Usability of the Combination of Brain-Computer Interface, Functional Electrical Stimulation and Virtual Reality for Improving Hand Function in Spinal Cord Injured Patients

Manuel Bayon-Calatayud, Fernando Trincado-Alonso, Eduardo López-Larraz, Luis Montesano, José Luis Pons and Ángel Gil-Agudo

Abstract This work assesses the usability of a system that combines a brain-computer interface, a functional electrical stimulator and a virtual feedback with the aim of promoting neuroplasticity. The system has been tested in a patient with C5 D ASIA spinal cord injury, who performed 5 sessions with the device as well as exertion, clinical and usability tests.

1 Introduction

Brain-computer interface (BCI) is a technology that allows the development of a direct communication channel between the human brain and machines from electroencephalographic (EEG) signals.

M. Bayon-Calatayud (✉)
Physical Medicine and Rehabilitation Department,
Complejo Hospitalario de Toledo, SESCAM, Toledo, Spain
e-mail: mrbayon@sescam.jccm.es

F. Trincado-Alonso
Biomechanics and Technical Aids Department,
National Hospital for Paraplegics, Toledo, Spain
e-mail: fernandotrin@gmail.com

E. López-Larraz · L. Montesano
Departamento de Informática en Ingeniería de Sistemas,
University of Zaragoza, Saragossa, Spain
e-mail: edulop@unizar.es

L. Montesano
e-mail: luis.montesano@gmail.com

J. Ibáñez et al. (eds.), *Converging Clinical and Engineering Research on Neurorehabilitation II*, Biosystems & Biorobotics 15,
DOI 10.1007/978-3-319-46669-9_56

Virtual reality (VR) is a useful tool that coupled to BCI could help subjects to control body movements in a simulated environment, providing more challenging and motivating tasks that may be suitable for rehabilitation. Functional electrical stimulation has been traditionally used for recovery of motor function in neurological disorders. Several neuroprostheses have been developed for tetraplegics in order to substitute absence of hand motor functions such as grasping [1].

BCI has been proposed to control FES in order to allow functional hand grasping in patients with tetraplegia [2].

The aim of this study is to analyze validity and usability aspects of BCI-FES-VR training to improve hand motor function of grasping in a tetraplegic patient.

2 Materials and Methods

2.1 Material

Three different technologies are involved in this experiment: BCI, functional electrical stimulator (FES) and virtual reality system (VR). The BCI system is synchronized with the FES and the VR device, throughout a high level controller, which allows activating both of them at the same time that the subject performs a movement attempt (MA).

For the BCI part, a commercial system was used to record EEG signal of the subject (g.Tec GmbH, Graz, Austria), with 32 channels. The sample frequency was 256 Hz.

The MA was decoded by using a one-second-long sliding window with a sliding step of 250 ms between −4 and −1 s for the rest period and between 0 and 3 s for the MA period (considering 0 as the instant when the MA cue is displayed). An automatized procedure based on z-scores was used to remove the trials containing artifacts [3]. The EEG features used to train and classify were Event Related Desynchronization (ERD) and Motor Related Cortical Potentials [4, 5]. Both features were used simultaneously as inputs for the classifier. A sparse discriminant

E. López-Larraz · L. Montesano
Instituto de Investigación en Ingeniería de Aragón (I3A),
Saragossa, Spain

J.L. Pons
Neural Rehabilitation Group, Spanish National Research
Council (CSIC), Madrid, Spain
e-mail: jose.pons@csic.es

Á. Gil-Agudo
Biomechanics and Technical Aids Department. Physical Medicine
and Rehabilitation Department, National Hospital for Paraplegics, Toledo, Spain
e-mail: amgila@sescam.jccm.es

analysis (SDA) was used to select the most discriminant features comparing rest and MA classes [6].

The FES consisted in a commercial stimulator (Technalia S.L., Spain). Forearm muscles were stimulated using 2 electrodes and one for reference, with the aim of eliciting a grasping movement.

The VR displays a virtual hand closing and opening in a first person point of view, with the objective of providing an additional visual feedback to reinforce both the learning of the task and the neuroplastic effects, based on mirror neurons theory [7].

2.2 Protocol

Inclusion criteria included patients with an incomplete spinal cord injury (C or D ASIA), certain degree of voluntary wrist movement (flexion- extension) but no voluntary motor function on fingers, age between 16 and 75 years old, neuromuscular responsiveness to FES, modified Ashworth scale (MAS) score below 3 and absence of cognitive impairment. Exclusion criteria included severe spasticity, upper extremity restricted range of motion, pressure ulcers, and severe osteoporosis.

This is a case study of a 55 five year old male with a spinal cord injury level C5 ASIA D. Time since injury was 4 months. Participant signed a written informed consent.

Neurological lesion level was assessed by the ASIA impairment scale. Before training, spasticity was assessed by MAS scale. Activities of daily living (ADL) performance was assessed pre-post BCI-FES-VR training with the spinal cord Independence measure (SCIM) scale, as well as hand grasping by the GRASSP scale (Graded and redefined assessment of strength, sensibility, and prehension) [8].

The training with the BCI-FES-VR system consisted in 5 sessions, approximately of one hour of duration, performed in different days within an interval of 10 days. Each session is composed of blocks of 20 trials in which the patient was seated in front of a screen where the virtual hand was displayed, and the FES electrodes were placed on the arm. In every trial the subject performed MA of his hand, receiving 2 s of FES and virtual feedback when the system correctly detected the attempt. Each repetition started with 10 s of rest, followed by 3 s of MA. If the BMI detected the motion intention in the MA interval, the patient was stimulated, otherwise the next repetition started.

The patient performed 1 h of occupational therapy simultaneously to the study with both hands, while he only performed BCI + FES + VR training with the intervention arm.

Exertion during BCI-FES-VR training was evaluated by Borg scale. Finally a usability questionnaire of the BCI-FES-VR procedure was administered to the patient.

3 Results

Quantitative prehension improved in participant`s intervention arm from 20 to 24 points with a pre-post-treatment difference of 4 points, while control arm prehension score was 28 points before and after treatment. There were no differences regarding strength and sensation between intervention and control arms. Participant´s ADLs performance measured by SCIM scale improved after intervention from 28 to 42 points. Exertion perceived by participant during BCI-FES-VR training was scored 6 in Borg scale (“very, very light”). Participant scored BCI-FES-VR in a usability test as a useful tool, being easy to understand how to manage the controller for using the application, and more engaging and motivating than exercises done before. The averaged accuracy obtained by the patient during the 5 sessions was 85.8 ± 11.8 %.

Finally, participant considered that he could benefit from using this kind of applications in therapy.

4 Discussion

Prior studies have demonstrated feasibility of the integration of an EEG-based non-invasive BCI with FES systems in order to restore walking [9] and lower extremity paralysis [10]. In this study, preliminary results suggest that BCI-FES-VR systems provide moderate improvements on prehension and hand function, and may be used for neurorehabilitative purposes after SCI. It may be possible that BCI-FES-VR systems facilitate cortical excitability and brain plasticity mechanisms. Integration of virtual reality could provide a powerful sensorimotor feedback and a challenging and not boring environment for training. Nevertheless some limitations could be raised to these systems. These applications may not be useful to restore hand sensation during prehension. Furthermore, these systems can induce mental and physical demands that require an appropriate assessment with specific scales (Borg exertion scale, NASA-TLX scale). Limitations of usability could be saved by perception of good clinical effectiveness that reduces frustration, and a user-centered design with dry electrodes, more comfortable caps with wireless signal acquisition systems [11].

5 Conclusions

The BCI + FES + VR device is easily usable in a clinical environment and future studies with a larger sample size are required to show the efficacy of the therapy with this kind of systems.

Acknowledgments This work was supported by the Spanish Ministry of Economy and Competitiveness [projects HYPER-CSD2009-00067 CONSOLIDER INGENIO 2010, DPI2011-25892, DGA-FSE (group T04)].

References

1. S. Mangold, T. Keller, A. Curt, V. Dietz, Transcutaneous functional electrical stimulation for grasping in subjects with cervical spinal cord injury. Spinal Cord **43**(1), 1–13 (2005)
2. G. Müller-Putz, R. Scherer, G. Pfurtscheller, R. Rupp, EEG-based neuroprosthesis control: a step towards clinical practice. Neurosci. Lett. **382**, 169–174 (2005)
3. C. L. Maeder, C. Sannelli, S. Haufe, B. Blankertz, Pre-stimulus sensorimotor rhythms influence brain—Computer interface classification performance. 653–662 (2012)
4. E. López-Larraz, L. Montesano, Á. Gil-Agudo, J. Minguez, A. Oliviero, Evolution of EEG motor rhythms after spinal cord injury: a longitudinal study. PLoS ONE **10**(7), e0131759 (2015)
5. E. López-Larraz, F. Trincado-Alonso, L. Montesano, Brain-machine interfaces for motor rehabilitation : Is recalibration important ? in *IEEE International Conference on Rehabilitation Robotics (ICORR)*, pp. 223–228 (2015)
6. E. López-Larraz, L. Montesano, A. Gil-Agudo, J. Minguez, Continuous decoding of movement intention of upper limb self-initiated analytic movements from pre-movement EEG correlates. J. Neuroeng. Rehabil. **11**, 153–167 (2014)
7. G. Rizzolatti, M. Fabbri-destro, L. Cattaneo, Mirror neurons and their clinical relevance. Nat. Clin. Pract. Neurol. **5**(1), 24–34 (2009)
8. S. Kalsi-Ryan, A. Curt, M.G. Fehlings, M.C. Verrier, Assessment of the hand in tetraplegia using the Graded Redefined Assessment of Strength, Sensibility and Prehension (GRASSP). Top Spinal Cord Inj. Rehabil. **14**(4), 34–46 (2009)
9. C.E. King, P.T. Wang, C.M. McCrimmon, C.C. Chou, A.H. Do, Z. Nenadic, The feasibility of a brain-computer interface functional electrical stimulation system for the restoration of overground walking after paraplegia. J. Neuroeng. Rehabil. **12**(1), 80 (2015)
10. A.H. Do, P.T. Wang, C.E. King, A. Abiri, Z. Nenadic, Brain-computer interface controlled functional electrical stimulation system for ankle movement. J. Neuroeng. Rehabil. **8**, 49 (2011)
11. M. Bayón-Calatayud, F. Trincado-Alonso, Á. Gil-Agudo, I. Dimbwadyo-Terrer, A. Benavente-Valdepeñas, M. Del Alamo-Rodriguez, Usability of non-invasive brain computer interface systems for upper limb recovery after stroke. Eur. J. Phys. Rehabil. Med. **50(**Suppl. 1)(3), 4–63 (2014)