Brain–Computer Interface Using Functional Near-Infrared Spectroscopy for Post-Stroke Motor Rehabilitation: Case Series

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Abstract

Introduction. *Non-invasive brain–computer interfaces (BCIs) enable feedback motor imagery [MI] training in neurological patients to support their motor rehabilitation. Nowadays, the use of BCIs based on functional near-infrared spectroscopy (fNIRS) for motor rehabilitation is yet to be investigated.*
Objective: *To evaluate the potential fNIRS BCI use in hand MI training for comprehensive post-stroke rehabilitation.*
Materials and methods. *This pilot study included clinically stable patients with mild-to-moderate post-stroke hand paresis. In addition to the standard rehabilitation, the patients underwent 10 nine-minute MI fNIRS BCI training sessions. To evaluate the quality of fNIRS BCI control, we assessed the percentage of time during which the classifier accurately detected patient's mental state. We scored the hand function using the Action Research Arm Test (ARAT) and the Fugl-Meyer Assessment (FMA).*
Results. *The study included 5 patients at 1 day to 12 months of stroke. All the participants completed the study. All study participants achieved BCI control rates higher than random (41–68%). While three patients demonstrated the clinically significant improvements in their ARAT scores, one of them also showed an improvement in the FMA score. All the participants reported experiencing drowsiness during training.*
Conclusions. *Post-stroke patients can operate the fNIRS BCI system under investigation. We suggest adjusting the feedback system, extending the duration of training, and incorporating functional electromyostimulation to enhance training effectiveness.*

Keywords: *stroke; rehabilitation; motor imagery; brain–computer interface; near-infrared spectroscopy; neuro-bio-control*

Ethics approval. The study was conducted non-invasively in accordance with the ethics of the Declaration of Helsinki. The study protocol was approved by the Local Ethics Committee of the Research Center of Neurology (Protocol No. 5-4/22, 1 June 2022). All the participants signed informed consent.

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Conflict of interest. The authors declare no apparent or potential conflicts of interest related to the publication of this article.

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Интерфейс мозг–компьютер, основанный на спектроскопии в ближней инфракрасной области, в двигательной реабилитации после инсульта: описание серии случаев

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Аннотация

Введение. *Неинвазивные нейрокомпьютерные интерфейсы позволяют проводить тренировки представления движения с предъявлением обратной связи в двигательной реабилитации пациентов неврологического профиля. В настоящий момент практически не изучено применение интерфейса мозг–компьютер (ИМК) на основе регистрации спектроскопии в ближней инфракрасной области (БИКС) в двигательной реабилитации.*

Цель *исследования — оценить возможность применения БИКС-ИМК для проведения тренировок представления движения руки в комплексной реабилитации пациентов после инсульта.*

Материалы и методы. *В данное пилотное исследование включали клинически стабильных пациентов с постинсультным парезом руки лёгкой или средней степени выраженности. Пациенты получали 10 тренировок представления движения под контролем БИКС-ИМК, каждая длительностью по 9 мин, в дополнение к стандартной реабилитационной программе. В качестве показателя качества управления БИКС-ИМК оценивали достигнутый процент времени правильного распознавания классификатором ментального состояния пациента. Функцию руки определяли по шкалам ARAT и Фугл-Мейера.*

Результаты. *В исследование были включены и завершили его 5 пациентов с давностью инсульта от 1 дня до 12 мес. Все пациенты достигли качества управления БИКС-ИМК выше случайного (41–68%). Клинически значимое улучшение двигательной функции руки достигнуто у 3 пациентов по тесту ARAT, у одного из них — также по шкале Фугл-Мейера. В процессе тренировок все пациенты отмечали сонливость.*

Заключение. *Пациенты после инсульта способны управлять исследованной системой БИКС-ИМК. Для увеличения эффективности тренировок рекомендовано изменить сценарий предъявления обратной связи, увеличить продолжительность тренировок, включить в аппаратный комплекс функциональную электромиостимуляцию.*

Ключевые слова: *инсульт; реабилитация; представление движения; интерфейс мозг–компьютер; спектроскопия в ближней инфракрасной области; нейробиоуправление*

Этическое утверждение. Исследование выполнено неинвазивным методом в соответствии с этическими нормами Хельсинкской декларации. Протокол исследования одобрен Локальным этическим комитетом ФГБНУ «Научный центр неврологии» (заключение № 5-4/22 от 01.06.2022). Все пациенты подписали информированное согласие.

Источник финансирования. Работа Люкманова Р.Х., Иконниковой Е.С., Черкасовой А.Н., Супоневой Н.А. выполнена в рамках государственного задания Министерства образования и науки Российской Федерации ФГБНУ «Научный центр неврологии» на 2021–2023 годы (тема № 210). Работа Боброва П.Д., Исаева М.Р., Мокиенко О.А. выполнена в рамках государственного задания Министерства образования и науки Российской Федерации ФГБУН «Институт высшей нервной деятельности и нейрофизиологии РАН» на 2021–2023 гг.

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

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Introduction

Brain–computer interfaces (BCIs) are systems that translate brain activity signals into commands for the output devices. Non-invasive BCIs enable feedback motor imagery (MI) training in neurological patients to support their motor rehabilitation. At present, several systematic reviews comprise the evidence base for employing BCIs, which utilize sensory and motor EEG rhythms (EEG BCIs), in post-stroke rehabilitation [1–4]. We also conducted a randomized controlled trial (RCT) to evaluate effectiveness of using EEG BCI with visual and exoskeleton-mediated kynesthetic feedback in the post-stroke population [5, 6]. A series of training sessions for MI, controlled with this technology, resulted in improved grasping and pinching. However, the EEG-BCI use is complicated due to the necessity of applying EEG gel onto the scalp, signal artifacts in patient motion and muscle contraction during training, and the low spatial resolution of signal source detection.

Functional near-infrared spectroscopy BCIs (fNIRS-BCIs) is a non-invasive BCI to conduct feedback MI training. The sources of brain activity may involve alterations in concentrations of oxy-, deoxy-, and total hemoglobin up to 4 cm below the head surface. This technology does not require the use of any electrode gel, and patient movements during training do not result in significant signal distortion. At present, fNIRS-BCI remains largely unexplored approach to post-stroke rehabilitation. The latest review [7] of biofeedback methods mentions only one fNIRS-BCI study in post-stroke rehabilitation [8]. The study protocol implied the presentation of the signal amplitude as the color and the height of the bars on the monitor rather than signal classification.

The exploratory study of this technology with assessment of the attained level of online signal detection was necessary as an initial test prior to the development of the fNIRS BCI effectiveness RCT protocol.

The study **objective** is to evaluate the potential fNIRS BCI use for customized hand MI training in comprehensive post-stroke rehabilitation.

Materials and methods

Study design

This pilot study is a case series of post-stroke rehabilitation integrating standard management with additional fNIRS BCI mental training.

The study was conducted at the Institute of Neuro-Rehabilitation and Recovery Technologies of the Research Center of Neurology from June to October 2022. The study included inpatients receiving scheduled rehabilitation. Each patient participated for a total of 12 days including five training days followed by two days off, and then five more training days. fNIRS BCI training supplemented the standard clinical rehabilitation program. Prior to the first fNIRS BCI training session and post the last one, hand motion was assessed and scored using international validated scales.

The study protocol was approved by the Local Ethics Committee of the Research Center of Neurology (Protocol No. 5-4/22, 1 June 2022). Patient participation in this study was entirely voluntary, and all participants provided informed consent. The study protocol was pre-registered in the local research project protocol database of the Institute of Neuro-Rehabilitation and Recovery Technologies (ID 210).

Inclusion criteria

Inclusion criteria: primary or recurrent stroke with a supratentorial CT or MRI-confirmed focus, mild-to-moderate clinical paresis of the distal upper limb, the stroke time of one day to 12 months, clinically stable state without any life-threatening conditions, and informed consent to participate in the study.

Exclusion criteria: severe speech, vision, and/or cognitive function impairment and/or hand tissue contractures.

Standard rehabilitation course

All patients underwent a two-week rehabilitation course that included personal instructor-led exercise therapy, neuro-muscular electric stimulation of lower limb muscles, therapeutic massage, robotic biofeedback mechanotherapy to recover hand fine movements, and stationary cycling exercises. The above activities were performed on daily basis, except for the days-off (10 sessions each).

fNIRS BCI training

MI fNIRS BCI training was performed on a daily basis except for the days-off in addition to the standard rehabilitation course. Each patient underwent 10 training sessions.

The study used a non-invasive BCI based on the recognition of a BOLD cortical signal in the hand MI expressed as changes in the relative concentrations of oxy- and deoxyhemoglobin assessed by near-infrared spectroscopy. The NIRScout system (NIRxMedicalTechnologies), with 8 detectors and 16 sources, was used for fNIRS. The study protocol, the filtration method, and the classification of brain activity signals and the software used were described previously [9]. The patient received visual feedback on the 22" computer monitor. The flow chart is presented in Fig. 1.

The investigator customized movement types for MI during BCI training and selected the most difficult (for which, accordingly, the lowest score on this test was assigned) movement based on the patient's ARAT results. Before each training session, the investigator asked the patient to repeat the target movement several times until they confirmed their readiness to perform it mentally (priming). If the movement implied manipulating an item (ARAT), the item was provided to the patient during priming.

During the procedure, a BCI cap equipped with sources and detectors was put on the patient's head. During

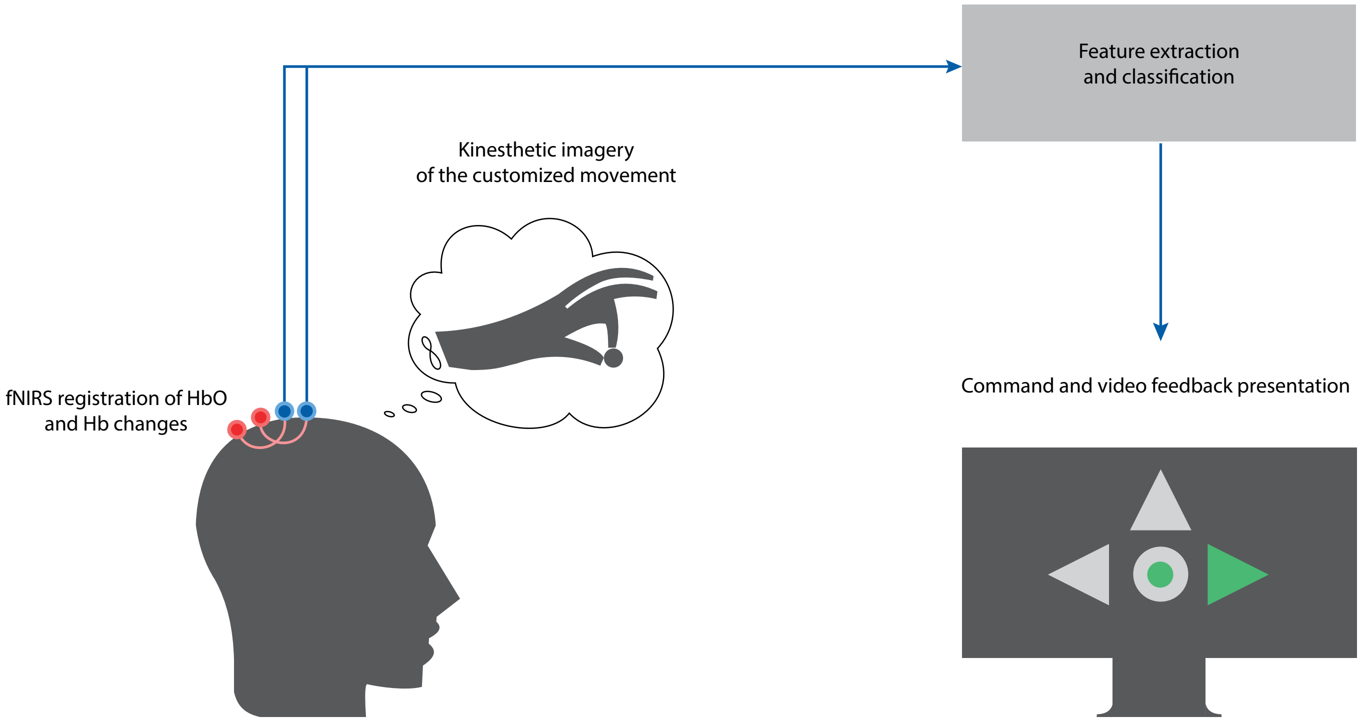

Fig. 1. The fNIRS BCI and post-priming training flow chart
Hb, deoxyhemoglobin; HbO, oxyhemoglobin.

the session, the patients sat by the computer monitor at the desk with their hands comfortably positioned on either the armrests or the desk. There was a fixation point consisting of a circular shape in the center of the dark screen to stabilize the patient's gaze. Additionally, three arrows surrounded the fixation point, which provided commands with colors that changed dynamically. Following one of three commands, the patient either kynesthetically imagined slow motion of their left or right hand (with the corresponding arrow changing color) or relaxed and directed their gaze towards the center of the screen (with the upper arrow changing color). When MI task was successfully detected by the classifier, a gaze fixation point in the center of the screen was gradiently coloring green. Following the command to relax, the point color did not change in any classifier response.

Each nine-minute training session consisted of four units, with two commands randomly given to the left and right hand for 15 seconds, interspersed with rest intervals. Two-second preparatory instruction preceded the main commands.

Signal acquisition and processing

Sources and detectors were nested on the EEG cap. Signal recording frequency was 15.625 Hz. Recorded radiation intensities were calculated as oxyhemoglobin (HbO) and deoxyhemoglobin (Hb) using the modified Beer–Lambert law. To classify active states, the signal was filtered with a first order Chebyshev type I filter with 1 dB passband ripple and 0.005 Hz cutoff frequency. To classify rest vs active state, the signal was filtered with a second order Chebyshev type I filter with 1 dB passband ripple. The cutoff frequencies were selected for zero drift at the command frequency. For classification, we used linear discriminant analysis with additional learning based on the previous units of the current session and the participant's previous test sessions. In gradual classification, we first classified resting vs. active state and left hand vs. right hand in the following classification of active states. Per-second record intervals were classified.

Endpoints

First of all, this pilot study evaluated the quality of the detection of patient's mental states during training by the classifier. This indicator is measured as the percentage of correctly detected intervals. Over 33% of the total amount of the classified intervals is considered to be higher than random because the patients performed three mental tasks (100% / 3 ≈ 33%).

For the pre- and post-rehabilitation assessment of the hand function, we used the ARAT scale (with a maximum possible score of 57 points and a clinically significant increase in 6 points in the chronic stroke period and 12–17 points in the acute stroke period) [10, 11] and the Fugl-Meyer Assessment of the Upper Extremity (with a maximum possible score of 126 points and a clinically significant increase in 5 points) [10, 12]. The trained physician performed the blinded movement assessment.

Statistical data processing

The resulting percentage of the detection of brain signal activity is presented as the median and the 25th and 75th quartiles. The MatLab R2019b package (MathWorks, Natick, MA, USA) was used for analysis.

Because the study was a non-comparative exploratory case series, we did not use other statistical methods.

Results

Population

While eight patients were successfully screened, five were included in the study and three were not included. Table 1 shows the profiles of the participants. All five participants completed the study with no withdrawals.

In order to train MI, we selected the following movements: 'to pinch and hold a 6-mm ball with their digit 1 and digit 4 for P1, P3, and P4; 'to pinch and hold a 6-mm ball with their digit 1 and digit 2 for P2; 'to pinch and hold a 1.5-mm ball with their digit 1 and 4 for P5.

Motor control and improvement

All patients were able to control MI fNIRS-BCI with better than random classification accuracy rate (>33%; Table 2).

Following comprehensive inpatient rehabilitation and additional MI fNIRS-BCI training, all patients showed improved motor scores (Fig. 2). While three patients demonstrated the clinically significant improvement in ARAT score, one of them also achieved significant improvement in FMA score (Fig. 2).

The MI fNIRS BCI training was not associated with any adverse events. However, all participants reported experiencing drowsiness during training, which impaired concentration and task performance by the end of the session.

Discussion

In this study, we demonstrated the potential fNIRS BCI

Table 1. Patient demographics and baseline characteristics

Patient	Sex	Age, years	Stroke type	Stroke lesion side	Stroke time, months ago	APAT score	FMA score (upper extremity)
P1	Male	71	Primary	Left	12	44	107
P2	Male	58	Primary	Left	12	39	104
P3	Male	58	Secondary	Right	8 and 2	35	114
P4	Male	49	Primary	Right	< 1	35	116
P5	Female	43	Primary	Left	1	52	122

Table 2. Resulting BCI control and motor score improvement

Patient	Classifier accuracy, %	ARAT score improvement	FMA score improvement
P1	68 [57; 73]	6*	1
P2	41 [37; 47]	4	3
P3	45 [41; 47]	6*	0
P4	45 [34; 50]	20*	9*
P5	49 [46; 59]	5	3

Note. *Clinically significant improvement as adjusted by the stroke time [10].

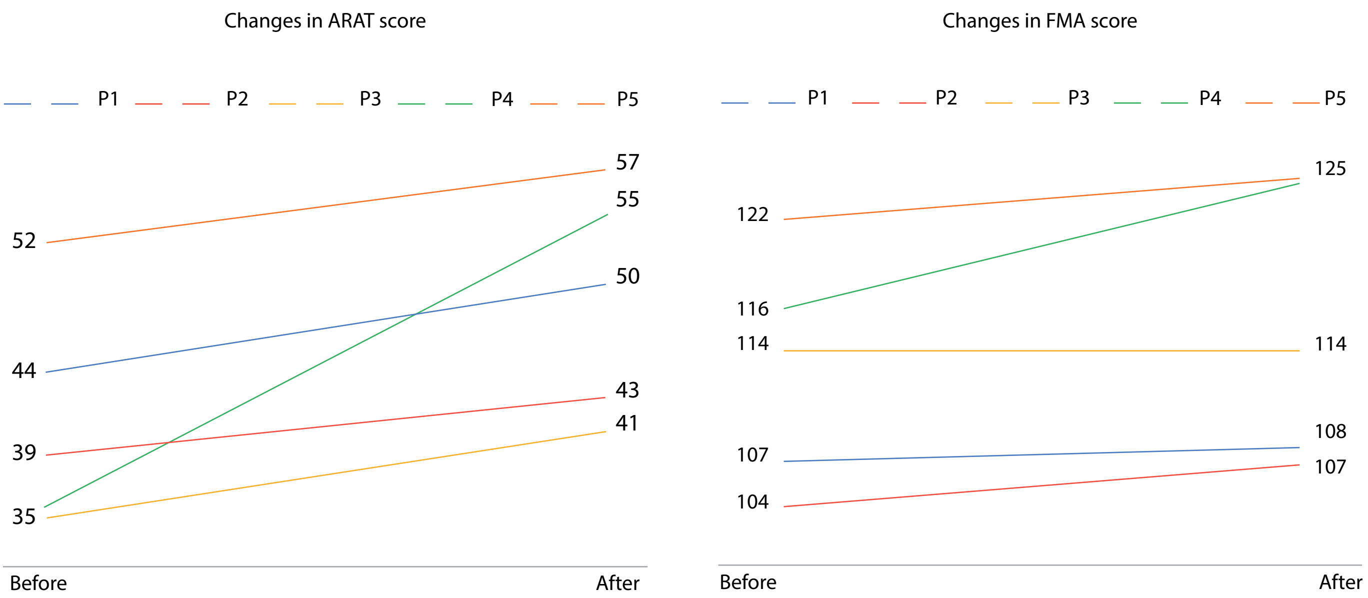

Fig. 2. Changes in motor scores during rehabilitation and additional fNIRS BCI training.

use for customized hand MI training in comprehensive post-stroke rehabilitation. All study participants achieved BCI control rates higher than random.

In the study, the total MI training exposure was 1.5 h (10 nine-minute sessions), which is significantly lower than the total training exposure of 5–27 h, with the session duration of 0.5–1.5 h, in other non-invasive BCI studies [13]. Nevertheless, patients developed drowsiness even during the shorter sessions. Thus, we find it reasonable to change the feedback scenario for play or various visualizations and to break the session units with pauses. Notably, MI drowsiness was mentioned in other studies [13].

Following the fNIRS BCI, all study participants showed improvement in motor function on at least one scale, including clinically significant improvement in three patients. However, the study design did not include a control group and the range of inclusion criteria was quite broad, which limits this exploratory study. Therefore, it is impossible to prove that the resulting improvement was caused by fNIRS BCI training. Nevertheless, the effectiveness of MI fNIRS BCI training has been demonstrated in a number of meta-analyses and systematic reviews based on multiple RCTs [1–4, 13]. Nowadays, professionals are searching for the most convenient and practical BCI systems and feedback scenarios [14].

Although the fNIRS BCI is a more convenient method than EEG BCI, it is the EEG BCI that has been evaluated in the vast majority of studies the present systematic reviews are based on. M. Mihara et al. showed fNIRS BCI effectiveness for rehabilitation of patients with subcortical stroke in the only randomized trial involving 20 patients: six 20-minute training sessions contributed to a better improvement of motor function measured as FMA score in the active group than in the sham fNIRS BCI group [8]. Interestingly, unlike the system we used in our study, the fNIRS BCI technology used by M. Mihara et al. did not involve any online signal classification. Therefore, additional, unobvious actions are needed to translate the recorded signals into commands to start exoskeleton operation or electrostimulation, if these methods are used for additional sensorimotor feedback.

The hallmark of our study is customisation of the movement type for further in-training MI based on the ARAT. This approach corresponds to the modern concept of customized rehabilitation and allows the use of goal attainment scaling [10].

A recent meta-analysis showed a better effect of BCI systems with functional electrostimulation in rehabilitation setting, as compared to those with the exoskeleton for kinesthetic feedback or with visual feedback only [13]. Therefore, we recommend to supplement the fNIRS BCI hardware with functional electromyostimulation controlled by brain activity signals in the MI during further rework.

Conclusion

In this pilot study, we demonstrated the potential fNIRS BCI use for customized hand MI training in comprehensive post-stroke rehabilitation and identified the ways to improve this technology and the training protocol.

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