Development of a low-cost upper limb rehabilitation system using BCI, eye-tracking and direct visual feedback

A Duenser[1], D Rozado[1, 2], B Howell[1], G Rosolen[1], M Callisaya[3], M Lochner[1], M Cochrane[4]

[1]Data61, CSIRO,
College Road, Hobart, AUSTRALIA / Vimiera Rd, Marsfield, AUSTRALIA

[2]School of Enterprise and Development, Otago Polytechnic,
Forth Street, Dunedin, NEW ZEALAND

[3]Menzies Institute for Medical Research, University of Tasmania
Liverpool Street, Hobart, AUSTRALIA

[4]Faculty of Science, Engineering and Technology, Swinburne University of Technology,
John Street, Melbourne, AUSTRALIA

andreas.duenser@csiro.au, drozado@op.ac.nz, ben.howell@csiro.au, grahame.rosolen@csiro.au, michele.callisaya@utas.edu.au, martin.lochner@csiro.au, cochrane.maddy@gmail.com

[1]*www.csiro.au,* [2]*www.op.ac.nz,* [3]*www.menzies.utas.edu.au,* [4]*www.swinburne.edu.au*

ABSTRACT

We are developing a novel system to improve arm function in stroke patients who have no, or only residual upper limb movement. Such a system fills an important gap in treatment options for people with little-to-no upper limb movement after stroke, and for whom regular treatments often are unsuitable. The system provides real-time visual and proprioceptive feedback of the arm plus the ability for participants to steer the movement direction of the arm through an assistive movement platform. The patient controls the system by simply looking at stimuli and engaging in motor imagery. The patient gaze is monitored with an eye tracker and motor output intentions are monitored with an EEG-based brain computer interface. Stimuli are presented as games in order to create a motivating rehabilitation environment. In this paper we discuss our motivation and design of the system.

1. INTRODUCTION

Stroke is a leading cause of severe disabilities and death worldwide. The number of stroke sufferers and the associated financial costs will increase with an ageing population and the growing incidence of obesity and diabetes. Because there is no cure for stroke, the only method to improve functional movement is through rehabilitation. Approximately 30% of stroke survivors require rehabilitation to regain function. The main mechanism in motor rehabilitation is enhancing the activity of the primary motor cortex, as induced for instance by Active Motor Training (AMT). While effective, current rehabilitation approaches have certain limitations:

- Severely paralysed patients have difficulties using AMT. The patients require at least residual motor performance in the affected limb in order to engage in AMT.
- It is difficult to achieve the high numbers of repetitions necessary for rehabilitation to take effect, and challenging to sustain the patient's motivation in the highly repetitive and monotonous exercises.
- These exercises often require the continuous presence of a physiotherapist or occupational therapist helping the patient to perform the motor exercises. Conventional rehabilitation is very labour intensive and there are considerable costs associated with therapists engaging continuously with the patient during the rehabilitation exercises.
- There is a lack of immediate feedback to the patient.

Combining robotics-assisted rehabilitation with Brain Computer Interfaces (BCI) is a promising way forward. A BCI is a system that monitors brain activity (with electroencephalography (EEG) for example), which is analysed and then used as system input. Movement intent and motor imagery are generally not affected by stroke

(Ang & Guan, 2013). Hence, movement intent can serve as a substitute for AMT as a means to activate the motor cortex (and/or adjacent areas) and to control a BCI.

2. RELATED WORK

BCIs based on movement intent have previously been found to be effective for motor rehabilitation in stroke patients (Ang et al., 2011)(Ang & Guan, 2013)(Daly & Huggins, 2015). Repetitive exposure to a motor imagery EEG-based BCI can affect brain plasticity and induce persistent functional changes in the motor cortex. Pichiorri et al. (Pichiorri et al., 2011) found functional changes in the motor cortex in a group of people undergoing motor-imagery based BCI training. A key aspect of our project is that using a robotics-based BCI to assist with the movement of a person's arm once movement intent has been detected, allows stroke survivors to see and feel their arm moving as they intended and may engage not only the motor cortex of the patient but also adjacent areas in the neocortex such as the sensory cortex. This could play a critical role in the rehabilitation of the neural network engaged in motor control and therefore contribute to improving rehabilitation outcomes.

McCabe et al. (McCabe, Monkiewicz, Holcomb, Pundik, & Daly, 2015) compared treatment outcomes from non-technology assisted motor learning (ML) to ML plus robotics, and ML plus functional electrical stimulation. In a randomised controlled trial all group significantly improved but the authors did not find a significant difference between the three treatment groups.

Many repetitions are required for neuroplasticity to take effect (Verghese et al., 2014). Technology assisted rehabilitation can free up highly specialised therapists and provide patients with long and motivating treatment sessions. This can result in considerable cost savings. Lo et al. (Lo et al., 2010) conducted a cost analysis and found robotics-assisted therapy to be comparable to personal therapy. As general costs of technology tend to decrease and labour costs tend to increase over time, the cost-benefit relationship of technology-assisted therapy most likely will improve as well.

3. SYSTEM DESIGN

3.1 System overview

We are extending previous work by designing a novel combination of technologies that has the potential to increase the system's accuracy, its performance, and to improve feedback to the patient. We are developing an integrated assistive rehabilitation system that uses a patient's gaze fixation to inform the system about the location where the patient intends to move to, uses motor imagery-based BCI to detect movement intent, and employs a mechanical-robotic platform to assist with the movement of the patient's arm to the target location. This system provides a means for automated and assisted high-volume rehabilitation, with simultaneous real-time proprioceptive and visual feedback, even for those with minimal or no residual motor ability.

By combining visual (screen) and movement feedback into a shared reference frame, the patient can see his / her hand moving, while viewing the virtual stimuli at the same time. Most other systems present visual stimuli on a screen at eye level, separated from the actual hand. Our system features stimuli being presented on a screen underneath the patient's moving hand.

The system integrates new interaction paradigms for steering the movement platform. The patient can steer the platform and hence their upper limb to a specific location by simply looking at that location. To achieve this an eye-tracker translates the user's gaze fixation on the screen into x/y coordinates for the target location. This is similar to Frisoli et al. (Frisoli et al., 2012), who have presented a complex system that combines gaze and BCI control of an exoskeleton. In addition to using eye-gaze tracking for target acquisition, we use the eye-gaze as an input for multimodal signal processing which allows for enhanced BCI accuracy. Through combining gaze fixation with the information form the EEG signal we can improve the accuracy of detecting movement intent. In previous work we have shown how combining other eye-gaze parameters (such as real-time changes in pupil dilatation) with the EEG signal can improve BCI accuracy (Rozado, Duenser, & Howell, 2015).

For the collection and time synchronisation of the EEG signals, gaze tracking data and visual stimuli, we use the open source library Lab Streaming Layer (LSL). LSL provides a built-in time synchronisation functionality for recording psycho-physiology data that is designed to achieve sub-millisecond accuracy on a local computer network. Essentially, every collected sample (from the EEG amplifier, gaze tracker or visual stimuli engine) is associated with a timestamp, read off a clock source whose synchronisation is handled by LSL at the time of submission from the device driver to the LSL.

3.2 The prototype system

Our assistive rehabilitation system incorporates a horizontal x-y motion platform. We have developed an orthogonal ball screw and linear bearing arrangement to enable movement over the full extent of a 40″ LED screen. This low-cost platform can move a person’s arm in two degrees of freedom, using one motor per axis to drive a ball screw. The speed and acceleration of each axis is coordinated using proprietary software. Users rest their affected limb on a cradle / wrist guard that is magnetically attached (for easy de-/coupling). This assembly sits on a rod that connects to the movement mechanism at the back of the platform (this setup places the moving parts away from the user). The LED screen presents visual stimuli, ranging from a simple set of static objects that the patient has to reach for (e.g. moving the hand to the location of a cup displayed on the screen) to more complex and motivating games.

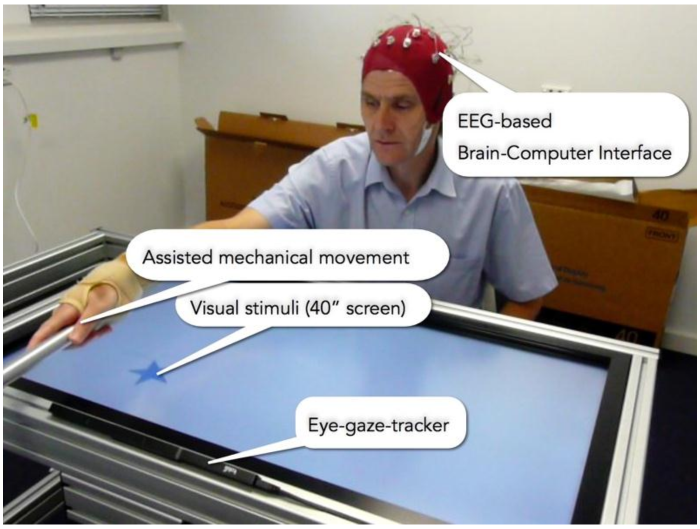

Figure 1. *System prototype***.**

The system locates the patient’s gaze fixation (a particular position being looked at) via an eye tracker (Tobii Eye X). If the gaze position correlates with a presented stimulus, and motor intent to move the upper limb is detected by the BCI, the robotic system assists in moving the patient’s hand to the gaze position. We use a BioSemi ActiveTwo electroencephalography (EEG) amplifier with 32 channels to measure scalp potential, the BCILab library (Kothe & Makeig, 2013) for detecting motor imagery, and the Lab Streaming Layer library for networking, data collation and time synchronisation for EEG and gaze time series streams. An in-house developed software package provides stimulus presentation, trial execution, trial analysis and outputs for controlling the robotics system. (A video showing the functionality the prototype is available on Youtube: http://tinyurl.com/BCI-rehab).

While the combination of eye-gaze tracking and BCI is the main operating mode is for our system, other means of interaction can be integrated in future development iterations. This may include other ways to trigger or initiate movements such as physical switches, voice commands, facial gestures, or other sensors such as EMG, force or positions sensors that can detect even slight movements by the patients. In addition to affording other ways to interact with the system, these sensors also could be used to interactively monitor and measure movements and provide progress feedback to patients and therapists.

To address problems with monotony associated with having to perform highly repetitive movements, we use games to improve patient motivation. For this we are collaborating with serious gaming experts, who have developed unique game concepts for this platform. These games are based on traditional game concepts but have been adapted to suit the platform and target audience. Due to the design of the platform, there are some constraints for game and interaction design ranging from game pace and range of motion (which varies between individuals and may change as a consequence of the intervention) to occlusion of the eye tracker by the patient’s hand. We anticipate that the systematic implementation of suitable game elements and reward systems can promote compliance with therapy regimens.

4. CONCLUSIONS

We present here a technical summary of our work-in-progress on a robotics-assisted BCI-based platform for upper limb rehabilitation. Our implementation is novel in that it allows the patient’s limb and the visual component of the technology to exist in the same reference frame, thus potentially enhancing the effectiveness of assisted rehabilitation. Combining visual stimuli and feedback as well as proprioceptive feedback may have unique benefits compared to previous implementations that mostly separate task and feedback spaces.

We use eye tracking to drive the positional movements of the assistive movement platform and as a means to improve the detection of movement intention. Combining information sources, in this case eye-gaze fixation on a target stimulus and an EEG-based BCI that detects a patient's intention to move, has the potential to improve detection accuracy compared to previous embodiments of similar systems.

Future work on this project will aim towards continually improving the detection and classification of EEG signals, with particular focus on the asynchronous detection of signals. Furthermore, we will continue our research into multimodal signal processing, combining a variety of psychophysiological signals, to improve the detection of movement intent.

Finally, we are in planning stages of a study to test the feasibility of the developed approaches with 10 stroke patients.

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