Brain–computer interface with robot-assisted training for neuro-rehabilitation

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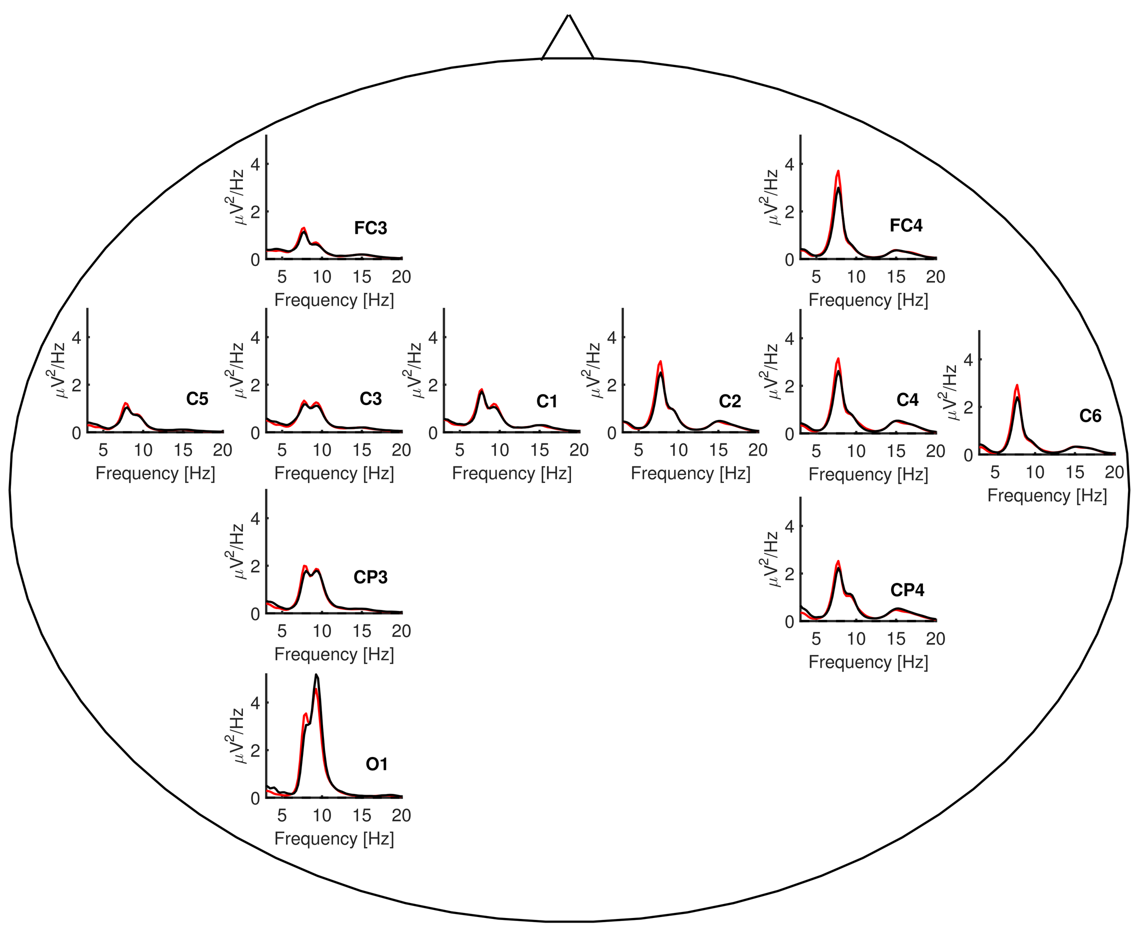
Summary

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: **(1)** We use mirror therapy not only to improve motor functions but also to identify subject's "atoms", i.e. specific EEG patterns associated with imagined or real-hand movements, using a parallel factor analysis. **(2)** We designed 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 frequency weights of the estimated sensorimotor atoms during the MT sessions.

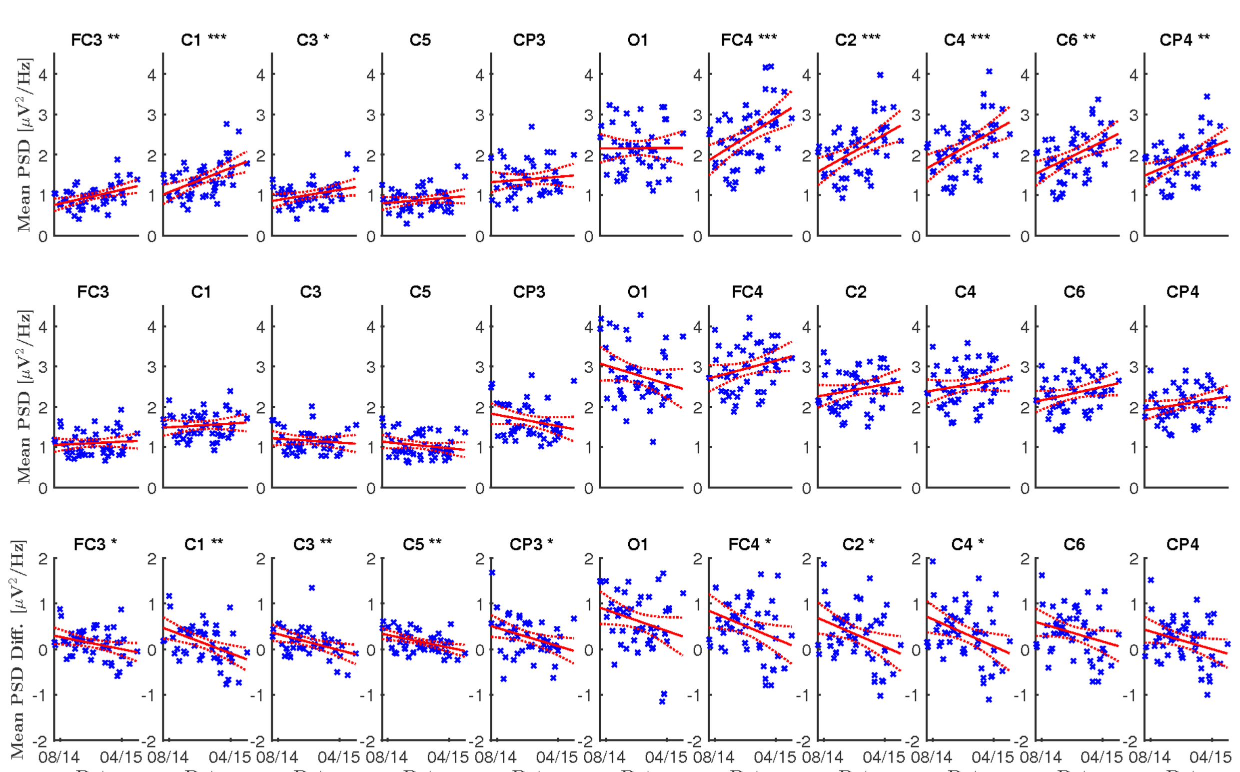
Mirror-box Therapy

Mirror therapy (MT) is a mental process where an individual rehearses a specific limb movement by reflecting the movements of the non-paretic side in the mirror as if it were the affected side [1].

A single-case longitudinal, over 9-month-long study indicates significant changes in sensorimotor EEG oscillatory rhythms (black/red curve = harmonic power spectral density before/after the session).



MT leads to an increased post-training resting state μ-rhythm in both left and right sensorimotor areas. This is true for both resting conditions: eyes open (O) and eyes closed (C). For eyes-closed condition, significant increasing trend of μ-rhythm is also observed longitudinally.



PARAFAC - EEG "Atoms"

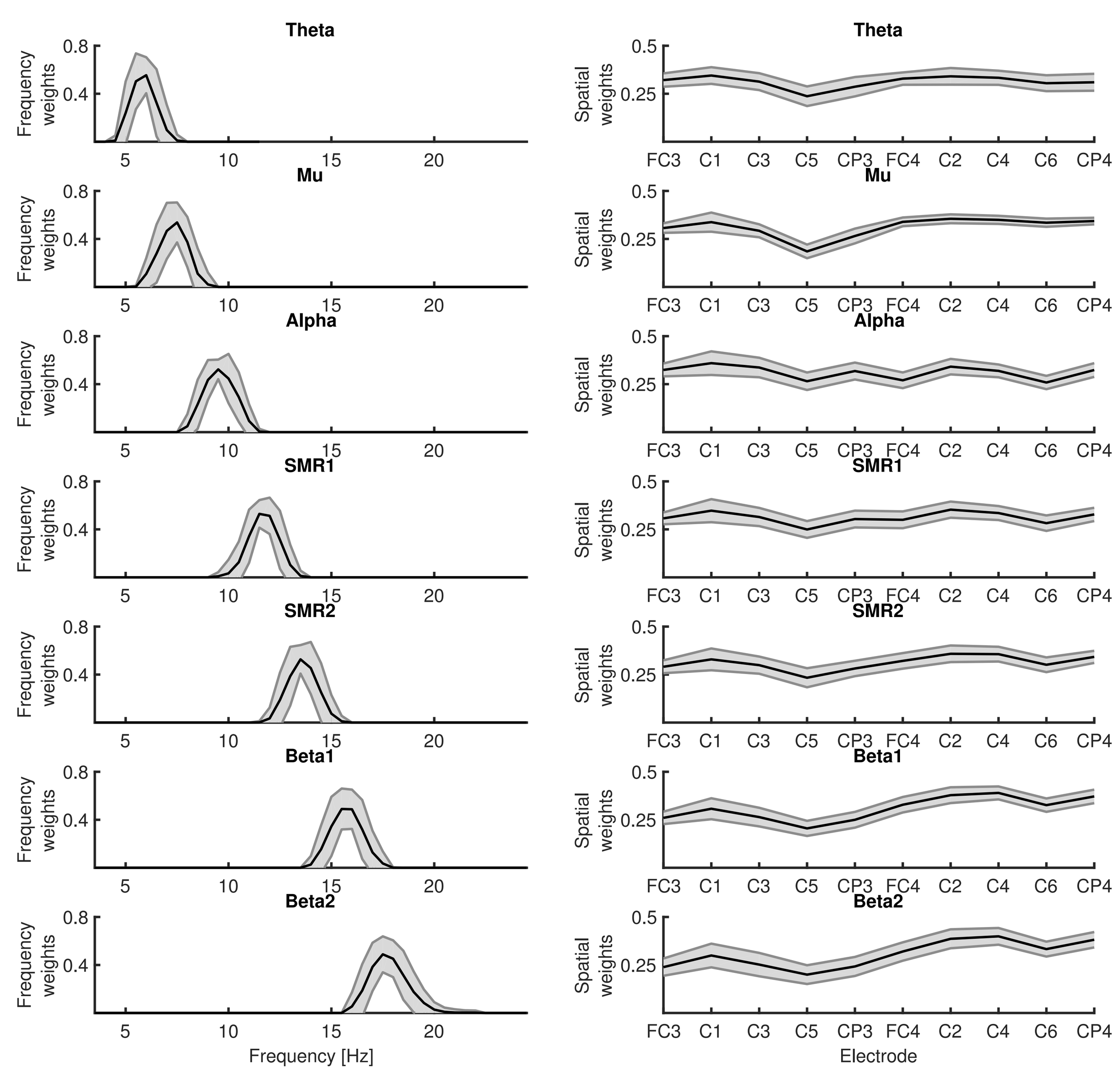
Logarithmically transformed power spectra densities (PSD) of EEG segments are analyzed by three-way parallel factor analysis (PARAFAC) [2, 3]. Define a 3-dim. data matrix $\mathbf{X}$ $(I \times J \times K)$ of PSD estimates at I time segments, J electrodes and K frequencies. Then, three loading matrices, $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{C}$ with elements $a_i^{(f)}$, $b_j^{(f)}$ and $c_k^{(f)}$ define the PARAFAC model which decomposes $\mathbf{X}$ as

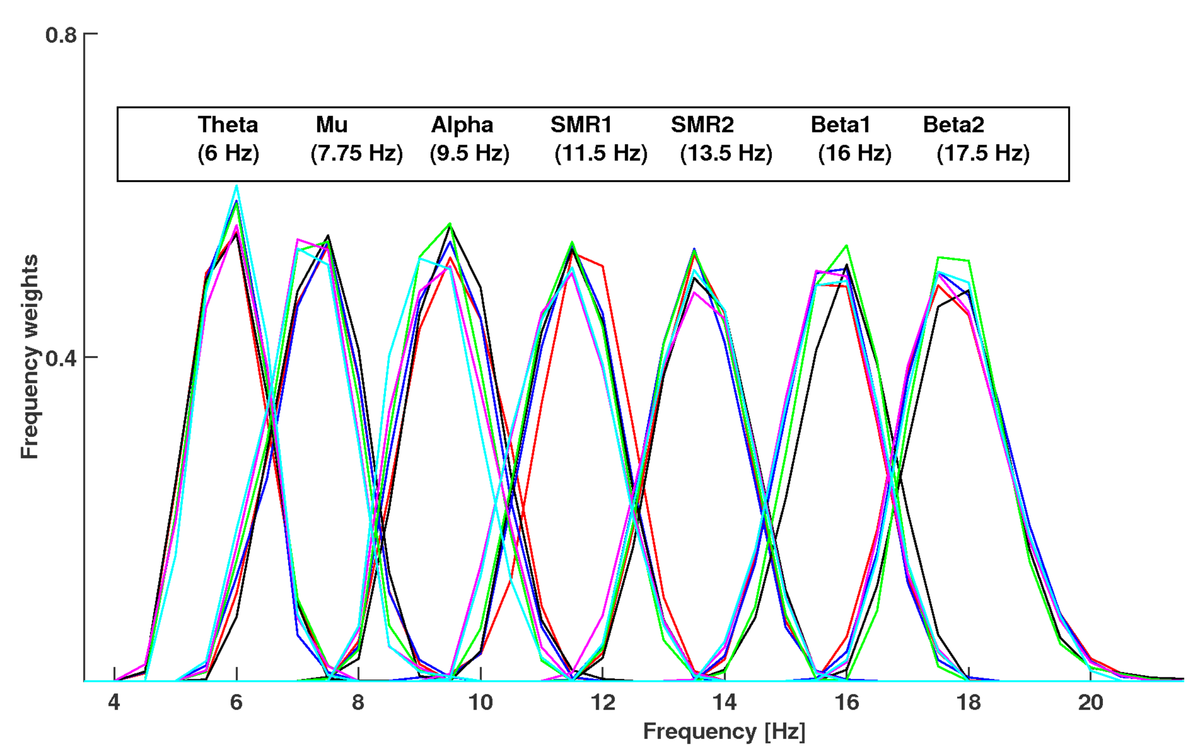
$$x_{ijk} = \sum_{f=1}^{F} a_i^{(f)} b_j^{(f)} c_k^{(f)} + \epsilon_{ijk}$$

where x_{ijk} are elements of $\mathbf{X}$, ϵ_{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 ϵ_{ijk} [2]

$$\min_{a_i^{(f)} b_j^{(f)} c_k^{(f)}} \|x_{ijk} - \sum_{f=1}^{F} a_i^{(f)} b_j^{(f)} c_k^{(f)}\|$$

Averaged frequency weights (left) and spatial weights (right) of the identified atoms:

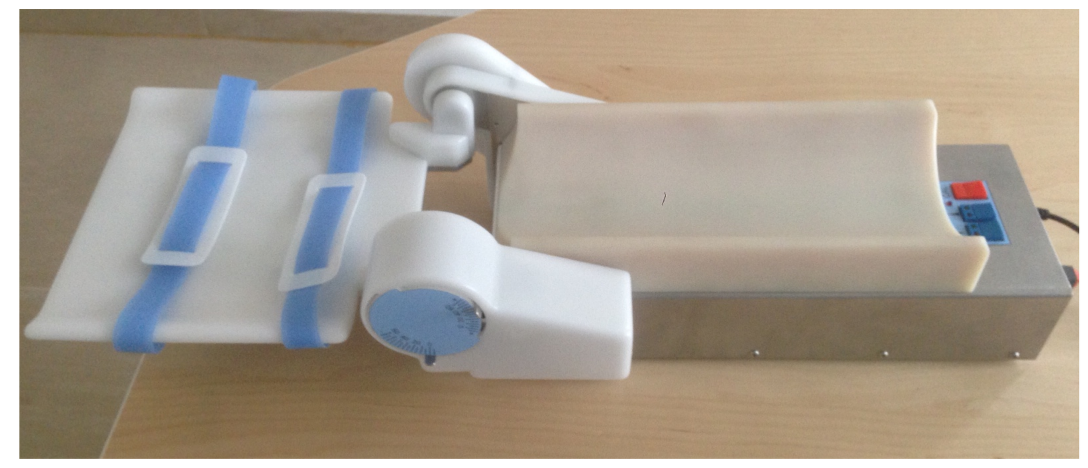




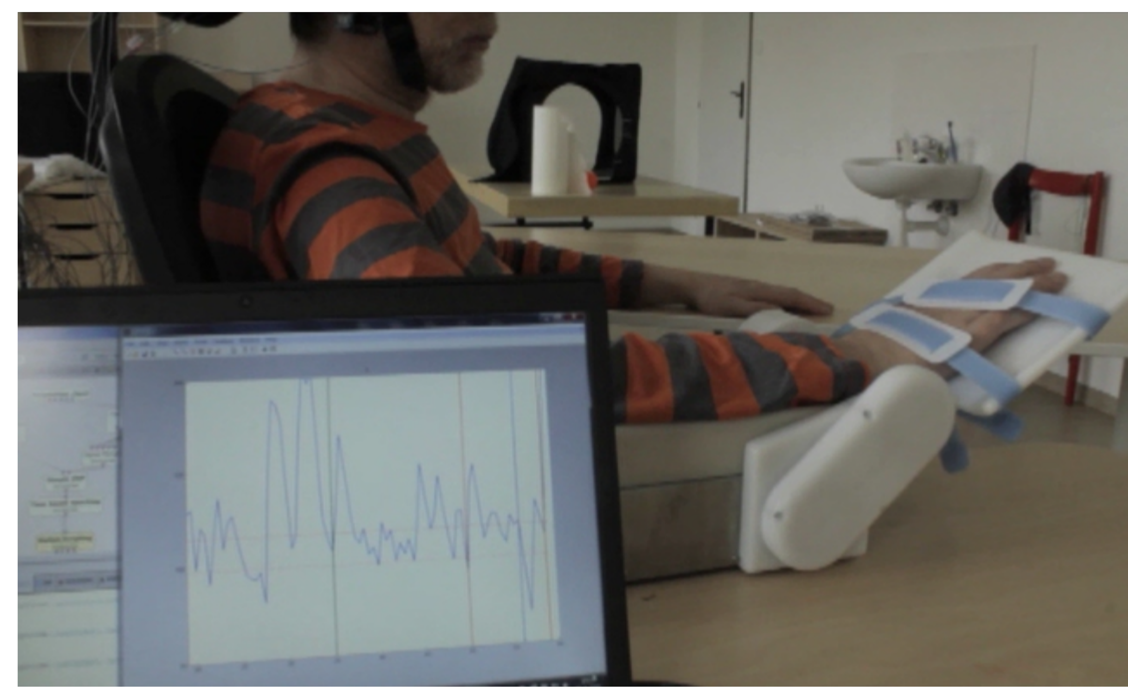
Time scores can be computed and used in BCI.

BCI-Controlled Robotic Splint

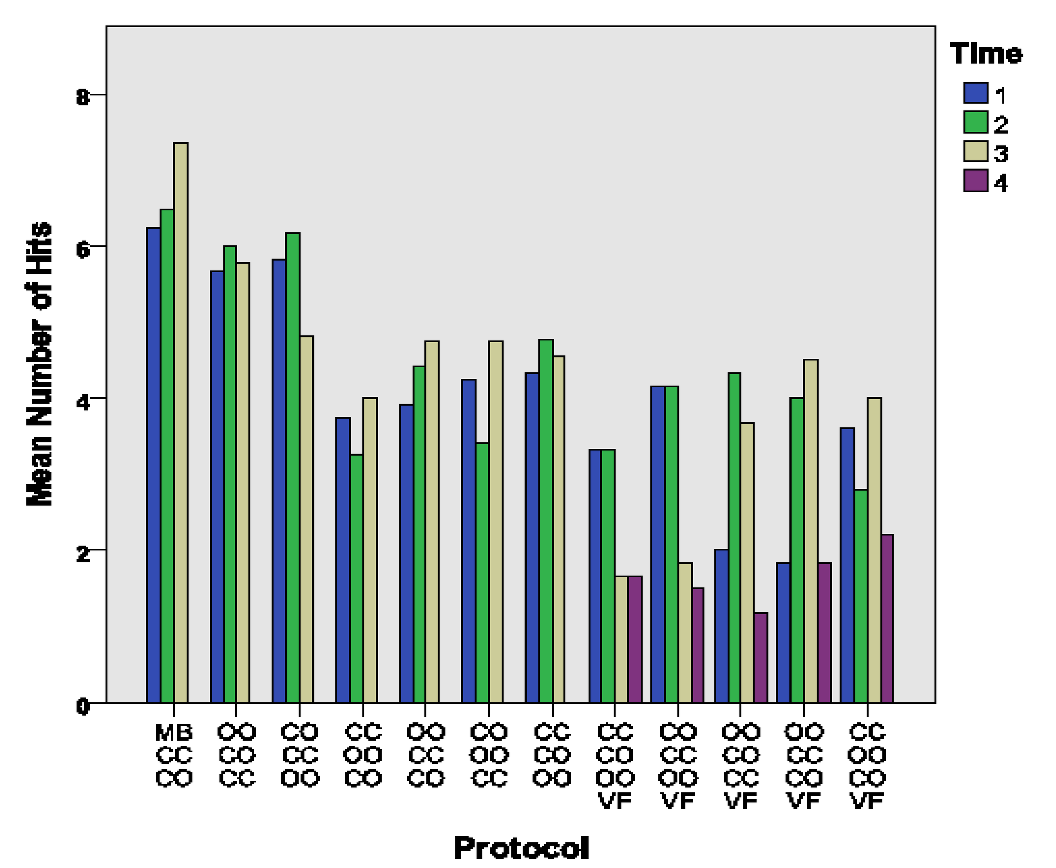
Following the recommendations of the clinical expert, we designed and constructed a robotic splint (with one degree of freedom):



The splint is controlled using the time scores of the selected atoms extracted from EEG recorded during the MT sessions.



To vary the difficulty of controlling the robotic splint, a set of different training protocols and time-scores threshold levels are investigated. Figure below shows the numbers of successful moves (out of 10 trials) of the splint (i.e. successful μ-rhythm desynchronization during motor imagery, manifested by getting under the preset power threshold, compared to relax state).



Clinical results are continuously evaluated and deeper analysis of EEG data recorded during the training is a matter of an ongoing research.

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 (a single session pre- versus post-training) as well as longer-term EEG effects lasting from day-to-day as well as spanning the whole period of the experiment. Analysis of the EEG data recorded during the MT sessions reveals stable day-to-day space and frequency atomic EEG representation of dominant sensorimotor oscillatory rhythms. This allows to construct an efficient BCI protocol for the control of the constructed robotic splint for neuro-rehabilitation. Clinical efficiency of this procedure needs further evaluation by considering a wider, clinically heterogeneous population of patients with motor impairment.

References

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Acknowledgement

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