Synopsis of an Engineering Solution for a Painful Problem
Phantom Limb Pain

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Abstract: This paper is synopsis of a recently proposed solution for treating patients who suffer from Phantom Limb Pain (PLP). The underpinning approach of this research and development project is based on an extension of "mirror box" therapy which has had some promising results in pain reduction. An outline of an immersive individually tailored environment giving the patient a virtually realised limb presence, as a means to pain reduction is provided. The virtual 3D holographic environment is meant to produce immersive, engaging and creative environments and tasks to encourage and maintain patients' interest, an important aspect in two of the more challenging populations under consideration (over-60s and war veterans). The system is hoped to reduce PLP by more than 3 points on an 11 point Visual Analog Scale (VAS), when a score less than 3 could be attributed to distraction alone.

1 INTRODUCTION

There are over 55,000 amputees in the UK with 5,000 new patient referrals to prosthetic limb services each year (NASDAB, 2009). The number in Europe is around 700,000. In the US, the estimates reaches 2 million, and the number of lower limb amputations is expected to increase to 58,000 per year by 2030 (Kurichi, 2012) in the US alone. Approximately 70% will develop phantom limb pain (PLP) and in 25% it will interfere with sleep, social activity and work (Davidson, 2010). Phantom limb pain is chronic and intractable. Despite many trials of a wide variety of treatments, few are effective (Flor, 2006). The need for newer, more effective treatments is clear. The populations most effected by PLP in the UK and EU are over 60s with vascular disease, and the war veterans.

PLP is a highly heterogeneous syndrome in terms of its development, frequency, intensity, and quality of pain. Peripheral, central and psychological mechanisms have been proposed as underpinning it. Several theories have been proposed for its development, including peripheral neuroma development and a loss of sensory input per se. After amputation, severed myelinated afferent nerves endings form neuromas, with ectopic neuronal discharges sending atypical messages to the spinal cord evoking stump pain (Karanikolas, 2011). It is noteworthy that stump pain is different from PLP and outside the scope of this research work. More central theories include the development of spinal cord sensitisation (Costigan, 2009) cortical reorganisation and cortical-motor sensory dissociation (Baron, 2010) as well as hypotheses around the body schema, neuromatrix and neurosignature (Diers, 2010). PLP can also be triggered and exacerbated by internal and external psychological factors such as anxiety, depression, self-pity, isolation, emotional distress and attention disorder (Stannard, 2010).

Numerous surgical, pharmacological and non-pharmacological treatments have been used to manage PLP, with limited success in most cases. Although there seem to be several pharmacological targets for PLP, there is inadequate evidence to support the effectiveness of any of the above agents (NICE, 2010). Non-pharmacological treatments fall under three categories: a) psychological interventions, such as eye movement desensitisation and reprocessing, hypnosis, cognitive–behavioural pain management (De Roos, 2010); b) psychophysical, electrical and sensory stimulation, such as acupuncture, sensory discrimination training, EMG biofeedback, TENS, spinal cord stimulation, TMS and electroconvulsive therapy (Giuffrida, 2010); and c) behavioural interventions such as mirror visual feedback, movement imagery, action observation, prosthesis embodiment, and immersive virtual reality (McAvinue, 2011). Treatment of PLP is difficult, and the successful ones employ a wide range of techniques (Black, 2009).

'Mirror Box' therapy was introduced as a new treatment (Ramachandran, 1995) for PLP. With a mirror placed vertically on a table and the missing limb 'hidden' in a cut-out box, the amputee could see the reflection of their normal hand 'superimposed' upon their phantom. Then, as the normal hand was moved, the phantom hand was seen and felt to move, resulting in a reduction of pain. Since then a variety of such illusion-based behaviourally oriented treatments have been used; results, however, remain contentious. In one study that compared mirror therapy, movement imagery and a covered mirror condition, mirror therapy was the only one effective. However, in a larger study (n=80) of mirror therapy, for PLP in the leg, no significant effect over imagery was seen (Brodie, 2007). The practical take-up of physical mirror therapy and motor imagery tasks in clinics is difficult to determine, but informed opinion suggests it is patchy and that mirror therapy whilst helpful for some people is not used by many (*"in part because physical mirror box techniques have practical limitations in the range of movements which are possible"*, Henderson Slater 2012).

Nevertheless, the effectiveness of mirror therapy led to a paradigm shift: rather than thinking in terms of loss of sensory input, Ramachandran's work led people towards considering PLP as being due to a mismatch between sensory input and the brain's innate requirement to command movement. Similar ideas have also been advanced by Mercier and Sirigu (2009), and some have speculated that comparable problems of cognitive mismatch may occur in Chronic Regional Pain Syndrome, and may even be relevant to the rehabilitation of stroke victims. Whether or not these ideas are correct in detail, for PLP at least they are supported in practice by mirror box therapy and similar empirical work. They show, for the first time, that if one gains the 'illusion' that one's amputated limb is present by seeing it, and one can gain a sense of agency for it, by moving it either via a mirror or through motion capture and VR, then one feels it is real.

Therefore, several groups (including the authors of this paper) have developed mirror box-like techniques using computer-generated virtual reality (VR) environments (Cole, 2007). These allow the amputee's remaining limb to control movements of a virtual limb presented in the "phenomenal space" of their phantom limb, which being unconstrained by real world geometry allows more complex movements. The patients have reported a substantial reduction in PLP (more than 3 points on an 11 point VAS, when a score less than 3 could be attributed to distraction alone) (Calderwood, 2009). These are astonishing empirical observations. One theoretical structure into which they fit is the Inverse and Forward Models of motor control derived from engineering principles. The present application thus rests on a combination of results from previous clinical work and theories of motor control overlapping neuroscience and engineering.

2 RESEARCH QUESTIONS

The key clinical questions when the system is operational are, for example: how important is the dimensionality of the virtual environment; what roles, if any, do the quality of the image, the frame-rate, and the graphical realism play in any reduction of pain felt by the patient?

The challenges for the engineers are to determine the best solution to create the necessary dimensionality and the environment that could be accepted as extension the user's real world? In addition, how can existing data acquisition technology capture the movement of the residual stump in relationship to the movement and reflexes of the whole body? How can the emulation of movement of the virtual embodiment accurately correspond to the user's intended action? How can the system be automatically adapted and configured to individual users? Will the employment of robotic limbs in addition to the virtual environment be helpful in reducing pain? What if we allow social networking and usage of technology in the form of group therapy? What are the key human factors that would make the device a suitable therapeutic solution from patients' perspective?

And finally, will the human machine-robot symbiosis in a shared near-real virtual environment (Nervebot) be a complimentary method to other methods in reducing pain?

Despite reports by researchers of its success in reducing PLP (Bohil, 2011), the cost of bespoke hardware, mechanical fragility and lack of flexibility of previous solutions has prevented their use outside controlled clinical environments. The challenge the research team has imposed on itself is to create a robust, customisable solution that builds on our recent successful novel technologies and technical achievements at a low cost for the users. Figure 1 provides an artist impression of Nervebot.

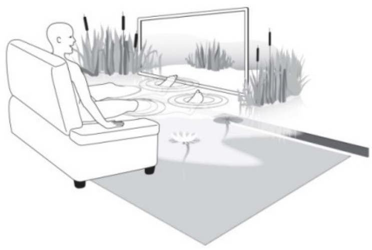

Figure 1: Artist impression of NERVEBOT (Illustrations by Elena Jackson).

3 SYSTEM OVERVIEW

3.1 Human Factors

The creation of innovative interactive technologies to improve the healthcare and well-being of individuals with physical and psychological disabilities or constraints becomes essential (Casale, 2009). The inclusion of a strong human factors approach at the outset for Nervebot was to avoid a "repeat" of the 1990s and early 2000s Virtual Reality (VR) era, where interactive (and particularly so-called "immersive") technologies were often specified in a highly prescriptive, "technology-push" manner, only to fail as a result of a lack of understanding of the perceptual, motor and cognitive qualities of the end user population. Significant statistical evidence demonstrates that "70% to 80% of new product development that fails does so not for lack of advanced technology, but because of a failure to understand users' needs" (Stone, 2004) A human factors (HF) approach provides the assurance that the selection and design of hardware/software interface technology elements (including simulation content, fidelity and interactive styles) results in a system or systems that are appropriately configured for the targeted end user populations and, therefore, are likely to yield reliable evaluation results and rehabilitation outcomes (Von Hippel, 2005). The key HF elements can be listed as follows:

Task Fidelity: the design of appropriate human computer interfaces and behavioural features into the end user's task that support the delivery of the desired rehabilitation effect(s). **Interactive Technology "Fidelity":** the degree to which input (control) and display technologies need to be representative of real life human-system interfaces.

Context Fidelity: the design of appropriate "background" sensory and behavioural detail (i.e. avatar/agent styles and behaviours) to complement – and not interfere with – the task being performed and the rehabilitation outcomes. **Hypo- and Hyper-Fidelity:** the inclusion of too little, too much or inappropriate sensory and/or behavioural detail (task, context and interaction systems) leading to possible negative effects on human performance and, thus, on the reliability of evaluation metrics and outcomes.

3.2 Personalised Motion Tracking

The purpose here is to track and capture the limited movements of the residual limb (Efferent Signals) and interpret them into predicted complete motor functions. These functions are then translated into motion commands (efferent related) to drive the remote robots or the animation of standalone version of Nervebot:

Motion Capture and Interpretation: off-the-shelf motion tracking devices such as the Kinect, Asus Xtion, and LEAP makes motion detection possible and affordable in a home environment. However this new technology is currently designed for able people whose movements are conspicuous and software using it is typically calibrated for tracking four intact limbs. The subtle movement of a residual limb brings a challenge to the current affordable tracking devices. To get around this limitation, two approaches are considered; first, to use an industry standard multiple camera motion capture (MCMC) system to verify and calibrate the accuracy and sensitivity of the tracking devices; and secondly, recognising that human bodies work as an integral biomechanical system. Therefore, a one-off mechanical human motion model that simulates the motion data of individual amputees using motion tracking devices (e.g. camera/accelerometers/EMG) becomes necessary. A presentation of the developed technology can be viewed on (http://www.youtube.

com/watch?v=Q-FuzKsPADU&feature=youtu.be). In this presentation, one can see how the motion capture can work using a single accelerometer and programming on XLINX FPGA. The model uses other intact limbs or if non-existing similar models from other patients to ascertain the simulation parameters. The one-off biomechanical model will help to correct the motions that may be missed by the MCMC. The use of a recently proposed real-time sensitivity analysis method (Tavakoli, 2013) can be investigated to ascertain if it helps to improve the quality of handled signals and data for optimal data processing and used to move the artificial remote robotic limbs.

3.3 3d Holographic Virtual System

The requirements of VIPER are:
Patient specific limb modelling; for increased sense of ownership of the virtual limb by the patient, the limb model should look similar to the patient's amputated limb. **Limb Animation;** to produce realistic animation of the avatar and its limbs, three layer bone-muscle-skin system is introduced (Depledge, 2011). The production-oriented muscle modelling technique developed from our previous research will be used to build the muscle structures. **Motion prediction for the virtual limb;** the Motion Capture Module acquires the motion of the residual stump. The motion of the virtual limb should be deduced from this limited captured data. **Image Rendering;** the rendering capabilities envisaged for the proposed solution will have the features to allow user lead customisation of skin and clothing appearances.

Autostereoscopic imaging system, where a large number of pairs of video signals are recorded and presented on a display that does not require glasses for viewing have been reported and a number of such systems are available on the market. However, such systems tend to cause eye strain, fatigue and headaches after prolonged viewing as users are required to focus on the screen plane (accommodation) but to converge their eyes to a point in space in a different plane (convergence), producing unnatural viewing. Here the employment of 3D holoscopic imaging technology is considered, a vision system inspired from "fly's eye" and is the closest form to holography to be captured in a single aperture camera setup using an array of micro-lenses producing images that are true optical models. For the unique advantages and capabilities of the proposed Holographic image-display processing technology see (Aggoun, 2011). The solution provides a cost effective natural stress-free viewing for the user.

3.4 Adaptable Shared Robotics

The Robostud follows the principles of the Video-Based Restorative Environment (Stone, 2012). The user sees a robot moving in the real world that they can identify with and that will move naturally, with human-like kinematics and dynamics. The anthropomorphic hardware, demonstrated in Figure 2, allows us to offer close to real limb experience for the user. The one of-a-kind fully-humanoid components developed by Shadow are capable of emulating all complex limb actions and movements (see http://www.shadowrobot.com/).

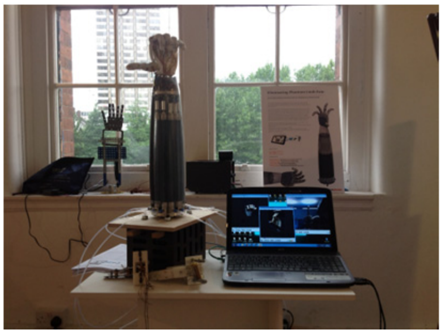

Figure 2: Nervebot, upper limb controlled by motion tracking devices, accessible via the internet.

The physical instantiations of the RoboStud environment is based around the provision of a general "sandbox" for interesting and challenging tasks. This will be based on the design of "black-box" studios in dance or theatre work, where any scenario can be constructed with appropriate props and backdrops. To simplify the implementation, any given RoboStud consists of upper or lower limb work at any time, allowing a "kicking" environment or a "grasping" environment to be set up, using these humanoid robotic components, possibly dressed to appear more "human". In this module the intended movement is translated into *motor commands.* For most users, consider a goal-directed approach where the user generates actions from a selection pre-chosen for the task being performed. Figure 2 demonstrates the capabilities of the designed robotic ambidextrous upper limb, enabled to respond to patient in the studio and remotely via internet.

Converting higher levels of command and control into scenario-directed activity is the key function of the front-end of RoboStud. The robotics studio environment will consist of well-known and easily-detectable objects, allowing simple motion tracking to locate all components of the scenario. The operator inputs will then be used to map onto trajectories and paths between known locations generated by standard motion-planning and grasp-planning software systems. Multiple cameras will be supported by the RoboStud, as well as operator tracking. All kinematic and force control data from the robotic components, as well as additional sensors measuring tactile and other interactions, will be collected and processed for rendering back to the user or users that part of a joint activity online. Immersion and users' connection to the wider social community and environment contribute to the psychological well-being and cognitive functioning of individual's rehabilitation programme. Patients that join the therapy sessions from home (normally in isolation) will have the opportunity to share experience, engage in group games and role plays, that may improve their experience and contribute to the improvement of their PLP.

3.5 System Integration

The purpose of SiMu software is to firstly, integrate the complex hardware technologies into an adaptable seamless human machine interaction device for amputees. Secondly, not to re-invent existing motion capture & interpretation technologies, but to encapsulate and re-interpret the capabilities of existing software and hardware for tracking into the required specification of the proposed networked system. The usage of EventTracker (Tavakoli, 2013) reduces the long latency observed in legacy devices that are not designed for the purpose is being currently studied with result being published in future publications.

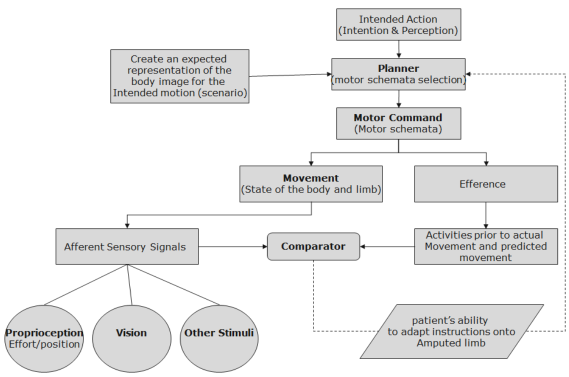

Figure 3: An interpretation of the IFM.

SiMu design is inspired by the Internal Forward Model (IFM) (Firth, 2000) making the solution as adaptable as possible to the condition and requirements of the user. The principles of the model are explained in the following diagrams (Figure 3 and Figure 4). Figure 4 shows the superimposed software modeller and algorithms for simulating the IFM.

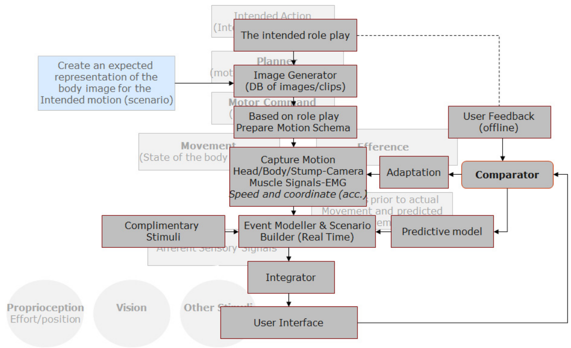

Figure 4: Software algorithm simulates the IFM.

4 CONCLUSIONS

In this paper the authors report on the latest research and development results of a multidisciplinary group of scientists who have embarked on the design and development of an instrument that could help people that suffer from Phantom Limb Pain (PLP). The proposed device will be the integration of a suite of recently developed technologies to serve clinicians for therapeutic purposes. The latest motion capture techniques, 3D multimedia, and intuitive robotics intertwined with an adaptive system build on the Internal Forward Model.

Individual components of the system have been developed, and are going through validation process. The next step is to integrate the components and conduct trials at designated clinics. Subsequently, we hope to be able to introduce the device in patients' treatments in a control laboratory environment, paving the way for larger scale at home.

REFERENCES

Aggoun, A. (2011) Compression of 3D Integral Images Using 3D Wavelet Transform. *IEEE/OSA Journal of Display Technology;* 7 (11): 586- 592.

Baron, R, *et al* (2010). Neuropathic pain: diagnosis, pathophysiological mechanisms, and treatment, *The Lancet Neurology*, 9(8): 807–819.

Black L. M. *et al* (2009). What is the best way to manage phantom limb pain? *Journal of Family Practice*, 58(3): 155–158.

Bohil, C. R., *et al* (2011) Virtual reality in neuroscience research and therapy. *Nature Reviews on Neuroscience*: 2011.

Brodie EE, Whyte A, Niven CA. Analgesia through the looking-glass? A randomized controlled trial investigating the effect of viewing a 'virtual' limb upon phantom limb pain, sensation and movement. *European Journal of Pain* 2007;11:428–436

Calderwood, M. D., *et al* (2009) Adding head tracking to desktop virtual reality with the wii remote as an aid to spatial cognition. In Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization. *APGV, ACM:* 125–125

Cole J. (2007) Virtual & augmented reality, phantom experience and prosthetics. In: Gallagher P, Desmond D, McLachlan M, editors. Neuroprostheses. Springer: 141–153.

Costigan M, *et al* (2009). Neuropathic pain: a maladaptive response of the nervous system to damage. *Annual Review of Neuroscience*, 32: 1–32.

Davidson, J, *et al* (2010) A cross-sectional study of post-amputation pain in upper and lower limb amputees, experience of a tertiary referral amputee clinic. *Disability and Rehabilitation*, 32(22): 1855–1862.

De Roos, C, *et al* (2010) Treatment of chronic phantom limb pain using a trauma-focused psychological approach. *Pain Research & Management*, 15(2): 65-71.

Depledge, M., *et al* (2011). Can Natural and Virtual Environments be used to Promote Improved Human Health and Wellbeing? *Environmental Science and Technology*; 45(11); pp.4659-5064.

Diers, M. *et al* (2010). Mirrored, imagined and executed movements differentially activate sensorimotor cortex in amputees with and without phantom limb pain. *Pain*, 149(2): 296–304.

Firth, C.D. et al, Abnormalities in the awareness and control of actions, Philos Trans R Soc Lon B Biol Sc 2000; 335: 1771-1788.

Flor, H, *et al* (2006) Phantom limb pain: a case of maladaptive CNS plasticity? Nature Reviews | Neuroscience, Vol. 7: 873-881.

Giuffrida O, *et al* (2010) Contralateral stimulation, using TENS, of phantom limb pain: two confirmatory cases. *Pain Med*, 11:133–141.

Karanikolas M, *et al* (2011). Optimized perioperative analgesia reduces chronic phantom limb pain intensity, prevalence, and frequency: a prospective, randomized, clinical trial. *Anesthesiology*, 114(5): 1144–1154.

Kurichi J.E, Bates B.E, Stineman M.G. Amputation (2012). *International Encyclopaedia of Rehabilitation.*

McAvinue L and Robertson I (2011). Individual differences in response to phantom limb movement therapy, *Disability and Rehabilitation*, 33(23–24): 2186–2195.

Melita, J. et al, Phantom Limb pin and bodily awareness: current concepts and future directions, Current Opinion in Anesthesiology 2011; 24, 1-8.

Mercier C and Sirigu A (2009). Training with visual virtual feedback to alleviate phantom limb pain. *Neurorehabilitation and Neural Repair*, 23(6), 587-594.

Ramachandran V.S, *et al* (1995) Touching the phantom limb. *Nature*, 377: 489–490.

Stannard, C, *et al* (2010) Evidence-based chronic pain management. Singapore: Blackwell Publishing, Ltd.

Stone, RJ and McCloy, RF (2004). Ergonomics in Medicine and Surgery. *British Medical Journal*; 328 (7448); pp.1115-1118.

Stone, RJ *et al* (2012) Virtual Restorative Environments: Preliminary Studies in Scene, Sound and Smell; *International Journal of Gaming and Computer-Mediated Simulations*; 4(3) – Ludica Medical Special Issue; In Press.

Tavakoli S. and Mousavi A.**,** (2013) Event Tracking for Real-Time Unaware Sensitivity Analysis (EventTracker), *IEEE Trans. On Knowledge and Data Engineering, 25(2): 348-359.*

Von Hippel, E. (2005). Democratizing Innovation. MIT Press, Cambridge, Massachusetts, USA.

Yu, H.C., Lee, T.Y., Yeh, I.C., Yang, X.S., Li, W.X., Zhang, J.J., 2011. RBF-based Reparameterization Method for Constrained Texture Mapping. *IEEE Transactions on Visualization and Computer Graphics*, 8(7): 1115 - 1124.