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Design of a Robotic Sensorimotor System for Phantom Limb Pain Rehabilitation*

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Abstract— **The use of robotics in rehabilitation has shown to have a positive outcome when applied to stroke patients and other movement based therapies. Despite recent studies looking at these types of therapies in helping patients with Phantom Limb Pain very few have looked at employing the elements that make robotics successful with stroke patients towards amputees. Phantom Limb Pain affects the majority of amputees, resulting in the need for further study due to the vast range of potential treatments available. This paper examines the effects of Phantom Limb Pain, its treatment, paradigms based on robotic rehabilitation, and provides an outline of a possible therapy method based on an immersive system providing proprioceptive and kinaesthetic feedback to the user while performing a manipulation task.**

I. Introduction

Losing a limb through amputation, regardless of the cause, is a traumatic experience and as a result all attempts are made to salvage the limb [1]. Amputation poses physical effects, such as learning how to live with a prosthesis, the loss of the limb and subsequent pain post amputation. It also affects mental wellbeing such as coping with the limb loss, the psychological trauma and chronic pain effects imposed by phantom/residual limb pain. It is this combination of both physical and mental effects, which makes the subject of amputation, inter disciplinary, and provides a varied range of research topics.

In recent years the issues and exposure of amputation have been accentuated due to prolonged wars such as, the Afghanistan and Iraq campaigns, primarily as a result of improvised explosive devices [2] [3] [4]. This has lead to a spur in research focusing on improving limb salvation via improved battlefield armour, medical procedures and post amputation aspects such as prosthesis design and improved rehabilitation. Although this surge in development is based on military background, the effects are now being transferred to civilian use. This coupled with lessening cost of sensors, computing and robotics combine to create avenues of research that wasn't possible a decade ago. By using various techniques and subject areas, questions that have remained unanswered, such as phantom limb pain could in the foreseeable future yield results [5].

Although the use of robotics in rehabilitation is not new, the use of haptic therapies in the investigation of how cortical reorganisation is affected by phantom limb pain is still in its infancy. This paper focuses on the area of haptic neurorobotics and suggests how therapies based on proprioceptive feedback can be used to treat phantom limb pain and how it can affect cortical reorganisation during rehabilitation.

II. Phantom Limb Pain

The Phantom Limb phenomenon was first coined by Mitchell in 1872, to describe the sensation that an amputated or missing limb (even an organ, like the appendix) is still attached to the body and is moving appropriately with other body parts [6]. Pain as a result of Phantom Limb phenomenon (also called phantom limb pain) and has been reported to be present in 50-80% of amputees with implications to the quality of life of those experiencing the symptoms [7]. Pain can have a negative effect on the rehabiliation outcome due to varied mental/physical symptoms (e.g. wetness/burning/locking sensations) and the lack of evidence explaining why the symptoms persist. Recent work on the diagnosis and treatment methods in Phantom Limb Pain highlights the sensation of pain as overlapping with specific brain areas during movement onset[8]. Previous Phantom Limb Pain treatments have included further amputation of the already amputated limb. Although some of these radical treatments seem to have some positive effects, the Phantom Limb Pain often returns and in some cases more aggressively than before.

Ramachandran and Hirstein's [9] work showed how the plasticity of neurological connections mapped touch and sense affected Phantom Limb Pain. As a result Ramachandra's team conducted a simple experiment with a mirror box, which helped alleviate Phantom Limb Pain both in the short term and long term with some of the participants of the experiment. This has lead to research into virtual mirror box type studies by Cole & Murray [10] to name but a few. Recent work looked at not only replicating Ramachandran's [9] mirror box using virtual reality but also have explored the neurological aspects of the mirror box use,

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using modern imaging techniques such as Magnetic Resonance Imaging [11]. These modern imaging techniques have proved essential [8] into gaining a deeper understanding and interpretation of the unsolved parts of the Phantom Limb Pain phenomenon.

The notion that cortical reorganisation is responsible for phantom limb pain has been put forward by Weeks and colleagues [12] and backed up by studies carried out by Lotze [13] and Flor [14]. Although these studies show a possible origin relating to phantom limb pain, the work carried out by Tsao and colleagues [12] have postulated the concept of proprioceptive memory. This theory is based on the view that the brain keeps possession of a memory of specific limb positions and that post amputation results in a conflict amongst the brain and visual system. This concept is tied into our approach in that we investigate how virtual systems can affect cortical reorganisation.

A recent publication [15] reviewing various phantom limb pain treatments highlight that each mechanism can be triggered by physical sensations, can have psychological/emotional origins (in the case of an amputation) and could also arise from climate-induced triggers, like temperature or changes in weather. These triggers where investigated by Guinmarra and colleagues [5] who have shown the need for optimising stump and neuoma mechanisms to manage spontaneously triggered phantom phenomena.

III. EMBODIMENT

One area related to cortical reorganisation that appeals to Phantom Limb Pain is that of embodiment. Embodiment has been described as the sense of one's own body [16] which when examining the effects of a surrogate limb virtually on the amputee population is an important area to study. Both visual and multisensory cues can lead to embodiment [17][18]. The use of a prosthesis with some amputees who suffer from Phantom Limb Pain has been shown to lower the perceived levels of phantom limb pain. This is due to the phantom limb embodying the prosthesis [19], the two-way interaction of using the prosthesis and therefore controlling the phantom limb, having an effect on the amputee's existing body schema.

Some amputees who use either standard functional or myoelectric prostheses experience vivid Phantom Limb Phenomena [20] but reduced Phantom Pain [21] [22]. Such results can be explained by the fact that once an amputee engages with the prosthetic limb their proprioception extends to embody the prosthesis [5] [23]. Several strategies have been devised to enhance limb embodiment (magnifying the limb seems to increase pain, whereas minifying the limb seems to reduce pain) with virtual realities with varying degrees of success [24] [25]. Most studies however, have shown more vivid embodiment within amputees whose phantom limb is extended and equates to a sensory map on the amputated stump [25]. Paradigms such as the rubber hand illusion have shown to provide the amputee with a greater sense of embodiment if the amputation is recent [26] with further research showing that tactile feedback enhances the embodiment of a prosthetic limb [27]. It is also suggested that proprioceptive feedback enhances targeted motion within upper limb prosthesis control [28].

IV. TRADITIONAL THERAPY APPROACHES

Many treatments and therapy paradigms have existed to lessen or resolve the acute and chronic pain sufferer's experience. These can be broadly grouped into three main categories: symptom specific pharmacological intervention, tailored psychological, physical and behavioural paradigms and surgical interventions [15]. What this shows is the difficultly faced by phantom limb pain treatment research due to the biological regions affected.

Physical, behavioural and psychological treatments (usually integrated into multimodal rehabilitation paradigms can be further broken down as follows:

- Electrical and sensory stimulation - has traditionally been seen as an effective treatment option for phantom limb pain [29]. However the published findings of this type of intervention yield low-level evidence to support its efficacy [30]. On the other hand, sensory stimulation studies have shown reductions in phantom limb pain and correlated normalisation of cortical reorganisation [31] [32] in combination with other multimodal rehabilitation paradigms mentioned below.
- Psychological intervention - the emotional trauma caused by an amputation can trigger and amplify phantom pain. Cognitive behavioural therapy can be used to treat some elements of the pain along-side other paradigms.
- Visual illusions - therapies such as the mirror box therapy have shown to be efficient at phantom pain management, due to the restoration and manipulation of body representations using mirror visual feedback [33]. A recent study has shown that this type of therapy is most effective with long-term patients with muscular type phantom pain [34].
- Phantom movement therapy - mental imagery has been shown to modify the cortical map associated with the amputated limb and to both relieve [35] and worsen [36] phantom pain experienced by patients. Combinations of various movement therapy paradigms yield greater results [37] however the long term effects of these studies have been called into question.
- Prosthesis use and embodiment - has shown to reduce phantom pain due to embodiment [15] [38] [22]. Prosthesis usage has demonstrated that a patient's sense of proprioception extends to embody their prosthesis, however issues arise in that the phantom limb can differ in size related to the prosthetic limb which causes conflict between the perceived and actual limb [39]. Ehrsson and colleges [25] work suggest that embodiment is strengthen for patients whose phantom extends and can be associated to a sensory map on the stump.

One aspect that is clear from the reviewed literature is the need to combine various paradigms in order to provide more effective means of identifying and managing phantom limb pain. At this point the use of robotic therapy and neurorobotics provides opportunities to explore this multi-modal approach, such as combining movement therapy with prosthesis use.

V. OUR APPROACH

Our approach combines the virtual surrogate residual limb (as used in traditional mirror box therapy) with added haptic feedback using a HapticMaster robot [40]. The work with strokes shows some parallels with upper limb phantom limb pain treatment where similar motor acquisition tasks are used. However seeing the missing limb seems to have the biggest effect on reducing pain in amputees. Building on the work carried out with stroke patients, we combine proprioceptive and kinaesthetic feedback through direct physical contact with a haptic device, and map the information from the device to a virtual representation of the physical limb in an application that maintains challenge and interest to the individual. Which we believe will increase levels of embodiment and thus ensure that the therapy paradigm is more effective than previous work, which has focused purely on visual aspects. As shown in section IV, research has been carried out on primarily the visual system which although have shown positive results often are not as effective on stubborn phantom limb pain. As a result we hypothesise that patients who use the combination of visual (3D life like graphics) and haptic feedback will experience much quicker and longer lasting embodiment and resulting pain relief, as opposed to patients who experience the sole treatment of visual but no haptic feedback. An example of how a patient uses our system can be seen in Figure 1.

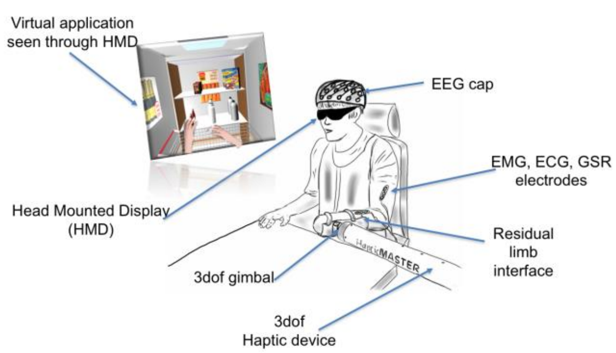

Fig. 1. Illustration showing a user during therapy using the proposed system.

The sensors shown collect both physiological (EMG, GSR, Respiration) and biomechanical (HMD, haptic device, gimbal) data while the user interacts with the system. The patient's residual limb is connected via a custom interface to the haptic device's gimbal that facilitates movements in 6 degrees of freedom (DOF). The system allows for traditional exercises such as the box and blocks test [41] and tasks relating to Activities of Daily Living (ADL) similar to the kettle test [42] to be performed. Grip detection of the residual limb is achieved by the use of EMG pickups. The HMD provides 3D video output to help immerse the patient in the exercises (first person view), an ability that strengthens embodiment and can lead to successful rehabilitation paradigms [11] [43] [44].

VI. SYSTEM ARCHITECURE

The system architecture (Fig. 2) is represented as a closed-loop system where the loop is closed around certain human responses while interacting with a virtual task. Such components are characterised by four main modules.

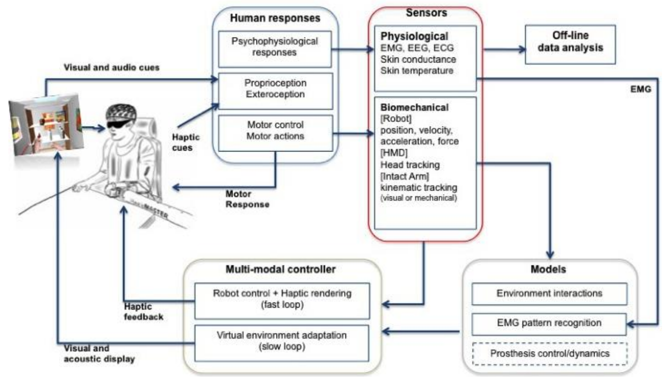

Fig. 2. AMPSIM system architecture overview

A. Human Responses

The human responses represent the user interaction with the system, which takes the various human input from responses to visual, audio and haptic cues from the exercises and results in output from these cues. The resulting data that is logged via the sensors is fed back into the system (via the controllers). These human responses to events during the exercises are logged into a database and are used as event triggers in the offline analysis of the data. A range of haptic effects can be applied to the system such as springs, dampers, biasforces and shakers. The HapticMaster API can also render a range of simple haptic primitives such as blocks, spheres, flatplanes, cylinders and torus, which is broad enough to render everyday objects such as, cans, books, tables etc needed for ADL tasks. The maximum force the HapticMaster can exert is 250N, nominal 100N, which allows the system to provide realistic forces to allow differentiation between, objects such as a solid table and a plastic bottle for example.

B. Sensors

Physiological sensor information is used to quantify psychophysiological responses to the audio-visual and haptic cues provided by the system. Perception of the environment (and from the haptic cues) will invoke proprioceptive and exteroceptive user responses that will result in motor actions and a subsequent response (e.g. movement of the limb, feeling the weight of an object). Possible motor control actions are picked up by a range of different biomechanical sensors present in the robot, by the Oculus Rift [45] HMD and kinematic tracking of the intact/residual limb via AR markers and inverse kinematics. The kinematic tracking of the intact limb is provided via the three gears system [46] which uses a 3D camera pointed downwards to the patient work space to detect and process the intact arm's hand and subsequent hand/finger position and gesture tracking. This allows the system to accurately track and display the intact limb thus delivering a more immersive experience. With

EMG sensors detecting grasp/release with the amputated limb to allow a greater number of tasks, and also to enhance embodiment. This part of the system acts as the throughput from the human responses module and other joining modules.

C. Models

Representations of the environment interactions are used to define behaviour and interaction paradigms upon a certain input (e.g. object to change colour when touched), whereas simple EMG pattern recognition helps identifying motor intention (e.g. move limb, open hand). OpenVibe [47] is used to collect and classify data from the EMG pickups sent via VRPN [48] into the system as well as the database.

D. Multi-modal Controller

The control and interaction loops close around a multi-modal controller consisting of a fast loop (control and haptic rendering) for haptic feedback that runs at an update rate of 2500Hz and a slow loop (virtual environment adaptation) for audio-visual feedback. The virtual environment in which the exercises take place is located in this module, along with the haptic effects, which change the parameters of the environment. The workspace of the HapticMaster is 80.10^{-3} [m^3] which is suitable for simple tabletop ADL tasks.

E. Typical usage

Figure 3 shows the system prototyped, which uses a single Primesense camera for the three gears system and the Oculus Rift to provide a more immersive experience for the user. The screenshots from the right hand side of Figure 3 also show an example of the exercises developed (a simple pick and place exercise). The environment is created using Vizard [48] from WorldViz running on a single windows 7 workstation.

Fig. 3. Healthy user interacting with a pick a place exercise during system development in the lab. Left images show the user wearing a HMD with limb connected to the haptic device. Right images show an example of a virtual exercise.

VII. Future Work

Short to long term clinical trials with the system are underway using two groups of patients. A VR only group and a VR with Haptics group to contrast the results between the two to examine the effectiveness of haptics applied to patients with Phantom Limb Pain. We believe that the latter group will experience a stronger and quicker decrease of perceived pain compared to the former group. In the future we would like to expand the length of the clinical tests as well as examining the cortical reorganisation and other neurological paradigms. Previous studies have highlighted the need for more in-depth examination of neurological effects using robotic based therapy, in order to gain a deeper understanding of Phantom Limb Pain overall. Table 2 highlights how the project can improve on these areas.

Conclusions	Addressed by AMPSIM
Posture affects kinematic recordings of the residual limb[49].	Both the residual and intact limbs position and orientation are tracked using a hybrid kinematic and visual tracking approach.
Long(er) term intervention is required. Most studies consist of short term interventions (a week or two maximum)[15].	The AMPSIM study consists of a two-phase clinical study where the intervention phase will be carried out over a three-week duration and a three-week follow-up to evaluate retention gains.
High quality 3D environments and textures (via a high quality display) are needed to provide a totally immersive experience to the user [50].	The method of display used within AMPSIM not only has very high quality video output but in 3D providing a fully immersive training paradigm. The 3D element is a necessity due to depth perception whilst performing reach and grasp movements.
The majority of current systems do not provide haptic feedback [51], [52], [50].	In order to aid immersion and strengthen embodiment the main interface that connects the user is the haptic device and provides force feedback while interacting with virtual objects.
Often studies focus more on verbal feedback (pain questionnaires) about the effect of pain and do not examine the real-time biological effects of pain [51],[52], [50].	Real time recordings taken during the exercises will aid off line data analysis, with the psychophysiological sensors acting as biomarkers for the recordings. These measures are used in conjunction with standardised pain questionnaires (e.g. McGill pain questionnaire).
The use of multiple psychophysiological sensors are essential to detect cognitive stress during clinical studies [53] [54].	GSR readings have been shown to be a reliable indicator of cognitive stress[55], [56] however as [53], [54] have shown multiple sensors are needed to detect cognitive changes. As well as GSR the AMPSIM clinical studies will also use a respiration sensor to measure changes in breathing.

Table. 2. How the project will address current issues with existing robotic rehabilitation paradigms.

VIII. CONCLUSION

This paper has introduced a system developed to examine the effectiveness of haptic therapies on relieving Phantom Limb Pain in amputees compared to current therapies. We believe that by combining several technologies such as immersive 3D HMD's, accurate intact hand tracking and gesture recognition added to the already proven benefits of robotic therapies, will yield positive results. The complex nature of Phantom Limb Pain has lead to many potential treatments all with various levels of results. The key to a successful treatment paradigm points to a multi modal approach which due to cost or lack of technological advancements have eluded previous treatment success rates. The level of immersive therapy and its subsequent results poses more questions when transferring such paradigms to other movement-based treatments. However more long term studies are required with more emphasis on how these paradigms affect the patient's neurological state both long term.

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