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Hemodynamic response in the motor cortex to execution of different types of movements

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Abstract. *Purpose* of this work is the analysis of the hemodynamic response to the execution of various types of movements (single movement, series of movements, "tapping") by the right hand. *Methods.* In this paper, the hemodynamic response was recorded using functional near infrared spectroscopy (NIRScout instrument from NIRx, Germany). The NIRScout system uses 16 optodes (8 sources and 8 detectors) to record the hemodynamic response in the cerebral cortex with a sampling rate of 7.8125 Hz. Optodes are non-invasively placed on the patient's scalp by inserting into the sockets of a special cap "EASYCAP". *Results.* We show that the total hemodynamic response in the motor cortex of the left hemisphere slightly differs between all the considered types of movement, while the severity of contralaterality demonstrates significant differences between the types of movements. Contralaterality is most pronounced when performing a series of movements, while a single squeeze of the hand causes the least contralaterality. *Conclusion.* The results obtained in this paper demonstrate the high sensitivity of functional near-infrared spectroscopy technology to the performance of various types of movements. It should be especially noted here short single hand squeezes, which are clearly visible on the characteristics of HbO and HbR, which can be used in the development and design of various brain – computer interfaces, including multimodal ones.

Keywords: hemodynamic response, functional NIRS, tapping, hand movement, brain activity.

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Introduction

The study of the principles and physical laws of the brain is an important task of modern science [1–7]. The most promising and powerful noninvasive neuroimaging tool for recording brain activity is functional near infrared spectroscopy (fBICS, fNIRS) [8, 9]. This technology uses light in the near infrared range to detect changes in the level of oxygenated (HbO) and deoxygenated (HbR) hemoglobin due to hemodynamic activity of the brain and rapid delivery of oxygenated blood to active cortical areas through the neurovascular junction. There is a relationship between the electrical activity of the brain and the hemodynamic response. In [10], a high and significant correlation of HbO and HbR concentrations with the amplitudes of electrical activity in the alpha and beta ranges (8...13 Hz and 13...30 Hz, respectively). The HbO concentration is negatively correlated with the desynchronization of alpha and beta rhythms. The HbR concentration is characterized by a positive correlation with a decrease in the amplitudes of both rhythms.

fBICS registers signals of the same physiological basis as functional magnetic resonance imaging (fMRI). Therefore, both technologies provide interconnected data. At the same time, fBICS has a number of advantages: portability, ease of use, the ability to monitor in real time, low sensitivity to motor artifacts, higher time resolution, the possibility of separate registration of changes in both deoxyhemoglobin and oxyhemoglobin [10, 11].

Currently, with the help of fBICS, research is being actively conducted that is aimed at studying the neural activity of the brain [12]. A lot of work is aimed at assessing the mental load, that is, the amount of mental effort spent to perform a particular task. In the paper [13], the authors found that the change in the difference between oxygenated and deoxygenated hemoglobin significantly increases with increasing complexity of the task. Changes in the hemodynamic response are sensitive to large differences in the complexity of the task, while sensitivity to smaller differences is absent and requires additional research.

Another application of fBICS is found in various hybrid multimodal brain-computer interfaces [14–16]. For example, to assess the level of attention [17] in studies on the diagnosis of various cognitive disorders [18] and other applications. Due to the presence of a time delay between the activation of a certain area of the cerebral cortex and the appearance of a hemodynamic response in it, in most experimental paradigms, subjects are given a long load with long pauses between tasks. When analyzing motor activity using fBICS, a series of identical movements are usually performed within the same task [10]. It is important to study and compare the hemodynamic response to performing various types of movement by analyzing changes in concentrations of deoxyhemoglobin and oxyhemoglobin [19]. At present, these issues are little studied.

This paper presents the results of the analysis of the hemodynamic response of the brain when performing various types of movements. The dynamics of oxyhemoglobin and deoxyhemoglobin were considered as the analyzed signals.

1. Methods

The fBIX signals were recorded using the NIRScout device (NIRx, Germany). The NIRScout system uses 16 optodes (8 sources and 8 detectors) to register a hemodynamic response in the cerebral cortex with a sampling frequency of 7.8125 Hz. Optodes are noninvasively placed on the patient's scalp by installing a special EASYCAP cap in the sockets. Each fBIX channel is formed by a pair of "source-detector which are located close enough to each other. The optimal distance between the source and the detector is about 3 cm due to the specific shape of the near-infrared radiation trajectory. The light is scattered in the tissues of the cerebral cortex and at a depth of about 3 cm is reflected towards the detector.

The arrangement of optodes was similar to the one given in the work [12] and covered the motor cortex. Fig. 1, *c* shows the mounting used with 23 channels fBICS. For a better understanding of the placement of optodes, fig. 1, *c* shows the location of EEG channels according to the international scheme "10–10".

Twelve healthy volunteers took part in the experiment: age — 22...38 years old, male to female ratio — 7/5, right-handed, not professionally engaged in sports, non-smokers. None of the subjects were diagnosed with diseases of the musculoskeletal system or the central nervous system. Each participant was asked to adhere to a healthy lifestyle for 48 hours before the experiment, which included an 8-hour sleep, abstinence from alcohol, limited consumption of caffeinated products, moderate physical activity. Each participant provided informed written consent before participating in the experiment. The experimental procedure was carried out in accordance with the Helsinki Declaration and approved by the Ethics Commission of Innopolis University.

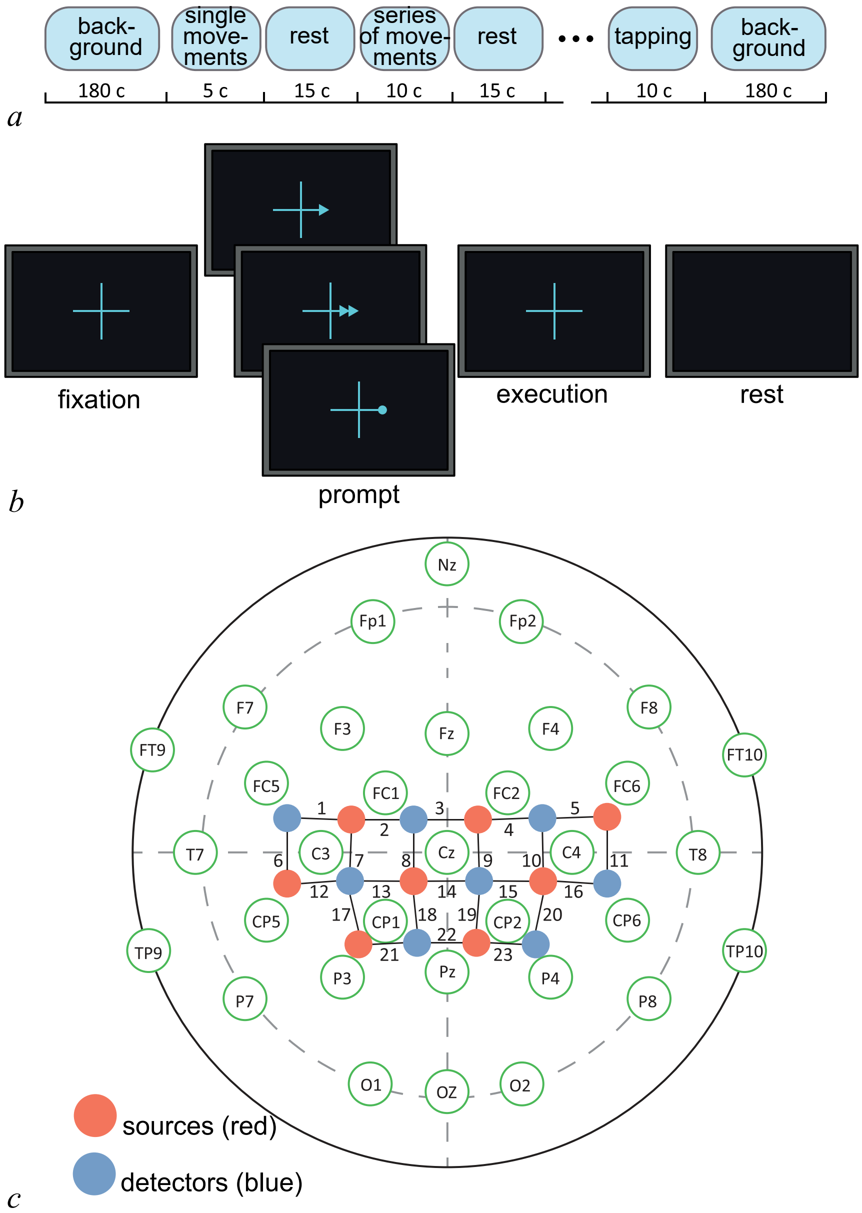

Fig. 1. *a* — Общий дизайн эксперимента; *b* — демонстрация предъявляемых испытуемому команд; *c* — используемая расстановка оптодов (цвет online)

Fig. 1. *a* — General design of the experiment; *b* — demonstration of commands presented to the subject; *c* — arrangement of optodes used (color online)

The experiments were carried out in the morning. Before starting the experiment, the participants were informed about its goals and methods, as well as about possible inconveniences. The subjects had the opportunity to ask any questions of interest and get detailed answers.

The experiment was conducted as follows. The subject sat in a comfortable chair and performed various types of movements with his right hand according to the instructions on the monitor. The monitor was placed in front of the eyes of the subject at a distance of 70...80 cm. The design of the experiment includes three types of movements: single movement — the subject clearly squeezes and unclenches the brush once, 5 seconds are allotted for execution; a series of movements — the subject clearly squeezes and unclenches the brush several times at a convenient pace for 10 seconds; "tapping" — alternate tapping of the thumb on the rest of the fingers of the brush at a comfortable pace for 10 seconds.

The general design of the experiment is schematically shown in fig. 1, *a*. Each experiment began and ended with a 3-minute recording of background activity, during which the subject was asked to relax and not move his hands. The main part of the experiment consisted of 60 trials. The general scheme of one trial is shown in fig. 1, *b*. Each fBICS trial began with attention fixation — a light cross appeared on the black screen in the center for 2 seconds. Then a hint appeared on top of the cross for 1.5 seconds. She told the subject what type of movement needed to be performed: arrow — single movement, double arrow — a series of movements, point — tapping with fingers. After that, the hint disappeared and the subject was given time to perform the required movement. At the end of the trial, a black screen was shown for 15 seconds and time was given to rest. 20 trials were performed for each type of movement. The trials for all types of movements were mixed and presented in random order. In experiments with fBICS, radiation with two wavelengths was used: $\lambda_1 = 785$ nm and $\lambda_2 = 850$ nm, which pass through skin, bone tissue and water, but are well absorbed by oxyhemoglobin and deoxyhemoglobin.

The experimental data of fBICS must be pre-processed so that they can be used as an indicator of changes in tissue oxygenation. Since oxyhemoglobin and deoxyhemoglobin absorb light in the near infrared differently, we calculated the changes in reflected two-wave light using a modified Behr's law−Lambert [20]. As a result, two characteristic measures of HbO and HbR were obtained, which reflect the rate of relative changes in the concentration levels of oxyhemoglobin and deoxyhemoglobin.

Data collection fBICS and the preprocessing procedure were performed using the NIRScout software. The experimental data of fBICS are often influenced by side physiological noises and artifacts. Their characteristic frequencies are in the fBICS frequency range, including Mayer waves (with a typical frequency close to 0.1 Hz), respiration (close to 0.25 Hz) and heartbeat (about 1 Hz). As mentioned in the review article [18], in many cases bandpass filtering is sufficient to remove low-frequency physiological noise in the fBICS data. In this regard, a 0.01 bandpass filter was also applied...0.1 Hz to fBICS signals using NIRScout to prevent the effect of side physiological effects.

2. Results

Dependences of changes in oxy- and deoxyhemoglobin were obtained for the three types of movement under consideration. For this purpose, a 5-second fragment was used before each motor act, taken from the rest phase of the previous trial (or from background activity in the case of the first test). This additional fragment was used to perform the baseline correction procedure to exclude the influence of any previous activity on the execution of the current task. Then the obtained dependences of changes in oxy- and deoxyhemoglobin were averaged over 20 repetitions for each type of movement (fig. 2).

Performing the movement causes an increase in HbO and a decrease in HbR throughout the motor cortex. At the same time, there is a pronounced contralateral characteristic of hand movements. The amplitude of changes in HbO and HbR concentrations in the left hemisphere is greater than in the right. This is due to the movement of the right hand. Changes in HbO and HbR concentrations in response to movement are caused by an increased metabolic demand of the brain for oxygen, which leads to an overabundance of regional cerebral blood flow to meet the metabolic needs of the brain. The hemodynamic response to an increase in neural activity is determined by several mechanisms of neurovascular interaction, in particular, a change in the diameter of capillaries [21]. Thus, an excess of cerebral blood flow causes an increase in the concentration of HbO and a decrease in the concentration of HbR.

The maximum hemodynamic response is located near the position of the EEG sensor C3

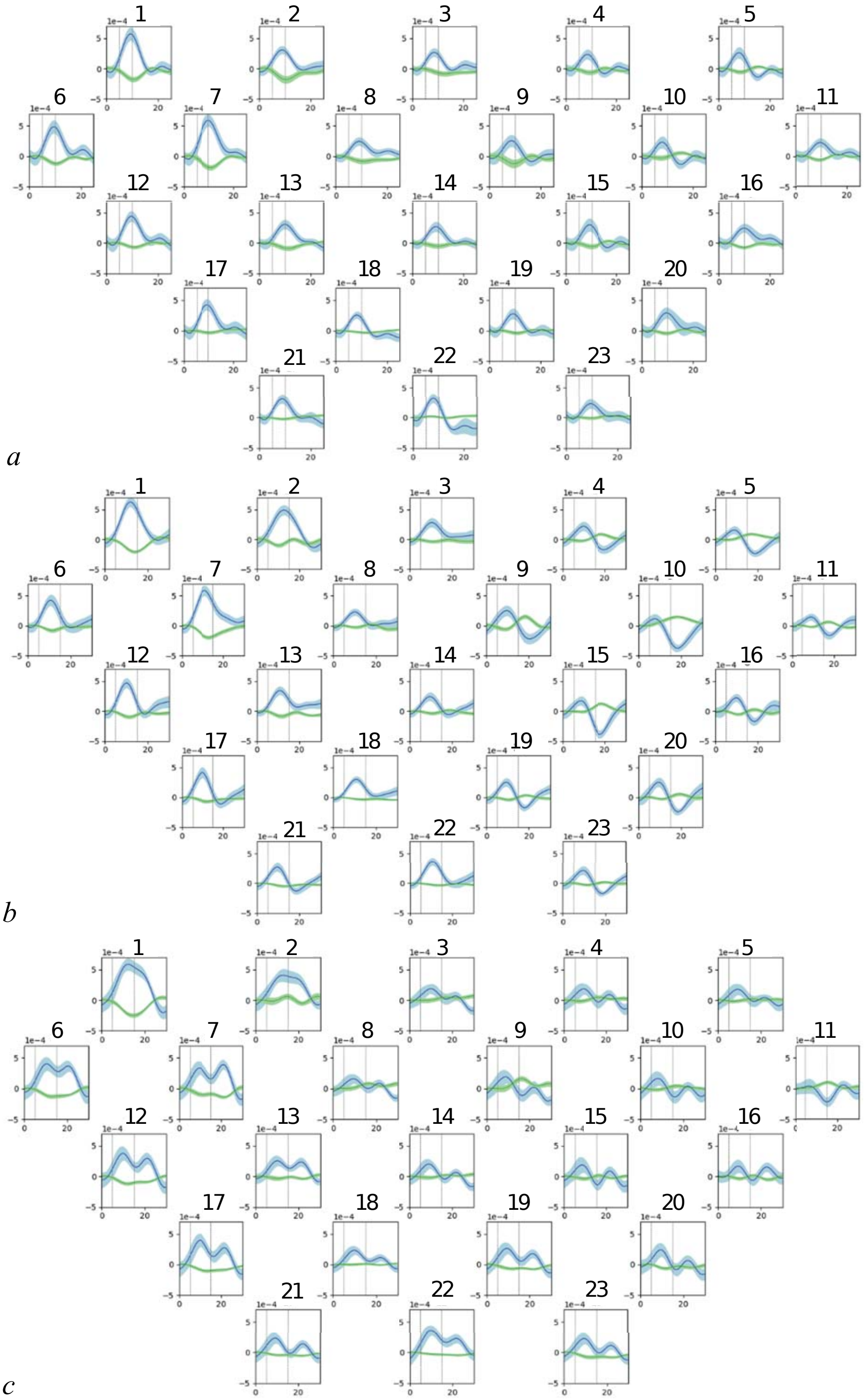

Fig. 2. Изменения окси- (синий) и дезоксигемоглобина (зеленый) для различных типов движения: *a* — одиночное движение; *b* — тэппинг; *c* — многократные повторения. Более светлым областям тех же цветов соответствует стандартная ошибка. Вертикальные штриховые линии обозначают начало/конец выполнения движения (цвет online)

Fig. 2. Changes in oxy- (blue) and deoxyhemoglobin (green) for different types of movement: *a* — single movement; *b* — tapping; *c* — multiple repetitions. Lighter areas of the same colors correspond to the standard error. Vertical dashed lines indicate the beginning/end of the movement (color online)

(см. рис. 1, *c*). According to the latest results, this area coincides with the location of the primary motor cortex (M1).

To analyze the differences between the movements, it was proposed to use a single characteristic, including changes in the concentrations of HbO and HbR. In the role of such a

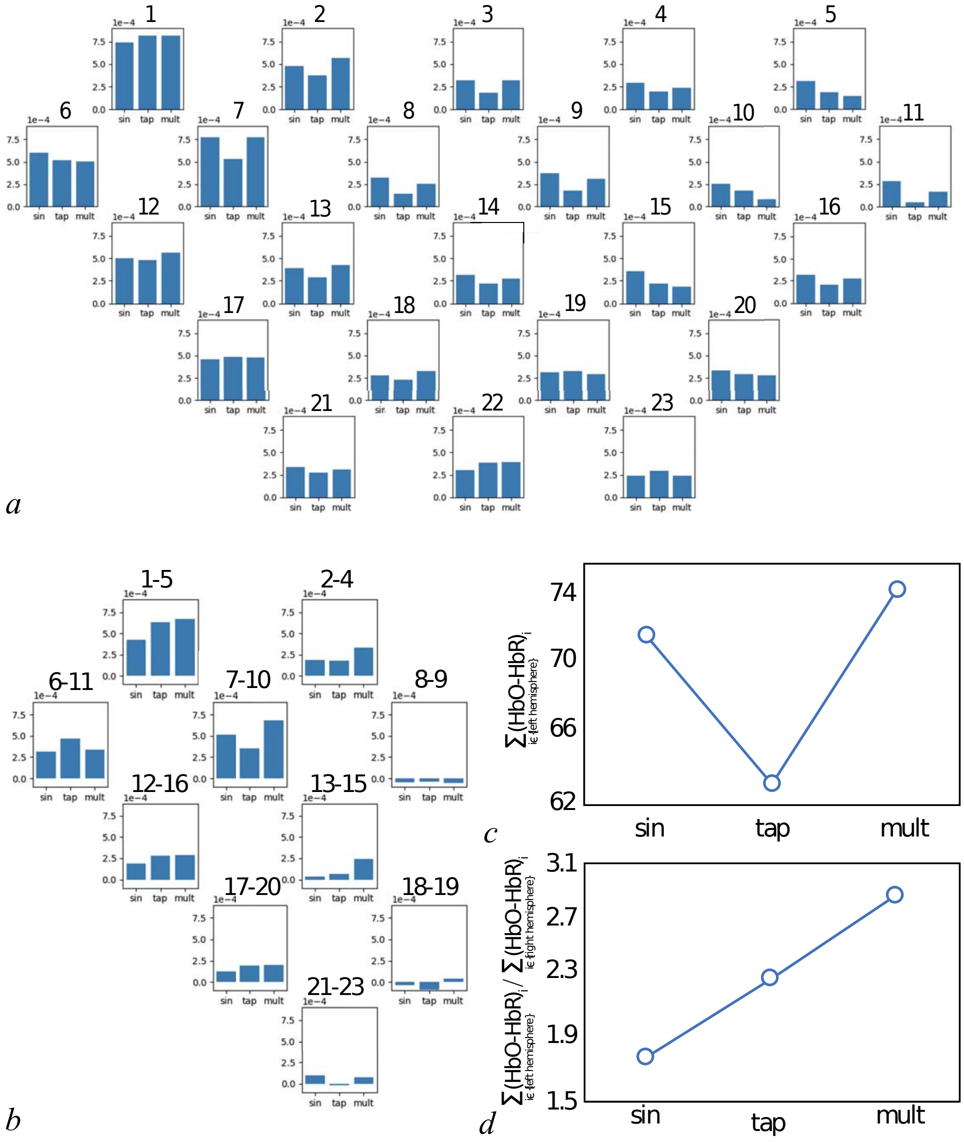

Fig. 3. *a* — Распределение по каналам максимальных значений амплитуды гемодинамического отклика для каждого типа движения; *b* — разница между максимальными значениями амплитуды гемодинамического отклика симметричных каналов левого и правого полушарий; *c* — суммарный гемодинамический ответ в левом полушарии для каждого из типов движения («sin» — одиночное движение, «tap» — тэппинг, «mult» — серия движений); *d* — отношение суммарного гемодинамического ответа левого и правого полушарий для рассматриваемых движений. Здесь в качестве гемодинамического ответа рассматривается разница между HbO и HbR

Fig. 3. *a* — distribution over channels of the maximum values of the hemodynamic response amplitude for each of the movement types; *b* — difference between the maximum values of the hemodynamic response amplitude of symmetrical channels of the left and right hemispheres; *c* — total hemodynamic response in the left hemisphere for each of the movement types (“sin” – single movement, “tap” – tapping, “mult” – series of movements); *d* — ratio of the total hemodynamic response of the left and right hemispheres for considered movements. Here, the difference between HbO and HbR is considered as a hemodynamic response

value is the difference between them — (HbO-HbR). This value often has a greater sensitivity to changes in the hemodynamic response than HbO or HbR individually [16].

The maximum values of the hemodynamic response for each channel and type of movement were found (рис. 3, *a*). It can be seen that the maximum values for all types of movements differ slightly from each other. The severity of contralterality for different types of movements was investigated, as the difference between the maximum amplitude values (HbO-HbR) between the symmetrical channels of the left and right hemispheres (рис. 3, *b*). An increase in the severity of contralaterality for tapping and multiple hand compressions was found, compared with a single hand compression.

The total hemodynamic response in the left and right hemispheres for each type of movement was studied (рис. 3, *d*). It is shown that the total hemodynamic response in the left hemisphere differs slightly between all types of movements. At the same time, the degree of contralaterality, considered as the ratio of the total hemodynamic response of the left and right hemispheres, demonstrates a significant difference between movements (рис. 3, *c*). Contralaterality is maximally expressed when performing a series of movements, and minimally expressed with a single compression.

Conclusion

The paper presents the results of comparing different types of movement, as well as various approaches to the analysis of hemodynamic response.

It has been confirmed that the distribution of response when performing a movement depends on the brain region. It is shown that the maximum responses appear in the hemisphere contralateral to the performing limb.

It is shown that the total hemodynamic response in the motor cortex of the left hemisphere differs slightly between all the types of movement under consideration, while the severity of contralaterality demonstrates significant differences between the types of movements. Contralaterality is most pronounced when performing a series of movements, while a single compression of the hand causes the least contralateral reaction. The presence of such asymmetry in the performance of the considered types of movements is probably caused by differences in associated neural activity, as a result of which each of the movements involves neural networks of different sizes or requires a different degree of their activation.

Differences in contralaterality also reflect changes in interhemispheric interactions between M1 regions of each hemisphere, as a result of which increased activation of neurons in M1 of one hemisphere causes a decrease in activity in M1 of the opposite hemisphere. This, in turn, causes an increase in oxyhemoglobin in the contralateral M1 cortex due to the presence of compensatory mechanisms and an increase in deoxyhemoglobin in the ipsilateral M1 cortex due to the activation of inhibitory connections between the hemispheres and ongoing metabolic processes.

The results obtained in this work are in good agreement with the previously known [22–24]. In particular, in work [22], an increase in neural activity in the contralateral hemisphere associated with the intensity of movement was found, leading to higher positive BOLD (Blood-oxygen-level-dependent) responses transmitted to the ipsilateral hemisphere and accompanied by a more pronounced negative BOLD response in this hemisphere. It should be noted here that a negative BOLD response compared to the baseline level occurs as a consequence of an increase in the content of deoxyhemoglobin.

Note that the results obtained in the work demonstrate the high sensitivity of fBICS technology to performing various types of movements. In particular, short single brush compressions are clearly visible on the characteristics of HbO and HbR, which can be used in the development and design of various brain-computer interfaces, including multimodal ones, as it opens up the possibility of using shorter commands when creating them. It should be noted that usually brain-computer interfaces based on fBICS technology require a long load, in particular, among motor tasks, the most popular is "tapping which requires activity of the order of 10 seconds.

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