On Usage of EEG Brain Control for Rehabilitation of Stroke Patients

Tom Verplaetse*, Filippo Sanfilippo†, Adrian Rutle‡, Ottar L. Osen§, and Robin T. Bye§
* Faculty of Engineering and Architecture
Department of Industrial Technology and Construction
Ghent University
Valentin Vaerwyckweg 1, BE-9000 Gent, Belgium
Email: `tom.verplaetse@ugent.be`
† Department of Engineering Cybernetics
Norwegian University of Science and Technology
NO-7491 Trondheim, Norway
Email: `filippo.sanfilippo@ntnu.no`
‡ Department of Computing, Mathematics and Physics
Bergen University College
P.O. Box 7030, NO-5020 Bergen, Norway
Email: `adrian.rutle@hib.no`
§ Software and Intelligent Control Engineering Laboratory
Faculty of Engineering and Natural Sciences
Norwegian University of Science and Technology
NTNU in Ålesund, Postboks 1517, NO-6025 Ålesund, Norway
Email: `{robin.t.bye,ottar.l.osen}@ntnu.no`

KEYWORDS

Motor imagery, brain-computer interface, virtual reality, game-stimulated rehabilitation, low-cost commercial-off-the-shelf products.

ABSTRACT

This paper demonstrates rapid prototyping of a stroke rehabilitation system consisting of an interactive 3D virtual reality computer game environment interfaced with an EEG headset for control and interaction using brain waves. The system is intended for training and rehabilitation of partially monoplegic stroke patients and uses low-cost commercial-off-the-shelf products like the Emotiv EPOC EEG headset and the Unity 3D game engine. A number of rehabilitation methods exist that can improve motor control and function of the paretic upper limb in stroke survivors. Unfortunately, most of these methods are commonly characterised by a number of drawbacks that can limit intensive treatment, including being repetitive, uninspiring, and labour intensive; requiring one-on-one manual interaction and assistance from a therapist, often for several weeks; and involve equipment and systems that are complex and expensive and cannot be used at home but only in hospitals and institutions by trained personnel. Inspired by the principles of mirror therapy and game-stimulated rehabilitation, we have developed a first prototype of a game-like computer application that tries to avoid these drawbacks. For rehabilitation purposes, we deprive the patient of the view of the paretic hand while being challenged with controlling a virtual hand in a simulated 3D game environment only by means of EEG brain waves interfaced with the computer. Whilst our system is only a first prototype, we hypothesise that by iteratively improving its design through refinements and tuning based on input from domain experts and testing on real patients, the system can be tailored for being used together with a conventional rehabilitation programme to improve patients' ability to move the paretic limb much in the same vain as mirror therapy. Our proposed system has several advantages, including being game-based, customisable, adaptive, and extendable. In addition, when compared with conventional rehabilitation methods, our system is extremely low-cost and flexible, in particular because patients can use it in the comfort of their homes, with little or no need for professional human assistance. Preliminary tests are carried out to highlight the potential of the proposed rehabilitation system, however, in order to measure its efficiency in rehabilitation, the system must first be improved and then run through an extensive field test with a sufficiently large group of patients and compared with a control group.

INTRODUCTION

A stroke is a medical condition when blood supply to the brain is interrupted or reduced, usually because a blood vessel bursts or is blocked by a clot (*Stroke, Cerebrovascular Accident | World Health Organization*, 2016). As a consequence, brain cells are deprived of oxygen and begin to die, resulting in a loss of control of muscles that are controlled by the dead area of the brain. The effects of a

Corresponding author: Robin T. Bye.

stroke may vary from minor problems, such as temporary weakness of an arm or leg, to permanently paralysis on one side of the body or losing the ability to speak, depending on which part of the brain is injured and how severely it is affected. Some people recover completely from strokes, but more than 2/3 of survivors will have some type of disability (*What is Stroke? | National Stroke Association*, 2016). A typical result of stroke is monoplegia, where the patient loses control over a single limb, usually an arm.

The focus of this paper is on the development of a first prototype of a rehabilitation system for partially monoplegic patients with a paretic hand. Such patients have not completely lost all motor function of the limb and therefore have the potential for rehabilitation. The main components of our system are a computer application with a game-like 3D virtual environment, and an electroencephalography (EEG) brain-computer interface (BCI) providing control inputs to the application by means of brain waves.

In the following sections, we first provide some background on existing stroke rehabilitation methods, with a particular focus on mirror therapy and game-stimulated rehabilitation; EEG and BCI; the steady state visually evoked potential (SSVEP); and our motivation and aim. We proceed with presenting our proposed method, before turning our attention to the implementation details of our system. Finally, we present some preliminary test results and a discussion of our work.

BACKGROUND

Stroke Rehabilitation

Whilst stroke rehabilitation has come a long way since the early ages of medicine, it is still an active field of research with room for improved methodologies. Before the 1950s, stroke rehabilitation was practically non-existent and damage control was the only approach. Thomas Twitchell was one of the first to accurately describe the possible recovery after a stroke (Twitchell, 1951). He posed that it was possible to achieve full recovery within a certain period of time if stroke patients underwent a suitable rehabilitation programme. Around the same time Signe Brunnstrom developed the Brunnstrom approach (Brunnstrom, 1966; Brunnström, 1970), an approach to determine the stage of the recovery and consequently evaluate different rehabilitation techniques.

As noted by Nudo and Duncan (2004), an increasing number of studies demonstrate the property of neuroplasticity in the brain, with sensorimotor regions of the brain undergoing both structural and functional alterations as a function of use and injury. The development of interventions for stroke rehabilitation have been shown to result not only in adaptive reorganization in the cerebral cortex but may also invigorate recovery in the impaired limb months or years after the stroke (Nudo and Duncan, 2004). A number of various rehabilitation methods and their effects in improving upper-extremity motor control and functioning have been reported in the literature, including exercise training of the paretic arm (Kwakkel, Wagenaar, Twisk, Lankhorst and Koetsier, 1999), impairment-oriented training of the arm (Platz, Eickhof, Van Kaick, Engel, Pinkowski, Kalok and Pause, 2005), functional electric stimulation (Ring and Rosenthal, 2005), robotic-assisted rehabilitation (Masiero, Celia, Rosati and Armani, 2007), and bilateral arm training (Summers, Kagerer, Garry, Hiraga, Loftus and Cauraugh, 2007). However, as pointed out by Yavuzer, Selles, Sezer, Sütbeyaz, Bussmann, Köseoğlu, Atay and Stam (2008), most of the rehabilitation methods that exist for the paretic upper extremity are labour intensive, and require personal interaction and instructions from trained personnel such as therapists for several weeks, which makes it difficult to ensure proper intensive treatment for all patients. In addition, the equipment and systems used in stroke rehabilitation are often expensive, non-portable, and complex, thus requiring being located in a hospital or institution and operated by trained medical personnel.

Mirror Therapy

Contrary to most rehabilitation methods, mirror therapy is a simple, inexpensive, and patient-directed rehabilitation method that has been shown to improve hand functioning when used in conjunction with conventional stroke rehabilitation programmes (e.g., Yavuzer et al., 2008). Yavuzer and colleagues instructed patients to perform wrist and finger extension and flexion movements simultaneously with both their paretic and nonparetic hand, whilst the paretic hand was hidden from sight. While doing the movements, patients watched a mirror image of their normal functioning hand, thus tricking the brain into believing that the paretic hand was actually able to perform the movements. Compared with a control group of patients who received sham treatment, the patients who received mirror treatment significantly improved their motor recovery as measured by Brunnstrom stages.

The findings of Yavuzer et al. (2008) have later been enforced in a metastudy by Thieme, Mehrholz, Pohl, Behrens and Dohle (2013), who examined 14 studies that compared mirror therapy with other interventions, and found that compared with all the other interventions, mirror therapy had a significant effect on motor function, although effects were dependent on the type of control intervention. Thieme and colleagues also found that mirror therapy was found to significantly improve everyday living activities and reduce pain but found limited evidence for improving visuospatial neglect.

Game-Stimulated Stroke Rehabilitation

There are several studies in the literature of using serious games for game-stimulated stroke rehabilitation (e.g., Burke, McNeill, Charles, Morrow, Crosbie and McDonough, 2009*a*,*b*; Alankus, Lazar, May and Kelleher, 2010; Yavuzer, Senel, Atay and Stam, 2008; Vogiatzaki and Krukowski, 2014; Lewis, Woods, Rosie and McPherson, 2011; Joo, Yin, Xu, Thia, Chia, Kuah and He, 2010). Effective stroke rehabilitation requires intensive and repetitive exercises that can be demotivating for the patient, however, game-stimulated rehabilitation can improve patient motivation, enjoyment, and engagement (e.g., Yavuzer, Senel, Atay and Stam, 2008; Lewis et al., 2011; Joo et al., 2010).

For example, Joo et al. (2010) found that using the Nintendo Wii as an adjunct to conventional rehabilitation of patients with post-stroke upper limb weakness was more enjoyable than conventional therapy and showed that there were small but statistically significant improvements in the Fugl-Meyer Assessment and Motricity Index scores.

Another example is that of Yavuzer, Senel, Atay and Stam (2008), who examined the effects of using the Playstation EyeToy Games on upper extremity motor recovery and upper extremity-related motor functioning of patients with subacute stroke. They found that the functional independence measure (FIM) significantly improved in the patients with the EyeToy intervention compared to the control group. However, no significant differences were found between the groups for the Brunnstrom stages for hand and upper extremity.

Another advantage of using serious games is that the therapy can take place in the patient's home, making it easier for the patient to complete the necessary number of exercise repetitions in her own time, and with the game easily customized to the patient's needs and progression (Alankus et al., 2010).

In addition to the use of game development platforms such as the PlayStation and Nintendo Wii mentioned above, the Unity 3D game engine has also been used, as have control interfaces such as Microsoft Kinect, Cyber Glove, Rutgers RMII Master, Leap Motion, Emotiv EPOC EEG, the Viacon camera system, and electromyography (EMG) measurements, and 3D projectors, thus enabling a great variety of game-stimulated stroke rehabilitation methods (e.g., see Vogiatzaki and Krukowski, 2014).

Electroencephalography (EEG)

EEG is an electrophysiological monitoring method that measures the natural electric potential on the scalp (Niedermeyer and da Silva, 2005). Physiologically, EEG power reflects the number of neurons that discharge synchronously (Klimesch, 1999). This electric potential is a result of brain activity and behaves in a periodic, wavelike fashion referred to as brain waves and can be recorded with a portable EEG headset such as the Emotiv EPOC EEG (e.g., Duvinage, Castermans, Petieau, Hoellinger, Cheron and Dutoit, 2013). The brain waves are divided into frequency bands, where each band corresponds to different brain functions. The EEG frequency bands are categorised as the delta ($<$ 4 Hz), theta (4–7 Hz), alpha (8–15 Hz), beta (16–31 Hz), and gamma ($>$ 32 Hz) bands, of which the alpha band, which is active during an alert and cognitive state of the patient (Klimesch, 1999), and the beta band, which is closely related to purposive movement (Niedermeyer and da Silva, 2005), are most important with respect to stroke rehabilitation.

Brain waves and brain wave pattern recognition have been widely investigated in the recent literature. For instance, this technology has been employed for monitoring and prevention purposes, motivated by the fact that there is physiologic coupling of EEG morphology, frequencies, and amplitudes with cerebral blood flow (Ueki, Linn and Hossmann, 1988). Intraoperative continuous electroencephalographic monitoring (CEEG) is an established modality that is used to detect cerebral ischemia during carotid surgery. These facts have generated interest in applying EEG/CEEG in the intensive care unit to monitor cerebral ischemia. There is also evidence that EEG and CEEG add value to early diagnosis, outcome prediction, patient selection for treatment, clinical management, and seizure detection in acute ischemic stroke (AIS) (e.g, Jordan, 2004).

Motor Imagery Brain-Computer Interface (MI-BCI)

In a large clinical study on the ability of stroke patients to use an EEG-based motor imagery brain-computer interface (MI-BCI) presented by Ang, Guan, Chua, Ang, Kuah, Wang, Phua, Chin and Zhang (2011), it was shown how BCI technology has the prospects of helping stroke survivors by enabling the interaction with their environment through brain signals rather than through muscles, and restoring motor function by inducing activity-dependent brain plasticity. The same work presented a clinical study on the extent of detectable brain signals from a large group of 54 stroke patients in using an EEG-based MI-BCI. A clinical study that investigated the ability of hemiparetic stroke patients in operating an EEG-based MI-BCI was also presented in (Ang, Guan, Chua, Ang, Kuah, Wang, Phua, Chin and Zhang, 2010). This work also assessed the efficacy in motor improvements on the stroke-affected upper limb using EEG-based MI-BCI with robotic feedback neuro-rehabilitation compared to robotic rehabilitation that delivers movement therapy.

Recent studies have found distinct cortical physiology associated with contralesional limb movements in regions distinct from primary motor cortex (e.g., see Fok, Schwartz, Wronkiewicz, Holmes, Zhang, Somers, Bundy and Leuthardt, 2011). These findings allow researchers to implement closed-loop interaction systems with valuable kinesthetic feedback for the user. For instance, based on these findings, a BCI that localises and acquires these brain signals to drive a powered hand orthotic was designed and implemented in (Fok et al., 2011). In this work, the patient's hand was guided with appropriate force feedback, thus enabling the hand to open and close.

Steady State Visually Evoked Potential (SSVEP)

Evoked potentials are specific patterns in brain activity which are caused by inputs to the patient from the inside or the outside of the body. These potentials can be recorded through the use of EEG. Steady state potentials are recorded potentials which show a phase, frequency and amplitude that are directly related to the input that caused the potential. If the patient is exposed to an input method which delivers the input at a steady frequency and brain activity is recorded at the same or a related frequency, this brain activity is called a steady state evoked potential. If for example the input in question is a flashing screen placed in front of the patient, it is called a steady state visually evoked potential (SSVEP) (Misulis, Fakhoury and Spehlmann, 2001), and may be used to increase brain activity in certain desired EEG bands.

According to a survey by Zhu, Bieger, Molina and Aarts (2010), BCI systems based on the SSVEP provide a higher level of information throughput and require shorter training than BCI systems using that are not augmented with SSVEP. On the negative side, repetitive visual stimuli modulated at certain frequencies can provoke epileptic seizures or induce fatigue (Fisher, Harding, Erba, Barkley and Wilkins, 2005).

With the increased activation of selected EEG bands, we hypothesise that in line with the previously mentioned properties of neuroplasticity and adaptive reorganization of the cerebral cortex (Nudo and Duncan, 2004), employing SSVEP could result in a faster rehabilitation process.

Motivation and Aim

Most of the stroke rehabilitation methodologies described in previous sections require technical assistance to be provided to the patient by professional and skilled personnel. In addition, these methods typically are dependent on systems and equipment that are normally very costly and therefore only available at specialised medical centres. Hence, patients cannot perform their rehabilitation programmes at home but instead have to physically commute to reach these centres, with accompanying cost, time expenditure, and physical stress. However, as we describe above, stroke rehabilitation methods like mirror therapy and game-stimulated rehabilition are able to counteract some of these drawbacks and improve motor functioning when used as an adjunct to conventional rehabilitation therapy.

Inspired by mirror therapy and game-stimulated rehabilition, our aim is to combine the two and present a first prototype of a flexible and easy-to-use stroke rehabilitation system for the paretic hand consisting of an interactive 3D virtual reality computer game environment interfaced with an EEG headset for control and interaction using brain waves. Our proposed solution is a customisable and extensible low-cost framework that allows patients to perform their rehabilitation programme in the comfort of their house, with potentially no need for human assistance, adapting to patients' progression and skill, and that can be extended to other interfaces and external devices, e.g., a robotic exoskeleton for manipulating the paretic hand.

METHOD

The following sections provide details on the Emotiv EPOC EEG headset, including data acquisition, training of mental commands, 3D modelling of the paretic hand, and a description of the first prototype of a computer application containing the 3D virtual environment using the Unity 3D game engine.

EEG Data Acquisition

The Emotiv EPOC EEG headset is a high resolution, multi-channel, portable system that has been designed for practical research applications (Emotiv, 2016*b*). It has 14 EEG channels with its sensors placed according to the international 10-20 system[1] such that EEG activity from the following brain areas is measured (see Figure 1): AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4. Each channel samples the small variations in electric potential on the scalp with a dynamic range of ±4.17 mV, a resolution of 0.51μV, and at a frequency of 2048 Hz, subsequently filtered and downsampled to 128 Hz (Emotiv, 2016*a*). The EEG signal data are transmitted wirelessly via bluetooth to a USB receiver that connects to a computer.

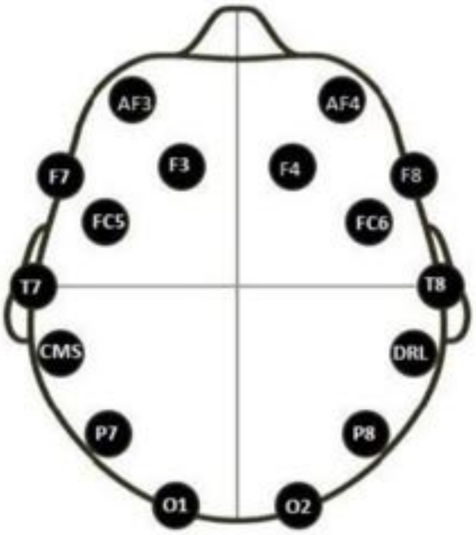

Figure 1: Positions of electrodes.

Training of Mental Commands

Emotiv software is able to perform pattern recognition of the received EEG data, thus building up a library of trained mental commands calibrated to each user of the equipment. Up to four different user-defined commands can be learnt and stored by the software. These commands typically have labels such as 'push', 'pull', 'lift', 'drop', 'left', 'right', however, by employing the application programming interface (API), one is free to access these commands and use them for whatever purpose the software developer finds suitable.

In our case, we used the Emotiv API to interface such commands to Unity for controlling a virtual hand in a 3D virtual environment but restricted to the 2D horizontal plane. In the reaching phase of a hand movement, the commands to be learnt by a user is therefore 'left' and 'right' (along the x-axis) and 'forward' and 'back' (along the y-axis), whereas in the grasping phase, the commands are 'open' and 'close'.

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[1] Wikipedia: http://en.wikipedia.org/wiki/10-20_system_(EEG)

Whilst Emotiv provide their own software training environment (in the Emotiv Control Panel), we have conveniently integrated this environment in our own Unity application. This serves the purpose of making our application standalone, but more importantly, lets us design our own training environment tailored for stroke rehabilitation patients.

It is well known from the literature (e.g., Pfurtscheller, Flotzinger and Kalcher, 1993) that EEG signals will display characteristic changes just prior to making a physical movement. Indeed, Emotiv (2016*b*) make use of this property in their own software, whereby making a facial expression such a lifting an eyebrow or blinking an eye will elicit a particular EEG pattern that the software can easily recognise and convert to a mental command. Therefore, as for mirror therapy, we believe it is crucial that patients try to physically move both the paretic and nonparetic hand while performing EEG training. The purpose of this is to link the particular EEG patterns that emerge when patients move their hands with brain control of the virtual hand.

3D Model of the Paretic Hand

The success of mirror therapy is based on tricking the brain of the patient into believing that the paretic hand moves without any problem when in fact it is just the mirror image of the functioning nonparetic hand that the patient observes. Whilst a 3D virtual representation can never be made as perfect as a mirror image, we hypothesise that by using a virtual hand that is very realistic both in behaviour and in looks, coupled with direct brain control using EEG, we can get a positive effect in rehabilitation similar to that of mirror therapy.

For creating a realistic 3D model of the paretic hand, we used Blender,[2] which is a free and open source 3D creation suite. It supports a variety of 3D modelling aspects, including rigging, animation, simulation, rendering, compositing, and motion tracking. The resulting virtual hand is visually realistic and equipped with an internal set of finger joints that can be accessed and individually controlled by a computer programme. Importantly, however, to be realistic, the virtual joints must programmed to move in a synergy, that is, a coordinated manner, just like real hand. After development, the 3D hand model was imported into Unity.

Unity 3D Application

The Unity 3D application is made up of four different scenes: a main menu, a settings panel, a training environment, and a game rehabilitation environment. Navigation between these scenes is done by using buttons that are readily available during the game. Fig. 2 shows some screenshots of scenes from the application, and how they are connected.

Main Menu: The main menu is the boot scene of the application, and is used to navigate to all the other scenes.

Settings Panel: The purpose of the settings panel is to calibrate the application to have the best possible effect on the patient. There are four different settings: (i) Hand movement speed, which is the speed with which the hand moves in an in the horizontal x-y plane. The faster the hand moves the more difficult it becomes for the patient to control the hand; (ii) The hand close speed, which is the time it takes for the hand to close and grasp target object (a ball, in this case) inside the environment. The longer the hand close speed, the longer the patient has to focus on the close command; (iii) target score, which is the number of objects (balls) the patient must succesfully be able to graps before the game ends; and (iv) SSVEP frequency, which is the frequency with which the screen's background colour will flash in order to evoke the SSVEP. The ideal frequency will have to be determined by physicians, likely through an experimental procedure, in order achieve the optimal level of brain activation.

Training Environment: The training environment has been developed by Emotiv. It is basically the same training environment they use in their own native software but ported to the Unity game platform, thus enabling us to use it as a separate scene in our Unity application. The EEG headset can be set up in this scene and the different mental commands can be trained. Since EEG patterns vary across users, the software stores and maintains a calibrated profile for each user of the headset.

Game Rehabilitation Environment: To limit the initial work, we have only fully implemented a virtual game rehabilitation environment for the left paraplegic hand, and only for a single kind or exercise. The extension to the right hand is straight forward due to the dual properties of the left and right hand and intended for future work. The developed environment can also serve as a template if other limbs need to be considered.

In the game rehabilitation environment, the patient is presented with a top view of the virtual hand and a randomly positioned target object, which in the current implementation is a ball. The purpose of the game is for the patient to move the hand in the horizontal x-y plane. This is achieved by the patient simultaneously sending two mental movement commands (e.g., 'right' and 'forward' for a movement in the positive x and y directions).

When the target is approached, the game view zooms in to a close-up and the hand speed slows. The patient must then send a mental 'close' command in order to grasp the target object. The 'close' command must last for a minimum duration (can be adjusted in the settings menu) for the virtual hand to successfully grasp the object, otherwise, the hand will open and the patient will have to try again.

After successfully having grasped the object, the score counter is incremented and the game resets with the target in a new random position. The exercise is repeated until the desired number of successful reach-and-grasps have been reached (can be adjusted in the settings menu).

Importantly, for both the reaching phase and the grasping phase of the exercise, we hypothesise that the patient should also try to move his physical paretic hand and

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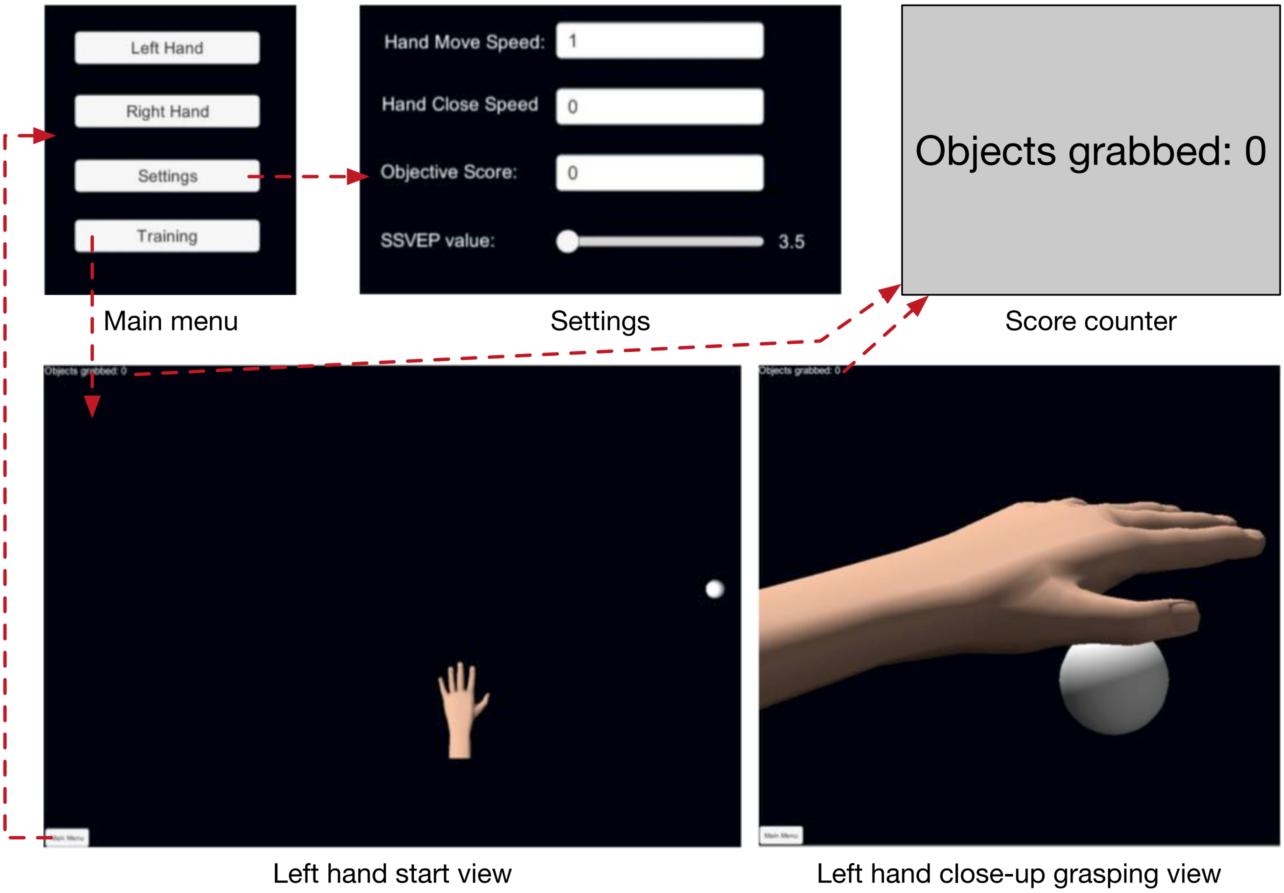
[2] www.blender.org



Hand Move Speed: 1

Hand Close Speed 0

Objective Score: 0

SSVEP value: 3.5

Objects grabbed: 0

Main menu

Settings

Score counter

Left hand start view

Left hand close-up grasping view

Figure 2: Selected scenes from the stroke rehabilitation application: main menu (top left); settings panel (top middle); and game rehabilitation environment, consisting of left hand start view (bottom left), left hand close-up grasping view (bottom right), and score counter (top right).

his well-functioning nonparetic hand, in order for the rehabilitation to get a positive effect similar to mirror therapy.

Finally, we highlight that during the rehabilitation exercise, the background can be set to be constantly flashing between two colours with the purpose of evoking the SSVEP for higher EEG activation and better mental control.

Application Overview and System Diagram

A high-level overview of the application is shown in Fig. 3, which shows how the application is built on top of the Emotiv EPOC EEG headset interfaced by an API with the Unity 3D game engine. Some of the features of the application are highlighted.

The system diagram in Fig. 4 shows the different system modules, data flow and usage modes of the stroke rehabilitation system. The top box in stapled blue line shows modules that provide the system setup. The SSVEP module is used for setting SSVEP parameters such as colours and flashing frequency. Blender is used to create 3D models such as a virtual hand. Data (settings and 3D model) is passed as inputs to the Unity 3D game environment. The game environment is presented to the user via the display. The user's EEG brain waves are sampled by the EEG headset and pattern-matched with a library of brain wave patterns and corresponding actions in order to generate the correct action, which is fed to back to Unity.

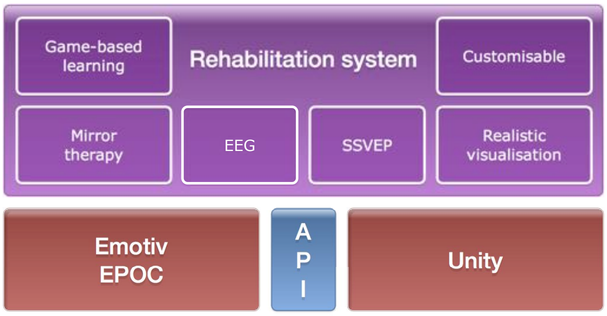


Figure 3: System overview.

PRELIMINARY TEST RESULTS

Having partially monoplegic patients testing this first prototype of our stroke rehabilitation system would have been unethical, as the system needs further development in close cooperation with medical experts before being tested on real patients. Nevertheless, the first author, a healthy 22-year-old male at the time, constantly tested the

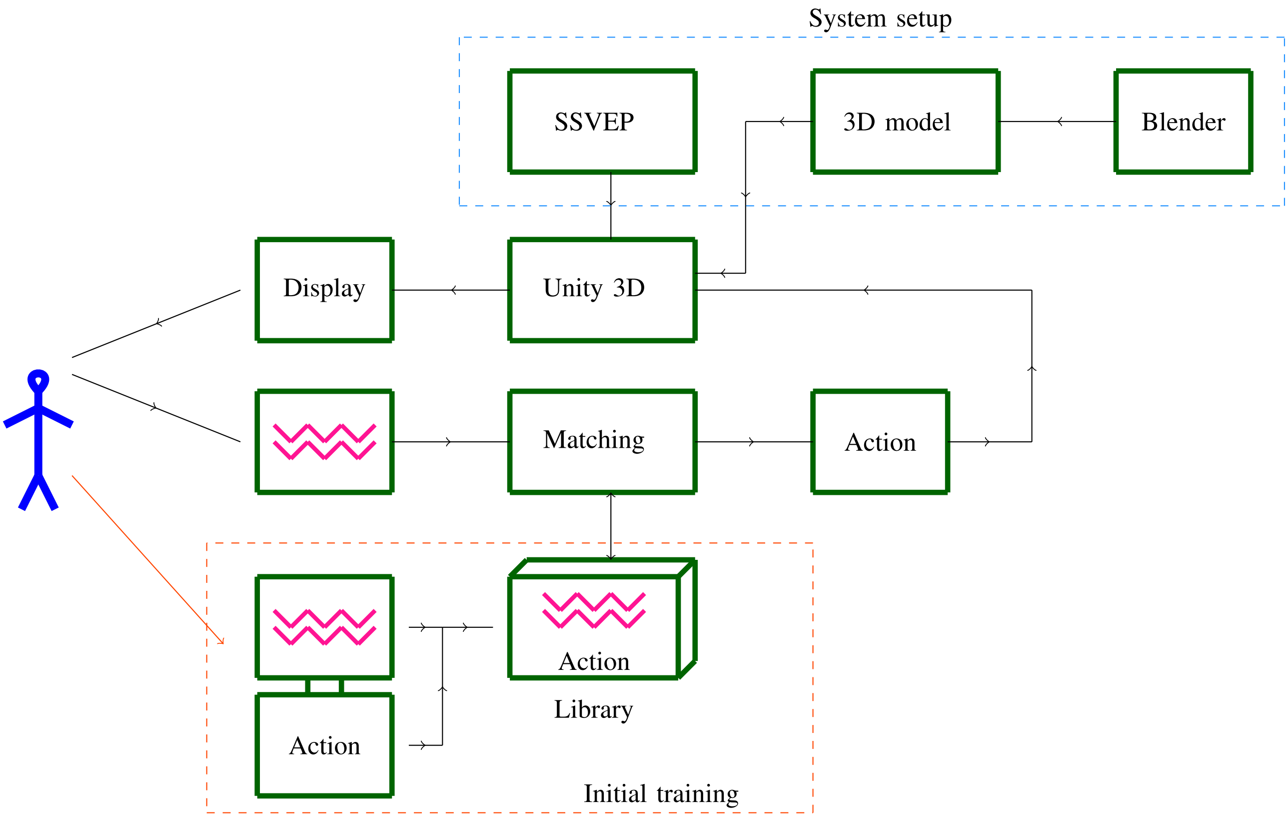


Figure 4: System diagram.

system during development and was able to achieve very precise control of the virtual hand only by using EEG brain waves, that is, without simultaneously moving his physical hands. Had the participant added physical movement we would have likely observed stronger EEG activation, easier brain wave pattern recognition, and even better control. Unfortunately, this was never tested.

To demonstrate proof-of-concept, we report below on the effects of including SSVEP on EEG activation and on game completion time for this single participant. We emphasise, however, that much more testing, under guidance of medical expertise, with a set of different exercises and execution regimes, and with many more participants, both healthy and partially monoplegic patients, is needed before any scientific conclusions can be made.

Effect of SSVEP on EEG Activation

Fig. 5 shows the typical effect on EEG activation with and without SSVEP that we observed for our single participant while performing the stroke rehabilitation game exercise. The effect was present both in early and late stages of testing. The magnitude of brain activity at brain locations is indicated by the spectrum of colours, with the highest activity shown in red and the lowest in blue.

Without the SSVEP, the AF4 and F8 (right frontal lobe) and FC5 (left frontal lobe) regions were the most active in both the alpha and beta bands.

Employing the SSVEP raised the EEG activity markedly across the entire scalp. For alpha waves with SSVEP, the increase in activity was greatest in the right frontal lobe in the AF4, F4, F8, FC6 regions but also the FC5 activity in the left frontal lobe increased. For beta waves with SSVEP, there was a great increase in activity across both frontal lobes (particularly left regions F3, F7, FC5 and

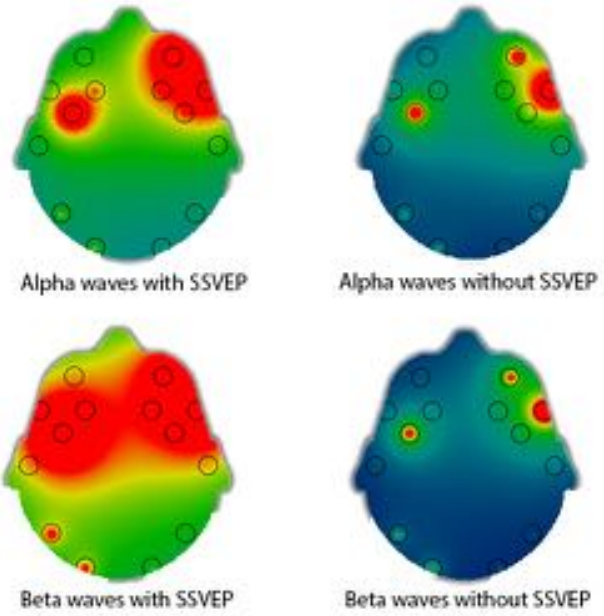


Figure 5: EEG activation with and without SSVEP.

right regions AF4, F4, F8, FC6) but also a marked increase in P7 (left parietal lobe) and O1 (left occipital lobe).

Effect of SSVEP on Game Completion Time

The participant had been using the rehabilitation system extensible before the trials and the effect of improvement due to practice during trials can likely be neglected. The rehabilitation game was configured to finish upon completion of four successful reach-and-grasp exercises. A single reach-and-grasp exercise typically took about half a minute, hence, completing a game would typically take about two minutes. The effect of SSVEP on game completion time is summarised in Table 1.

Trial	Without SSVEP (mm:ss)	With SSVEP (mm:ss)
1	02:04	01:43
2	01:58	01:46
3	02:34	02:06
4	02:16	01:55
5	01:52	01:59
Average	02:09	01:54
St. dev.	00:16	00:09

Table 1: Game completion times with and without SSVEP.

The participant completed the rehabilitation game five times with SSVEP turned on and five times with SSVEP turned off. With SSVEP turned on, the completion time was lower in four trials, whilst the average completion time was 01:54 with a standard deviation of 9 sec. With SSVEP turned off, the average completion time was 02:09 with a standard deviation of 16 sec. Hence, with SSVEP turned on, the average completion time was improved by 15 sec, corresponding to a 12% reduction.

The measurements may suggest that using SSVEP reduces game completion time and its variability as observed by the standard deviation and average completion time, respectively, however, we strongly emphasise that these results are obtained from a single participant and are meant only as an encouragement for further studies when stroke rehabilitation system has been largely improved.

DISCUSSION

This paper has demonstrated fast prototyping of a stroke rehabilitation system consisting of an interactive 3D virtual reality computer game environment interfaced with an EEG headset for control and interaction using brain waves. The system is intended for training and rehabilitation of partially monoplegic stroke patients, was developed over the course of only a few months, and uses low-cost COTS products like the Emotiv EPOC EEG headset and the Unity 3D game engine.

Preliminary testing of a first prototype of the system highlights its potential, however, in order to validate its efficiency in stroke rehabilitation, the system must first be adjusted and improved in close cooperation with medical experts and then run through an extensive field test with a sufficiently large group of patients for comparison with a control group.

COMPARISON WITH EXISTING METHODS

A number of rehabilitation methods exist that can improve motor control and function of the paretic upper limb in partially monoplegic stroke survivors. Unfortunately, most of these methods are commonly characterised by a number of drawbacks that can limit intensive treatment, including being repetitive, uninspiring, and labour intensive; requiring one-on-one manual interaction and assistance from a therapist, often for several weeks; and involve equipment and systems that are complex and expensive and cannot be used at home but only in hospitals and institutions by trained personnel. Mirror therapy, on the other hand, is a simple, inexpensive, and patient-directed rehabilitation method that has been shown to improve hand functioning when used in conjunction with conventional stroke rehabilitation programmes.

Inspired by the principles of mirror therapy, we have developed a game-like computer application in which we deprive the patient of the view of the paretic hand while being challenged with controlling a virtual hand in a 3D game environment only by means of EEG brain waves interfaced with the computer.

We hypothesise that by adopting a rehabilitation scheme similar to mirror therapy, where patients try to physically move their paretic and nonparetic hands whilst using EEG brain waves to control the virtual hand, patients may improve motor control and functioning of their paretic hand.

FUTURE WORK

Whilst our system is only a first prototype, we hypothesise that by iteratively improving its design through refinements and tuning based on input from domain experts and testing on real patients, the system can be tailored for being used together with a conventional rehabilitation programme to improve patients' ability to move the paretic limb much in the same vain as mirror therapy.

Such an improved system would have several advantages over mirror therapy and other conventional rehabilitation methods, namely being (i) game-based and immersive, counteracting laborious and repetitive training exercises and providing a rewarding environment that strengthens and improves rehabilitation; (ii) customisable, allowing for a library of different training exercises not limited by physical equipment; (iii) adaptive and stand-alone, removing the need for instructions from a therapist as the patient progresses and different exercises must be performed; and (iv) extendable, for example by interfacing to a robotic exoskeleton on the paretic limb. In addition, when compared with conventional rehabilitation methods, our system is extremely low-cost and flexible, in particular because patients can use it in the comfort of their homes, with little or no need for professional human assistance.

With respect to extending the system with external physical devices, using Unity as virtual environment enables initial virtual protyping of the devices. That is, a device first be first modelled, simulated, and interfaced and controlled by brain waves inside Unity, before an actual physical device is built and connected to the system.

For example, we could provide the user with valuable kinesthetic feedback by connecting the rehabilitation system to a hand exoskeleton or a low-cost haptic glove, such as the one presented by Sanfilippo, Hatledal and Pettersen (2015). With this integration, the patient's hand may be guided with appropriate force feedback for a more engaging learning experience.

Another example is to use EEG brain waves for controlling a prosthetic hand, similar to the mind-controlled, low-cost modular manipulator system presented by Sanfilippo, Zhang and Pettersen (2015). Such a robotic hand may be used for compensating hand function in chronic stroke patients.

Finally, we would like to draw attention to an accompanying paper we submit concurrently, in which we use a similar system as described here, designed to provide tetraplegic patients a training platform for EEG brain control of a virtual electric wheelchair (Hjørungdal, Sanfilippo, Osen, Rutle and Bye, 2016).

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AUTHOR BIOGRAPHIES

TOM VERPLAETSE received the BSc degree in electromechanical engineering from Ghent University and is currently studying for a MSc in automation engineering at the same university.

FILIPPO SANFILIPPO[3] received the BSc degree in computer engineering from the University of Catania, Catania, Italy, in 2009 and the MSc degree in computer engineering from the University of Siena, Siena, Italy, in 2011. In 2008, he was a Visiting Scholar at the School of Computing and Intelligent Systems, University of Ulster, Londonderry, United Kingdom and in 2010 a Visiting Fellow at the Technical Aspects of Multimodal Systems (TAMS) research group, Department of Mathematics, Informatics and Natural Sciences, University of Hamburg, Hamburg, Germany. In 2015, he received a PhD degree from the Department of Engineering Cybernetics, Norwegian University of Science and Technology (NTNU), Trondheim, Norway. For his PhD studies, he was awarded a research scholarship from the IEEE Oceanic Engineering Society (OES) Scholarship program. He is currently working as a Post-Doctoral Researcher at the Department of Engineering Cybernetics, NTNU in Trondheim, Norway. His research interests include control methods, robotics, artificial intelligence and modular robotic grasping.

ADRIAN RUTLE[4] holds PhD and MSc degrees in Computer Science from the University of Bergen, Norway. Rutle is an associate professor at the Department of Computing, Physics and Mathematics at the Bergen University College, Norway. Rutle's main interest is applying theoretical results from the field of model-driven software engineering to practical domains and has expertise in the development of formal modelling frameworks and domain-specific modelling languages. He also conducts research in the fields of modelling and simulation for virtual prototyping purposes.

OTTAR L. OSEN is MSc in Cybernetics from the Norwegian Institute of Technology in 1991. He is the head of R&D at ICD Software AS and an assistant professor at NTNU in Ålesund.

ROBIN T. BYE[5] graduated from the University of New South Wales, Sydney with a BE (Hons 1), MEngSc, and a PhD, all in electrical engineering. Dr. Bye began working at NTNU in Ålesund (formerly Aalesund University College) as a researcher in 2008 and has since 2010 been an associate professor in automation engineering. His research interests belong to the fields of artificial intelligence, cybernetics, and neuroengineering.

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[3] filipposanfilippo.inspitivity.com

[4] www.rutle.no

[5] www.robinbye.com