To improve upper-limb neuro-rehabilitation in chronic stroke patients we apply new methods and tools of clinical training and machine learning for the design and development of an intelligent system allowing the users to go through the process of self-controlled training of impaired motor pathways. We combine the brain–computer interface (BCI) technology with a robotic arm system into a compact system that can be used as a robot-assisted neuro-rehabilitation tool. (B) We use mirror therapy (MT) not only to improve motor functions but also to identify subject’s “atoms,” i.e. spectral-spatial EEG patterns associated with imagined or real-hand movements, using parallel factor analysis. (D) We designed and tested a BCI-based robotic system using motor imagery in a patient with an impaired right upper limb. The novelty of this approach lies in the control protocol which uses spatial and spectral weights of the estimated sensorimotor atoms during the MT sessions.

Study Design

Mirror therapy (9-months), is an innovative treatment approach where an individual rehearses a specific limb movement by reflecting the movements of the non-parietic side in the mirror as if it were the affected side [1]. A link between motor imagery and passive action observation was found and associated with the concept of mirror neurons [2].

Oscillatory Rhythms

PARAFAC - EEG "Atoms," logarithmically transformed power spectra densities (PSD) of EEG segments are analyzed by three-way parallel factor analysis (PARAFAC) [3, 4]. Define a 3-dim. data matrix $X$ (i x j x k) of PSD estimates at $t$ time segments, $J$ electrodes and $K$ frequencies. Then, three loading matrices, $A$, $B$, and $C$ with elements $a_{ijt}$ (time scores), $b_{ikj}$ (spectral weights) and $c_{ijk}$ (spatial weights) define the PARAFAC model which decomposes $X$ as

$$x_{ijk} = \sum_{t=1}^{T} a_{ijt} b_{ikj} c_{ijk} + e_{ijk},$$

where $x_{ijk}$ are elements of $X$, $e_{ijk}$ are the residual errors and $F$ stands for a number of components (atoms). The loading elements are found by minimizing the sum of squares of $e_{ijk}$.

$$\min_{i,j,k} \sum_{t=1}^{T} e_{ijk}^2 = \sum_{t=1}^{T} a_{ijt} b_{ikj} c_{ijk} + e_{ijk}^2$$

BCI-Controlled Robotic Splint (18 months), following the recommendations of a clinical expert, we designed and constructed a robotic splint (with one degree of freedom). The splint is controlled using the time scores of the selected atoms extracted from EEG recorded during the MT sessions. Flexible score thresholds can be set.

Clinical & Behavioural Results

A clinical evaluation of the subject’s upper limb movement abilities was carried out. The undertaken clinical tests indicate a slight improvement in movement and spasticity of the arm but without a detectable functional improvement. The subject was not able to stand and was not able to walk. The subject entered the study as late as two years after stroke with severe pleget hand. Subjectively, we observed an improvement in subject’s speech and social communication, but this was not clinically tested. The subject showed strong enthusiasm to participate.

Conclusions

To our knowledge, this is the first longitudinal study (over 9 months long) of the mirror-box therapy showing effects on the modulation of sensorimotor EEG oscillatory rhythms. We observed significant short-term (2 week session pre- and post-training) and longer-term EEG effects lasting from days to days as well as spanning the whole period of the experiment. Analysis of the EEG data recorded during the mirror therapy sessions reveals stable day-to-day space-spectral atomic EEG representation of dominant sensorimotor oscillatory rhythms. The atomic representation of EEG allowed us to develop and test an efficient and flexible BCI protocol for the control of the constructed robotic splint for neuro-rehabilitation. Longitudinal robotic splint training of a 58-years-old man who had a right-hand hemiplegia due to an ischemic stroke is promising and although it is a single case study, it is used as a proof of concept, not as a population based statistical proof. Clinical efficiency of this procedure requires further evaluation by considering a wider, clinically heterogeneous population of patients with motor impairment.

References


Acknowledgement

The work was supported by the Slovak Research and Development Agency (projects APVV-16-0202 and APVV-0566-12) and by the Slovak Grant Agency for Science for projects VEGA-2-0011-16 and VEGA 2-0151-18.