Development of a multimodal Brain-Computer Interface based on artificial intelligence for rehabilitation of people with motor disorders

ANNUAL REPORT

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Research and Development Progress

The project aims to develop a multimodal brain-computer interface (BCI) for control of devices, which is based on a combination of brain signals and residual movement recordings. The system performs decoding of brain and body signals, measured by EEG, accelerometers and gyroscopes, by means of advanced artificial intelligence techniques. The technology aims to improve quality of life of millions of people with severe movement disorders by satisfying their needs to be independent and able to participate in modern life by means of a software-hardware system for touchless control of devices and neuro-rehabilitation.

The developed AI-based classification system performs a real time cycle of 1) multimodal parallel acquisition of EEG and IMU signals; 2) signal processing; 3) advanced feature extraction (including principal component analysis, kinematic landmarks analysis, spectrum analysis, wavelet transform and feature selection); 4) decoding of motor commands by means of classifiers based on machine learning; and 5) control of devices. A detailed block diagram of the developed system is shown in Appendix Fig. 1. Results of the preliminary study demonstrated required performance of the system for control of devices *in real time* based on decoding voluntary movements from a combination of residual movement recordings and motor imagery (registered in EEG).

Currently the following *results* have been achieved:

- prototype of multimodal BCI system based on a combination of EEG and movement data decoding in real time has been developed;
- invention Disclosure Form was submitted to Technology Transfer Office TAU (Ramot) and United States Provisional Patent Application No. 62/756,156 "Multi-modal brain-computer interface based system and method" has been filed in November 2018;
- the study design in healthy subjects was developed and application has been filed to the human ethics committee of Tel Aviv University in December 2018;
- a letter of intent to conduct pilot clinical trials has been received from the Division of Neurological Rehabilitation of the Chaim Sheba Medical Center, Tel Hashomer

Thus, all the planned tasks for the first year of the grant were implemented, which allowed us to reach the *1st year milestone* – “Multimodal classification system based on AI for motor command decoding is developed and ready for testing on healthy subjects”.

Initial testing of the system. A prototype of multimodal real-time BCI prototype combining brain and body signal analysis has been developed. Decoded motor commands in real time are applied to control assistive devices and specialized applications. The basic principle of the multimodal system is to use mutual validation of motor command decoding obtained from both IMU and EEG pattern recognition. If one classifier recognizes the pattern corresponding to a motor command, the other classifier has to validate it, with minimal time delays. Within the scope of the project special neurofeedback applications in game form were developed and paired with the prototype (see Appendix Fig. 2).

<u>EEG – recording, feature extraction, selection and classification</u>. Using EEG, the initiation of any voluntary muscle movement is seen in unique electric patterns on the scalp. Similar patterns may also appear when a muscle contraction does not occur (e.g., imagined movements, including in the case of paralysis or amputation). Hence, we focused on developing a comprehensive system to record and quickly analyze EEG data from subjects. This online (real-time) analysis allows us to create a prediction of the intended movement, based solely on EEG data. EEG is recorded during

the training protocol, where subjects move (or imagine movement) at cue. Raw EEG data is transformed into the power-frequency domain. Then, frequency features are selected using statistical methods and are used to train an SVM classifier. Once a classifier is trained, new EEG segments can be classified by it in real-time. By experimenting with many parameters, at this point, we were able to increase accuracy of classification to more than 80% in some cases. For example, by selecting features individually, based on a subject's EEG recordings - the achieved classification accuracy was higher compared with using a set of features that are selected for a different subject or a general set of features.

Movement data - recording, analysis and classification. For signal acquisition two wireless Inertial Measurement Units (IMU) were placed on two shoulders inside special bracelets. 4 types of shoulder movements and rest were recorded. Filtering, time-series analysis and principal component analysis were performed on the 14-dimensional data to decrease its dimensionality to two dimensions. Descriptive features, such as kinematic landmarks, velocity peaks, were extracted from the first principal component for each IMU. A classifier based on machine learning was trained and tested for each subject (5-fold cross-validation was performed). 10 subjects participated in two types of experiments: in "Lab Conditions" experiment the patient trained the system and immediately tested it. In "Day to Day Usage" experiment a previously trained classification model was tested. In the "Lab Conditions" experiment the mean classification accuracy was on average 98±2%, whereas in "Day to Day Usage" the mean accuracy was on average 89±13%. Preliminary results indicate that the system learns to decode a subject specific movement profile accurately in real time. The position of the sensors affects the accuracy significantly, however usability of the system will be secured even without retraining of the classifier in day to day usage.

Continuation of R&D towards technology commercialization

The next stage of the project aims at bringing the technology to the market of rehabilitation devices. Market research has been done in order to specify and verify the need and future positioning. The postdoc in charge of the project in the lab was invited to join the Global MBA program of Tel Aviv University in order to elaborate go-to-market strategy and business models using MBA interns under the supervision of faculty professors. During the 2nd year of the project, a full business plan will be built.

Further development will include:

- minimal viable product development,
- testing of the system in real time conditions on campus,
- modification to target rehabilitation purposes,
- obtaining Helsinki committee approval and pilot testing on patients with motor disorders.

These steps will allow to develop a valuable Intellectual Property (IP) with high applicative potential in 2 main segments:

1. **B2C:** Touchless control of devices such as laptops and smartphones in special accessibility mode for communication and independent control of applications using imaginary and actual residual movements available for a user. Automatic adaptation is provided for users with different motor capabilities - from light impairment of fine motor skills (caused by stroke, traumatic brain injury (TBI), etc.) to severe disabilities and even paralysis (e.g. caused by spinal cord injury (SCI)).

2. **B2B:** Rehabilitation of impaired motor function, based on feedback from the combination of relevant brain signals and residual movements. By relying on brain plasticity, multimodal BCI helps train persisting cortical connections to execute motor output of the motor-impaired limb (e.g., hand). In general, BCI has implications for the potential of recovery while it can be considered as an assistive solution to traditional physiotherapeutic approaches. Several clinical studies showed evidence for the feasibility and positive effect of BCI-based neurofeedback systems for motor post-stroke recovery (Arvaneh et al., 2016; Lazarou et al., 2018).

In addition to the R&D process and clinical trial, a special analysis should be done in the field of regulation and reimbursement policy in the US and the EU markets, which together allocate more than 70% of the global neuro-rehabilitation market. This study aims to define a value proposition and market fit for optimal market penetration.

Thus, the second year of the project will develop a minimal viable product based on the developed technology, will test the technology in a target population of users, and will elaborate a market penetration strategy in order to improve the efficiency of rehabilitation for patients with motor disorders. We have started discussions with the Life Sciences business development manager at Ramot in order to determine the best way to commercialize our technology, and we look forward to discussing these options with representatives from the Zimin Institute.

Appendix

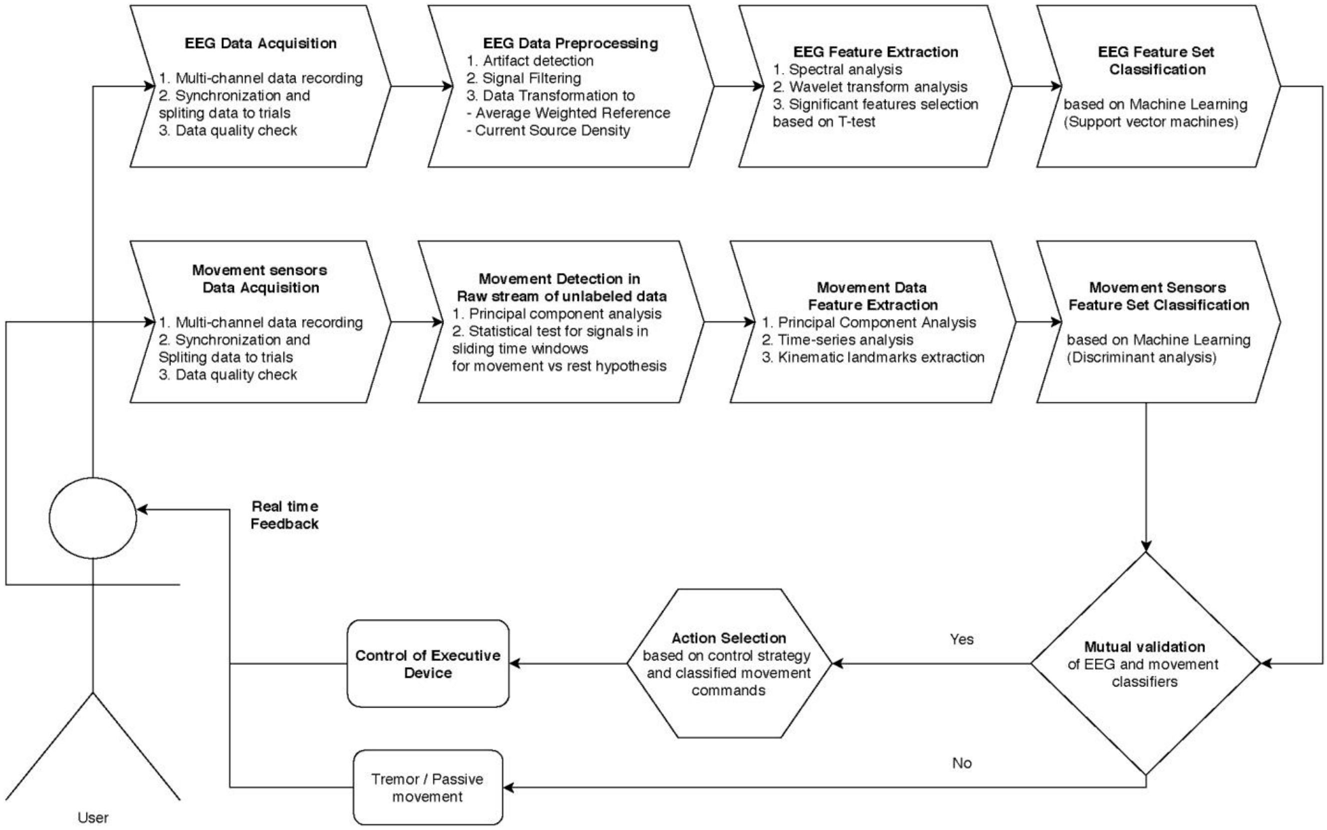

Fig. 1. A detailed block diagram of the developed system describing main steps in parallel signal processing and classification based on machine learning.

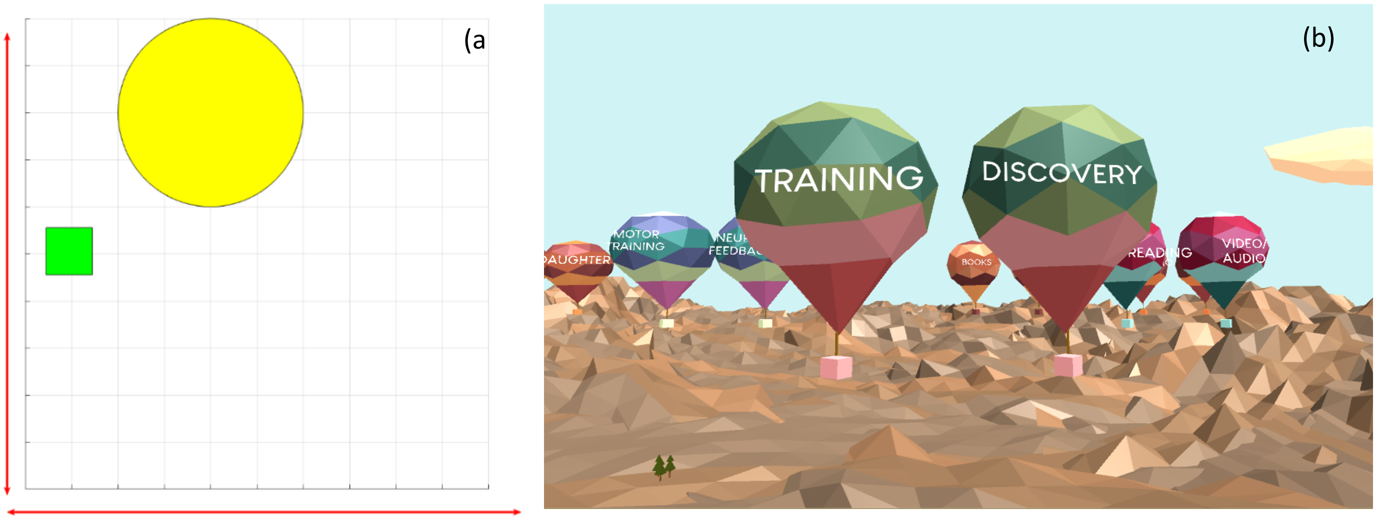

Fig. 2. Feedback interface for experiment phase (a) and for user application (b)

Notes: (a) In the experimental phase, a simple game will facilitate as interactive feedback platform. The task is to move the square towards the yellow circle. Classification of both types of data is done in parallel. By means of neurofeedback, this should encourage users to change their brain electrical patterns to be synched with actual movement. The difficulty level will be continually adjusted according to the patient's improvement (b) Later, the system would operate a range of applications that would benefit patients with severe motor deficit. This is an example of an application – a special environment, where user can navigate and select required actions and entertainments, call for help.