Investigation of Characteristics of a Motor-Imagery Brain–Computer Interface with Quick-Response Tactile Feedback

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Abstract—One of the approaches in rehabilitation after a stroke is mental training by representation of movement using a brain-computer interface (BCI), which allows one to control the result of every attempt of imaginary movement. BCI technology is based on online analysis of an electroencephalogram (EEG), detecting moments of imaginary movement representation (reaction of sensorimotor rhythm desynchronization) and presenting these events in the form of changing scenes on a computer screen or triggering electro-mechanical devices, which essentially is feedback. Traditionally used visual feedback is not always optimal for poststroke patients. Earlier, the effectiveness of tactile feedback, triggered only after a long-time mental representation of the movement, for several seconds or more, was studied. In this work, the efficiency of quick tactile feedback with motor-imagery-based BCI was investigated during classification of short (0.5 s) EEG segments. It was shown that quick tactile feedback is not inferior to the visual feedback and that it is possible to create BCI with tactile feedback that allows a quick reward of physiologically effective attempts of motor imagery and operates with acceptable accuracy for practical use. Furthermore, under certain conditions, tactile feedback can lead to a greater degree of sensorimotor rhythm desynchronization in subjects in comparison with the visual feedback, which can serve as a basis for constructing an effective neurointerface training system.

Keywords: brain-computer interface, electroencephalography, motor imagery, rehabilitation, feedback, ideomotor training.

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Over one third of survivals after stroke suffer from residual motor dysfunction [1, 2]. Therefore, further rehabilitation procedures are essential for restoring motor function [3, 4]. One of the approaches to this problem is mental training by representation of movement, or ideomotor training, resulting in coordinated activation of sensorimotor cortical regions in accordance with this movement, and corresponding plastic remodeling of neural networks [5, 6]. However, the efficiency of such ideomotor training is likely to be incomplete because of the patient’s inability to objectively control vividness and intensity of mental representation of the movement due to its subjective character. From this perspective, rehabilitation approaches maintaining ideomotor training using BCI technology are gaining importance [7, 8]. This technology allows one to register representation of the imaginary movement with the help of electronic computing means in the form of specific changes in EEG characteristics, such as desynchronization of sensorimotor rhythm, and transform them into feedback signals for the patient in real time. Therefore, BCI helps patients to objectively control the result of every attempt of imaginary movement, which obviously provides an increase in efficiency of the ideomotor training regarding initiation of plastic remodeling in cortex and formation of new motor coordination [9].

However, especially when the major disease is accompanied by partial cognitive or sensory disorders, poststroke patients require a precise elaboration of both protocol and organization of the feedback loop itself [10]. In particular, the currently topical question is which sensory modality of the feedback should be provided to a patient [11].

At the moment, the most widespread BCI for treatment of poststroke patients involves the visual feedback when the results of every attempt of motor imagery are presented to the patient as transforming objects on a screen or through external operating devices, for instance, hand exoskeletons [7, 8]. However, despite the high information capacity, visual feedback requires a constant eye focusing on the feedback object.
throughout the training, which is sometimes impossible for the patient.

Regarding this, researchers’ attention is attracted by the prospective creation of feedback pathways in BCI based on tactile stimulation with microbratomes or constructions with piezoelectric elements placed on specific body areas [12, 13]. Moreover, the qualitative characteristics of the motor imagery are coded in parameters of the vibration signal [14] or spatial location of tactile activity detectors on the body [15–17].

In our previous studies [18, 19], it was shown that BCI with tactile feedback applied for rewarding imaginary movements was not more effective in the acquisition of an ability to inhibit sensorimotor rhythm than traditional visual feedback. However, in these researches, the feedback signal was applied after a relatively long (up to 10 s) observation over EEG during mental presentation of a movement only if a significant desynchronization of sensorimotor rhythm was registered in 75% of the studied EEG period. Besides, this method allowed us to statistically estimate the level of desynchronization of sensorimotor rhythm in every 0.5 s [19].

The purpose of this research was to estimate the efficiency of BCI with tactile feedback based on motor imagery under conditions of its precise synchronization with the moments of sensorimotor rhythm suprathreshold suppression on sequential segments of EEG monitoring with a running time of 0.5 s.

MATERIALS AND METHODS

Participants

Eligible participants were over 18 years old with no history of CNS abnormalities and normal or previously normalized vision. The study involved six healthy volunteers (five women and one man) at the age of 18–28 years (mean ± standard deviation of 21.7 ± 3.8). All the participants had no previous experience in working with BCI and were right-handed (mean ± standard deviation of 0.87 ± 0.14 points according to the Edinburgh Handedness Inventory [20]).

EEG Registration

EEG was registered on an NVX52 encephalograph (OOO Medical Computed Systems, Russia) with 30 Cl/Ag-electrodes (F1, Fz, F2, FC5, FC3, FC1, FCz, FC2, FC4, FC6, C5, C3, C1, Cz, C2, C4, C6, CP5, CP3, CP1, CPz, CP2, CP4, CP6, P3, P1, Pz, P2, P4, POz). The integrated electrodes placed on mastoids were used as referents. The ground electrode was placed on the forehead. The contact resistance did not exceed 10 kΩ in all electrodes. EEG was digitized with a sampling frequency of 1000 Hz and filtered within a frequency range of 1–30 Hz using a Notch–filter of 50 Hz.

Study Structure

The experiment consisted of three stages performed on a particular day of the trial. At the beginning of each step, current state of health, activity, and mood were checked in each subject using the HAM test [21]. During the experiment, the subject sat in a comfortable armchair with a footrest in a reclining position.

Every stage was divided into sessions during which the subject completed several mental tasks in response to command pictograms presented on a 19-in. TFT monitor located 2 m in front of the subject’s eyes. The participant was allowed to have a rest between sessions for as long as needed. The mental tasks were represented by imagery movements of left and right hands and resting, during which the subject had to remain in a calm wake state. The “rest” command was illustrated as a fixation cross located in the middle of the screen; imagery movements of the left and right hand were assigned to arrows on the left or right from the fixation cross, respectively. Pictograms were demonstrated for 5 s in all stages of the experiment, with a grey empty screen shown for 3 s at rest. The sequence of displayed commands was randomized. Each session lasted 4 min and consisted of ten demonstrations of each of the three commands.

During the first stage of the experiment, subjects were learning to mentally represent movements during at least three training sessions. The subject could choose any hand movement that was subjectively comfortable for imagination. Fingerling or wrist rotation were given as examples. Upon that, the subject was to concentrate on imagination of tactile sensations. The training success was determined by the level of desynchronization of sensorimotor rhythm. To provide that, EEG signals were adjusted in spatial filtration with the help of a Surface Laplacian filter. Further, the power–density spectrum was calculated for every channel with an interval of 1 Hz, along with the desynchronization rate, counted as a ratio of difference between signal strength in motor imagery and at rest, to the “rest” signal strength. Maximally desynchronized frequencies were selected within the range of 7–16 Hz for each channel; these values were applied to construct a topogram used to assess the spatial localization and amplitude of desynchronization maxims. If diminution of EEG spectral power within the range of 7–16 Hz during imaginary movement reached 50% from the steady state rate in the process of training, the subject was considered to have successfully completed the training course of motor imagery and was included in further experimental stages.

During the second and third steps of the trial, the accuracy level of classification was assessed in subjects...
interacting with BCI in different feedback variants. Each step consisted of six experimental sessions. The first three sessions of the second and the third stages were conducted without any feedback, serving as a control. Either visual or vibrotactile feedback were applied during the other three sessions on every stage. The operating procedure for visual and vibrotactile feedbacks was randomized on the second and the third stages among the subjects so that three subjects were using visual feedback on the second step and vibrotactile feedback on the third and vice versa for the other three participants. The visual feedback was presented as a vertical animated green strip drawn from the center of the fixation cross to the lower screen edge that colored in case of the correct determination of a command. The tactile feedback was performed using vibratomes (flat LRA, linear resonant actuator, without an eccentric, 3 V, 10 mm in diameter, 500 Hz frequency of motor functioning): a vibrating motor was placed on the back of the neck, which informed the subject about successful recognition of “rest” mental task by a classifier, while the motors on right and left forearms reported BCI detection of a subject’s motor imagery of right and left hand movements, respectively.

Vibrating motors were fixed on skin with grip tapes. A vibration signal was given during 100 ms to report the correctly classified state.

Classification of EEG Changes Typical for Motor Imagery and Presentation of Feedback

Sequential intervals of EEG record with the length of 500 ms were analyzed with a specialized classification algorithm to detect mental effort with representation of movement. According to every EEG segment of 500 ms, we inferred in real time the correspondence of a current EEG signal with motor imagery for a certain extremity or with a steady wake state. A visual or tactile feedback with the duration of 200 ms was given to the subject in response to detection of motor imagery.

Therefore, the classification of EEG changes characterizing motor imagery occurred every 500 ms, after which there was an interruption for 200 ms to provide feedback.

To distinguish the features that are significant for classification of EEG changes seen in motor imagery, the signal was filtered in a band of 7–16 Hz followed by calculation of an individual spatial CSP–filter. Linear discriminant analysis was used for classification.

Relative frequency of correct classification was selected as an accuracy index calculated as the ratio of quantity of correctly classified tasks to the total number of tasks.

Statistical Analysis

The Mann–Whitney U–test was used to estimate the individual differences in classification accuracy of periods of mental representation of hand movements. The Wilcoxon test was applied to determine the differences in desynchronization level using different types of feedback. The Kruskal–Wallis test was chosen for group analysis of classification accuracy. All the tests were conducted with the “base” pack for R 3.4.0 software.

RESULTS

The results of the study involving six healthy subjects are quite congeneric, dispensing from enlargening the selection over the noted number, taking into account the complexity and duration of every test. The analysis of subjects’ productivity in interaction with BCI showed that maximal desynchronization of sensorimotor rhythm was seen in C3 and/or C4 derivations on the first step in all the subjects, attaining the criterion of the EEG spectral power decrease in the range of 11–14 Hz in over 50% from this value in a calm wake state.

Therefore, all the subjects were considered to successfully acquire the method of motor imagery and were admitted to participate in testing BCI with differ-

| Subject | No visual feedback, % | Visual feedback, % | No tactile feedback, % | Tactile feedback, % |
|---------|-----------------------|--------------------|------------------------|---------------------|
| TIV     | 56.7 ± 25.7           | 54.3 ± 26.0        | 57.5 ± 26.3            | 59.0 ± 26.5         |
| OOM     | 57.6 ± 18.8           | 64.4 ± 24.1*       | 64 ± 22.9              | 60.6 ± 26.7         |
| SAV     | 55.2 ± 31.9           | 57.3 ± 21.1        | 60.8 ± 24.9            | 66.0 ± 20.8         |
| KLV     | 54.3 ± 21.6           | 61 ± 19.7*         | 61.0 ± 24.6            | 67.0 ± 22.3         |
| RAD     | 52.7 ± 24.4           | 55.7 ± 24.2        | 55.9 ± 26.5            | 63.3 ± 26.9         |
| PEM     | 75.9 ± 15.7           | 71.1 ± 19.2        | 58.3 ± 26.2            | 72.9 ± 19.6*        |
| Mean    | 58.7 ± 24.8           | 60.6 ± 23.2        | 59.5 ± 25.3            | 65.3 ± 24.2         |

*Statistically significant difference from the control (p < 0.05).
Investigation of Characteristics

The group analysis for assessment of accuracy in classification of periods of mental representation of movements did not reveal any differences between four tested experimental conditions: the control test without feedback before testing visual feedback, test with visual feedback, control test without feedback before testing vibrotactile feedback, and test with tactile feedback (Kruskal–Wallis test = 5.5, \( p = 0.14 \), \( N = 6, df = 3 \)). The mean accuracy of classification in all the experimental conditions was 61.07\% (standard deviation was 24.5).

As a result, the supplement of BCI with feedback improved classification accuracy in three (OOM, KLV, PEM, see Table 1) of six subjects. In two of these subjects (OOM and KLV), the increase in classification accuracy was seen only with visual feedback, while only tactile feedback was suitable for the other subject.

C3 and C4 derivations were selected to analyze the differences in desynchronization level of EEG in four studied experimental states because desynchronization maximum of motor imagery was observed in these positions in all subjects. The comparative analysis demonstrated that desynchronization of sensorimotor rhythm of EEG statistically differed in vibrotactile feedback from the control (without feedback) in C3 derivation within motor imagery of both right (Fig. 1a) and left (Fig. 1c) hands. Furthermore, statistical variation of EEG desynchronization was found in C4 derivation during imaginary movements of the left hand (Fig. 1d).

**Fig. 1.** Comparison between desynchronization levels in representation of movement with hands in BCI without feedback and with vibrotactile feedback. The level of desynchronization in imagery movements with the right hand in (a) C3 and (b) C4 electrodes and with the left hand for (c) C3 and (d) C4 electrodes is represented. Statistically significant differences are marked with an asterisk (Mann–Whitney test, \( p < 0.05 \)).
With the visual feedback, the level of EEG desynchronization was significantly different from the control only within representation of movements of the right hand in the contralateral hemisphere in C3 derivation (Fig. 2).

**DISCUSSION**

The mean accuracy of detected EEG signs of mental representation of movements, or accuracy of classification in BCI, was 61% in this study, which was lower than the 70% considered a minimum requirement for comfortable work with BCI [22]. This was to be expected, since classification was admitted to be correct in this work if significant decrease in strength of sensorimotor rhythm was operationally registered on a short EEG segment of 0.5 s in duration, which is obviously harder to perform than with analogous actions on several-seconds-long segments ordinarily used in the majority of investigations in this direction.

Particularly, the classification accuracy was averagely 65.9–73% for all the subjects in various experimental conditions in our previous study on long EEG segments (up to 10 s), which is higher than in the present work involving the same algorithms [19, 23]. Apart from all, the increase in classification accuracy based on vibrotactile feedback can be possibly achieved by changing localization or number of vibrating motors and adjustment of their operating frequency. However, precisely the level of desynchronization of sensorimotor rhythm and resulting classification accuracy of respective EEG segments do not necessarily prove the increase in corticospinal excitability [6] and, therefore, do not guarantee the induction of plastic remodeling of cortical systems corresponding with a specific

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**Fig. 2.** Comparison between desynchronization levels in the representation of movement with hands in BCI without feedback and with visual feedback. The level of desynchronization in imagery movements with the right hand in (a) C3 and (b) C4 electrodes and with the left hand for (c) C3 and (d) C4 electrodes is represented. Statistically significant differences are marked with an asterisk (Mann–Whitney test, p < 0.05).
movement. As long as mental representation of movement is initiated by a conscious effort of the subject, not only intensity of the response but also quick awareness of the subject about the efficiency of mental effort is important to acquire the skill of a physiologically active representation evoking response in sensorimotor cortical systems. A physiologically effective, i.e. providing formation of plastic remodeling, skill of motor imagery can be developed only in this case [9].

In this context, the first physiological manifestations of the process of movement representation detected as desynchronization of sensorimotor rhythm showed to the subject using BCI in the form of feedback signals can be the most effective, though less reliable, reward in establishment of a new motor skill. At the same time, if the feedback is given just after collection of data on manifestation of sensorimotor rhythm desynchronization on the studied EEG segment over a few seconds, the connection between a physiological effect of movement representation and its reward can be obviously significantly attenuated or completely lost.

In the present work, it was firstly demonstrated that motor imagery based BCI technology is at least as efficient with tactile feedback as with visual feedback; secondly, tactile feedback provides the construction of BCI with a quick reward for effective attempts of mental representation of movements. Finally, it was found that BCI technology based on estimation of sensorimotor rhythm desynchronization on short EEG segments (of less than 0.5 s) allowed us to determine changes in EEG typical for mental representation of movements with acceptable accuracy for purposes of ideomotor training.

Specific analysis of the processes of EEG desynchronization during motor imagery showed that tactile feedback could result in the appearance of greater desynchronization of EEG than the visual feedback in subjects under certain modes of providing the feedback. These results correspond with data recently obtained by Barsotti et al. [24] investigating the effectiveness of functioning of motor-imagery BCI with visual-vibrotactile feedback presented to an operator continually during performance of mental tasks. It is necessary to mention the correspondence of our results with the work of Yao et al. [25], where it was demonstrated that vibrotactile stimulation can be applied to improve efficiency of training classifier of motor-imagery BCI.

The enhancement of desynchronization expressiveness can indirectly evidence a wider activation of sensorimotor cortical mechanisms in subjects during the work with BCI based on tactile feedback than with visual feedback under conditions of presenting the feedback after every successful imaginary movement in the subsecond range.

The impairment of sensibility or poststroke pain syndrome can be seen in patients with neurological diseases, thus limiting the application of vibrotactile feedback. In total, the results of this study show the abilities of constructing BCI based on motor imagery with operational tactile feedback and, therefore, the perspectives of creating more effective systems of ideomotor training for neurological patients incapable of proper eye control over the visual environment.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The authors declare that they have no conflict of interest.

Statement of compliance with standards of research involving humans as subjects. All the subjects signed informed consent on participation in the trial. The assay protocol was approved by the Ethical Committee of the Institute of Biology and Biomedicine, Lobachevsky State University, Nizhny Novgorod.

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