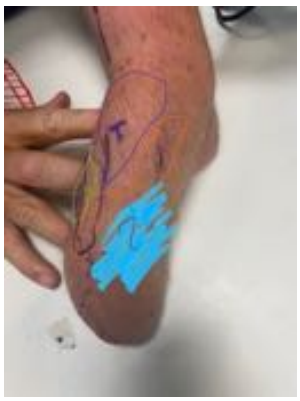

Figure 5 - Sensory phantom map. T (purple) - thumb, I (orange) - index finger, IV (green) - ring finger, ? (blue) - generalised referred sensation of hand with no specific area.

	Sensory stimulation Day 5	Sensory stimulation Day 6	Sensory stimulation Day 7
All digits	40%	25%	37%
Thumb	87.5%	50%	88%

Table III - Random hand map check for consistency. Showing the percentage of times when areas of the stump represented specific digits

IV. Discussion and conclusion

From a technical point of view the system and the intervention yielded positive results with no negative side effects. The results are in line with the outcomes being reported through our study with phantom limb pain (PLP) amputees (see Table I). Two groups were created for the PLP study: a virtual only group (V) and virtual and haptic (force feedback) group (VH). Both groups received identical intervention bar the use of force feedback for the virtual group.

The case study in this paper, is presented with long standing (30 years) complex combination of phantom limb and neuropathic pain. The fact that the participant has a combination of transradial amputation, because of a pan-brachial plexus injury, posed some new challenges for the designed system. Nevertheless, the participant was very active and eager participant. Technical difficulties were overcome by adjusting the system. The participant's ability to actively participate and immerse themselves in the VR interface should be taken into consideration. Participants that take a more active approach to rehabilitation are likely to receive full benefits from the immersive environment.

Immersive Virtual Reality (VR) has a growing supportive evidence base for reducing acute pain in several health care settings such as burn management [13], upper limb stroke [14], PLP [15] and musculoskeletal disorders [16]. In addition to replicating the effects of Mirror Therapy, VR overcomes the limitations of poor imagery and improves the sense of embodiment by combining visual and multisensory cues, allowing the user to interact within a three-dimensional environment as an avatar (a virtual character). To date, very few studies have examined the efficacy of VR for improving chronic limb pain and none have explored its potential for brachial plexus injury (BPI) as proposed in this paper.

Although we cannot ascertain with a single case study that this paradigm could work with BPIs, we are encouraged to proceed to recruit to the study with additional chronic cases but perhaps to be considered in acute patients to potentially stop or lessen maladaptive processes happening. The results seem to suggest that perhaps the use of VR might promote a sensory map within a short time which in turn could be used in future research to enable better control of prosthetics [15] and other such assistive devices, opening avenues for more rehabilitation and greater quality of life for patients with the possibility of such research leading to better pain management.

Based on this, we postulate that the delivery of VR in combination with Haptic (force) feedback will enhance the perception of 'embodiment' resulting in reductions in perceived upper limb pain in patients with BPIs, which are sustained in the longer term. Prior to testing this hypothesis with a future multi-centre RCT, there is firstly a need to obtain preliminary evidence of efficacy (proof-of-principle) for the intervention and to determine the feasibility of delivering the intervention to patients with BPIs.

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