COUPLING BRAIN-COMPUTER INTERFACE AND ELECTRICAL STIMULATION FOR STROKE REHABILITATION AND TREMOR REDUCTION IN PARKINSON'S DISEASE

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ABSTRACT
In this paper we describe the design of a novel Brain-Computer Interface (BCI) system for stroke rehabilitation and tremor reduction from Parkinson's disease. Hereby, the combination of EEG driven BCI with electrical muscle stimulation (EMS) is used with the idea to strengthen the sensory-motor feedback loop in order to stabilize the control of the affected extremities. Before testing the system in healthy people and then with patients, a feasibility study is done first, which is described in this paper.

Keywords: BCI, electrical stimulation, stroke rehabilitation and tremor reduction, sensory-motor feedback loop

1. INTRODUCTION
This paper presents the design of a non-invasive EEG-based BCI system for motor rehabilitation after a stroke and for tremor reduction on patients with Parkinson's disease. Rehabilitation therapy helps people with such conditions relearn to perform simple movements. Regular therapies generally involve physical therapy with or without the use of technology.
Robot-assisted arms, Functional Electrical Stimulation (FES) and BCI combined with exoskeleton are examples of technology-based rehabilitation therapies (Ramos-Murguialday, Schürholz, Caggiano, Wildgruber, Carea, Hammer, Halder and Birbaumer 2012). Methods using robot-assisted arms or classic neuro-muscular electrical stimulation require the patient to repeatedly perform a given movement. Over time, this may affect the patient's interest and decrease his motivation. The latter is an important factor on the success of rehabilitation therapy. A lack of motivation will therefore limit the effectiveness of the rehabilitation process. Combining these methods with BCI helps to overcome that problem.
Previous researches have shown the success of FES and EMG-triggered NMES in motor recovery during stroke rehabilitation (Noma, Matsumoto, Shimodozono, Iwase and Kawahira 2014). We propose an EEG-triggered NMES system - that combines BCI with EMS using a VisionBody ExoSuit, - which extracts features from continuously recorded EEG signals, especially the Movement-Related Slow Cortical Potentials (MRCP) related to volitional movement intention (Lew, Chavarriaga, Zhang, Seeck and Millan 2012), and only when an intention to move is detected, the system activates the electrical stimulation to the muscles via the EMS suit to help them contract until the desired movement is produced. The EMS suit is chosen in order to facilitate the application into real world application instead of using stimulators needing high personal efforts to be applied.

1.1. Stroke
Stroke patients are one target group for this kind of stimulation. Stroke occurs when blood flow to an area of the brain is cut off either by blocked or bursted blood vessels. The lack of oxygen in the brain cells will cause them to die, and thus abilities controlled by the concerned area of the brain such as memory or muscle control are lost (Bornstein 2009). Stroke survivors then need to relearn the skills lost by the stroke-affected part of their brain. That is the goal of stroke rehabilitation, which will help them to regain some independence and improve their quality of life (Kwakkel, Kollen and Wagennar 1999). It may involve either regular physical activities or technology-assisted physical activities.
FES has been used with some success to improve motor control in chronic stroke patients (Noma, Matsumoto, Shimodozono, Iwase, and Kawahira 2014). FES is a form of muscle re-education that uses electricity to stimulate weakened muscles and causing them to contract. These electric stimulations can be triggered by EMG, allowing voluntary movement detection from the subjects. Extremely small electrical EMG signals still measurable in paralyzed muscles after the stroke are detected and used to initiate the stimulation of the same muscles, which will result in actual movement (Qu, Xie, Liu, He, Hao, Bao, Xie and Lan 2016).
Lately, EEG-based BCIs for stroke rehabilitation has been the focus of numerous studies. BCIs translate brain activity into control signal of computer or external devices. Recent research on BCI for stroke

rehabilitation shows that they can work as assistive BCI to assist the patient in his daily life, but also as rehabilitation BCI to facilitate neuroplasticity (Sockadar and Birbaumer 2015).
Most research in the area focuses on the control of a robotic device, and consists on attempting repeatedly to perform cue-based movements. The main problem, however, is that this results in a lack of engagement from the subject and an unsatisfying outcome of the training (Bhagat, French, Venkatakrishnan, Yozbatiran, Francisco, O'Malley and Contreras-Vidal 2014). On the other hand, remarkable improvements of motor and cognitive capacities have been noticed in stroke patients who trained daily with a Brain-Machine Interface (BMI) coupled with a goal-directed behavioural therapy (Sockadar and Birbaumer 2015).

1.2. Parkinson's disease

Patients affected by Parkinson's Disease (PD) are another target group. PD is a degenerative disorder of the Central Nervous System (CNS) that affects the motor system. It typically appears between the ages of 50 and 69, and affects the nerve cells in the brain (*substantia nigra*) that produces dopamine (Janvkovic and Tolosa 2007). There is no known cause for primary PD but secondary PD is known to be caused by toxins. To date, there is no cure for this condition. The most apparent and well-known symptom of PD is rest tremor, which appears during rest and affects the patient in his daily living tasks (Grimaldi and Manto 2010; Manto, Topping, Soede, Sanchez-Lacuesta, Harwin, Pons, Williams, Skaarup and Normie 2003). Tremor is the involuntary shaking movement that affects mostly the hands and the head (Janvkovic and Tolosa 2007; Manto, Topping, Soede, Sanchez-Lacuesta, Harwin, Pons, Williams, Skaarup and Normie 2003). It is approximately rhythmic and roughly sinusoidal, with a frequency between 3 and 6 Hz (Grimaldi and Manto 2010).
Tremor has been quite unsuccessfully treated with medication, but has been well controlled by Deep Brain Stimulation (DBS) (Benabid 2003; Limousin and Martinez-Torres 2008). DBS requires electrodes to be surgically implanted into parts of the brain, the *subthalamic nucleus*, the *globus pallidus interna* or the *thalamus*. These electrodes are used to stimulate the brain to inhibit the signals that cause the motor symptoms. Unfortunately, apart from its invasiveness, the process to choose patients for a DBS surgery is very selective (Munhoz, Picillo, Fox, Bruno, Panisset, Honey and Fasano 2016)
Electrical stimulation has the potential to counter the effect of tremors, with the advantage of being non-invasive.

2. TOOLS AND METHODS

Motivation and engagement are important factors that can affect the outcome of stroke rehabilitation training. The goal of this study is to design a non-invasive BCI system that detects the subject's volitional movement intention and provides a feedback in the form of an electrical stimulation to the targeted muscles for rehabilitation; and to detect tremor onset in order to counter its effect by stimulating the muscle responsible for PD patients. In both cases an EMS suit will be used to facilitate the application in real life environments.

2.1. Movement Intention Detection

Voluntary hand and foot movements are preceded by a slowly increasing surface-negative cortical potential called Readiness Potential (RP). The RP, also known as Bereitschaftspotential (BP), is a negative cortical potential that develops beginning 1.5 to 1s prior to the onset of a self-paced movement (Jahanshah and Hallett 2003). It is measured over the primary motor cortex M1 and is maximal over the frontal rather than the occipital area, with amplitudes ranging from 10 to 15 µV. BP amplitude increases with intentional engagement and reduced by mental indifference of the subject. Yilmaz et al. (Yilmaz, Birbaumer and Ramos-Murguialday 2015) investigated movement-related Slow Cortical Potentials (SCPs) in severe chronic stroke patients with no residual paretic hand movement, and found that the SCPs appeared and peaked earlier during paretic hand movement compared to healthy hand movement. Paretic hand movement also elicited larger amplitude over the midline brain while for healthy hand movement, contralateral and midline amplitudes are much larger than ipsilateral activity.
Movement intention is also characterized by a decrease of power in the alpha bands (8 - 15 Hz) and an increase of power in beta bands (16 – 31 Hz) (Bhagat, French, Venkatakrishnan, Yozbatiran, Francisco, O'Malley and Contreras-Vidal 2014; Kornhuber and Deecke 1965; Shakeel, Navid, Anwar, Mazhar, Jochumsen and Niazi 2015; Shibasaki and Hallett 2006).

2.2. Tremor Onset Detection

There are some on-going researches to extract the best parameters from BCIs to detect tremor onset, and differentiate them from voluntary movements. These parameters include Event-Related Synchronization / Event-Related Desynchronization (ERS/ERD), muscle activity and MRCP (Grimaldi and Manto, 2010). In (Wu, Karwick, Ma, Burgess, Pan and Aziz 2010), the authors predicted PD tremor from recorded EMG signal using Radial Basis Function Neural Networks; they found that the tremor onset signal is between 1 and 10 Hz and that the pre-tremor signal contains a large amount of activity between 10 and 30 Hz.

2.3. Signal acquisition

In our experimental set up EEG signals are measured using a 16-channel g.USBamp amplifier at 256 Hz. Electrodes are placed according to the 10-20 system at C3, C4, Cz, F3, F4, and Fz. BCI2000 is used to extract features from the EEG signals and classify them. The experiment is performed using two computers: one for the stimulus presentation and another one for the acquisition and processing of the physiological signals.

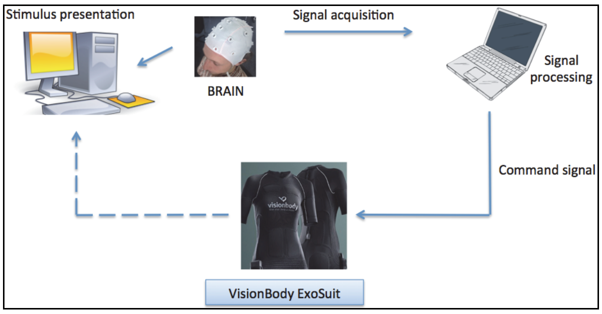

Figure 1: System Design

Fig.1 shows the design of the system. During the experiment, the subject is seated in a chair, in front of a computer screen where the cues are presented using BCI2000. He is asked to avoid moving too much to reduce muscle artefacts. The experiment is divided into two sessions: a system calibration session and a training session.
Each session has a certain number of trials, not too many to prevent fatigue. Each trial starts with a fixation period of 1000 ms, and is composed of 10s of Motor Imagination (MI)/Motor Execution (ME) followed by 3s of rest (Fig. 2). At the end of the fixation period, the subject is asked to wait at least 2s after the cue before attempting to perform a movement. The wait period is to avoid the presence of Contingent Negative Variation (CNV) in the recorded signal (Lew, Chavarriaga, Zhang, Seeck and Millan 2012). CNV is a negative cognitive Event-Related Potential (ERP) component related to expectancy. It peaks 260 to 470 ms after a warning stimulus, which requires a physical or mental response. It is most prominent at the vertex with maximal amplitude of 20 µV (Walter, Cooper, Aldridge, Mccallum and Winter 1964; Nagai, Critchley, Featherstone, Fenwick, Trimble and Dolan 2004).

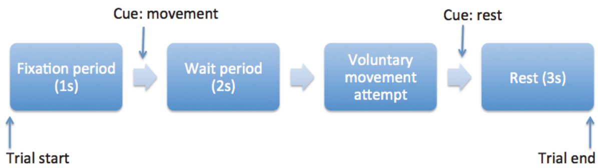

Figure 2: Experimental Setup

During the calibration session, brain signals are recorded during MI/ME, and during rest depending on the cue presented on the screen. The features extracted are MRCP and ERS/ERD of beta and alpha waves respectively. These features are used to train a classifier. During the training session, brain signals are recorded and the same features as in the calibration session are extracted. Volitional movement intention is detected using the trained classifier.
The detection of a voluntary movement or a tremor onset will trigger the electrical stimulation of the VisionBody ExoSuit, with an amplitude chosen between 0 and 50 mA, and a frequency of 20 to 50 Hz. Stimulation is sent by pulses of 0 to 0.5 ms and inter-pulse delays between 10-100 µs (Lee, Lin, Cheng, Wu, Hsieh and Chen 2015; Qu, Xie, Liu, He, Hao, Bao, Xie and Lan 2016; Ono, Mukaino and Ushiba 2013). The electrical stimulation is turned off once the subject reaches the end of the movement.

3. PRELIMINARY RESULTS

As mentioned previously, the aim of this project is to build a system that takes into account stroke and Parkinson's disease patient's motivation during rehabilitation using BCIs combined with a BodyVision ExoSuit that generates electrical stimulation to muscles.
EEG signals are very susceptible to artefacts that come from ocular and/or muscle activity, and from the external environment. First, we want to investigate how the electrical stimulation produced by the VisionBody ExoSuit is affecting the brain signals. This preliminary study is done to assess the feasibility of the project. To do so, we designed an experiment, which consists on simultaneously recording brain signals when the ExoSuit is producing electrical stimulation.
The EEG signals are acquired using a 16-channels g.USBamp amplifier, with 6 electrodes positioned at C3, C4, Cz, F3, F4, and Fz according to the 10-20 system. The ground and the reference electrodes are situated respectively at AFz and FCz (Yilmaz, Birbaumer and Ramos-Murguialday 2015).

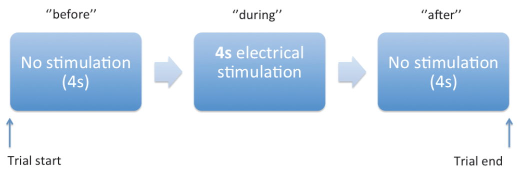

Figure 3: Experimental setup for the interference study.

During the experiment, the subject is wearing the BodyVision ExoSuit. The ExoSuit can be calibrated to deliver electrical stimulation raging from 0% (no stimulation) to 100% (maximum stimulation) on the arms and/or the legs among other locations. This study is done with stimulations ranging from 0 to 35% with an increment of 5% in each trial.
Each trial starts with a 4 seconds period without stimulation ("before") followed by a 4-second electrical stimulation period ("during") and another period without stimulation ("after"), as shown in Fig. 3.

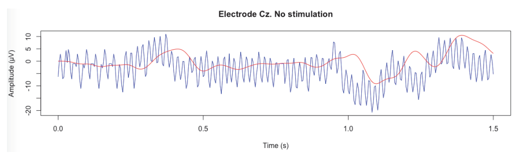

Figure 4: EEG signal recorded without electrical stimulation (ES). Raw signal are in blue, and filtered signal are in red.

Figure 4 shows a portion of EEG signal recorded at electrode Cz without electrical stimulation. The raw signal is presented in blue, while the signal in red represents the EEG signal after a 10 Hz cut-off low-pass filtering.

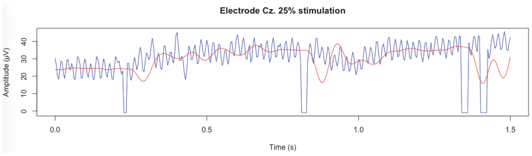

Figure 5: EEG signal recorded during a 25% ES. Raw signal are in blue, and filtered signal are in red.

It appears that starting at 20% ES, rectangular signal bursts arise from the EEG signal. Their amplitudes increase with an increase of the level of stimulation. Figure 5 shows a portion of EEG signal recorded while the BodyVision is delivering a 25% ES. It is reasonable to assume that these bursts are caused by the electrical stimulation, since they do not appear on the EEG signal "before" and "after" said stimulation.

As seen in the figure, the bursts are largely reduced after filtering. And since the characteristics of the electrical stimulation are known, these artefacts could be easily removed using convention artefacts removal methods like independent components analysis .

4. CONCLUSION

The paper describes an EEG-based BCI combined with electrical stimulation for stroke rehabilitation and tremor reduction for Parkinson's disease patients. SCPs are extracted from the recorded EEG to detect the subject's intention to move. Once a movement intention is detected or a tremor predicted, the targeted muscle is electrically stimulated to help the subject produce the movement, or to counter the effect of the tremor. Such system can make it possible to get more positive engagement from the subjects and a better outcome of the stroke rehabilitation process, and to reduce fatigue and improve the daily lives of PD's patients.

First experiments show, that starting at 20% stimulation intensity, the electrical stimulation contaminates the EEG signal with a number of rectangular bursts, but these artefacts are reduced by filtering and could be further removed by existing artefact removal techniques. This suggests the feasibility of the project from a technical point of view. Future direction will involve first healthy subjects, to prove feasibility in general, before targeting stroke patients.

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REFERENCES

Ramos-Murguialday A., Schürholz M., Caggiano V., Wildgruber M., Carea A., Hammer E. M., Halder S. and Birbaumer N., 2012. Proprioceptive feedback and Brain-Computer Interface (BCI)-based neuroprotheses. Plos One 7 (10).

Noma T., Matsumoto S., Shimodozono M., Iwase Y. and Kawahira K., 2014. Novel neuromuscular electrical stimulation system for the upper limbs in chronic stroke patients, a feasibility study. American Journal of Physical Medicine and Rehabilitation 93 (6): 503-510.

Lew E., Chavarriaga R., Zhang H., Seeck M. and Millan J.d.R., 2012. Self-paced movement intention detection from human brain signals: invasive and non-invasive EEG. 34th Annual International Conference of the IEEE EMBS, 3280-3283. 28 August – 1 September 2012, San Diego, California, USA.

Bornstein N.M., 2009. Stroke – Practical Guide for Clinicians. Tel-Aviv. Karger.

Kwakkel G., Kollen B.J. and Wagennar R.C., 1999. Therapy impact on functional recovery in stroke rehabilitation. Physiotherapy Journal 85: 377-391.

Qu H., Xie Y., Liu X., He X., Hao M., Bao Y., Xie Q. and Lan N., 2016. Development of network-based multichannel neuromuscular electrical stimulation system for stroke rehabilitation. Journal of Rehabilitation Research and Development 53 (2): 263-278.

Sockadar S.R. and Birbaumer N., 2015. Brain-computer interfaces in neurorehabilitation of stroke. Neurobiology of Disease 83: 172-179.

Bhagat N.A., French J., Venkatakrishnan A., Yozbatiran N., Francisco G.E., O'Malley M.K. and Contreras-Vidal J.L., 2014. Detecting movement intent from scalp EEG in a novel upper limb robotic rehabilitation system for stroke. 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 4127-4130. 26-30 August 2014, Chicago.

Janvkovic J. and Tolosa E., 2007. Parkinson's disease and movement disorders, 5th edition. Philadelphia, Lippincott Williams & Wilkins.

Grimaldi G. and Manto M., 2010. Neurological tremors: sensors, signal processing and emerging applications. Sensors 10: 1399-1422.

Manto M., Topping M., Soede M., Sanchez-Lacuesta J., Harwin W., Pons J., Williamss J., Skaarup S. and Normie L., 2003. Dynamically responsive intervention for tremor suppression. IEEE Engineering in Medicine and Biology Magazine 2003 (03): 120-132.

Benadib A. L., 2003. Deep brain stimulation for Parkinson's disease. Current Opinion in Neurology 23 (6): 696-706.

Limousin P. and Martinez-Torres I., 2008. Deep Brain Stimulation for Parkinson's disease. Neurotherapeutics 5 (2): 309-319.

Munhoz R.P., Picillo M., Fox S.H., Bruno V., Panisset M., Honey C.R. and Fasano A., 2016. Eligibility criteria for Deep Brain Stimulation in Parkinson's disease, tremor and dystonia. The Canadian Journal of Neurological Sciences Inc. 00: 1-10.

Jahanshani M. and Hallett M., 2003. The Bereitschaftspotential: movement-related cortical potentials. New York, Kluwer Academy/Plenum Publishers.

Yilmaz O., Birbaumer N. and Ramos-Murguialday A., 2015. Movement related slow cortical potentials in

severely paralyzed chronic stroke patients. Frontiers in Human Neuroscience 8: 1-8.
Kornhuber H.H. and Deecke L., 1965. Hirnpotentialänderungen by Willkürbewegungen und passive Bewegungen des Menschen: Bereitschaftspotential und reafferente Potentiale. Pflügers Archiv 284: 1-17.
Shakeel A., Navid M.S., Anwar M.N., Mazhar S., Jochumsen M. and Niazi I.K., 2015. A review of techniques for detection of movement intention using movement-related cortical potentials. Computational and Mathematical methods in medicine 2015: 1-13.
Shibasaki H. and Hallett M., 2006. What is Bereitschaftspotential?. Clinical Neurophysiology 117: 2141-2356.
Wu D., Warwick K., Ma Z., Burgess J.G., Pan S. and Aziz T.Z., 2010. Prediction of Parkinson's disease tremor using radial basis function neural networks. Expert Systems and Applications 37: 2923-2028.
Walter W.G., Cooper R., Aldridge V.J., Mccallum W.C. and Winter A.L., 1964. Contingent negative variation: an electric sign of sensori-motor association and expectancy in the human brain. Nature 203: 380-384.
Nagai Y., Critchley H.D., Featherstone E., Fenwick P.B.C., Trimble M.R. and Dolan R.J., 2004. Brain activity relating to the contingent negative variation: an fMRI investigation. NeuroImage 21 (4): 1232-1241.
Lee Y.-Y., Lin K.-C., Cheng H.-J., Wu C.-Y., Hsieh Y.-W. and Chen C.-K., 2015. Effects of combining robot-assisted therapy with neuromuscular electrical stimulation on motor impairment, motor and daily function, and quality of life in patients with chronic stroke: a double-blinded randomized controlled trial. Jounal of NeuroEngineering and Rehabilitation 2015: 12-96.
Ono T., Mukaino M. and Ushiba J., 2013. Functional recovery in upper limb function in stroke survivors by using BCI: a single case A-B-A-B design. 35th International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS), 265-268. 3-7 July 2013, Osaka, Japan.