Brain–computer interface technologies for monitoring and control of bionic systems

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Abstract. At the moment, neurocomputer interfaces (BCI) make it possible to implement on their basis devices for diagnosing a physical condition, implementing control systems for bionic prostheses, information input means such as neuro chat and character set systems based on brain potentials. At the moment, the main technology for obtaining brain activity for neurointerfaces is the electroencephalogram (EEG). There are promising technologies that will make it possible to achieve new results in the field of neurointerfaces. These technologies are functional near infrared spectroscopy (fNIRS) and magnetoencephalography (MEG).

1. Introduction

The rapid development of technology, the reduction in the cost of production and the increase in productive capacities through the inclusion of more and more advanced technical means, the development of computing systems, and medical technology sets the task of creating more and more advanced systems or devices for interaction and control of these technical means.

An interface is a device that allows a person to interact with and control machines and mechanisms. The culminating point of progress in this area is the control by means of reading signals from the brain, which science fiction writers have long dreamed of. Nowadays, it is gradually becoming a reality - so much so that the first wearable neurocomputer interfaces appear on sale. All this is becoming a common scientific and technical problem, a practical solution to which teams of scientists and developers around the world are looking for.

Neurocomputer interfaces are currently actively used in medicine for the treatment of people with impaired motor functions, serve as the basis for the development of control systems for external devices and systems. Modern neurocomputer interfaces are able to control mechanical prostheses of arms and legs.

In turn, there is the possibility of using neurointerfaces in solving the problems of creating adaptive control systems for robotic subsystems of various enterprises, diagnosing the human condition to identify various pathologies, diagnosing the state of operators to prevent errors associated with the human factor.
2. Brain biopotentials used in BCI

2.1. Brain rhythms
EEG activity, which is waves of approximately the same constant frequency, is called rhythm. The most pronounced rhythm in the EEG is called dominant. If the amplitude of the waves of rhythmic activity gradually increases and then decreases, the rhythmic activity is said to be spindle-shaped.

Usually, several basic EEG rhythms are distinguished: delta rhythm, theta rhythm, alpha rhythm, beta rhythm (Figure 1).

![Figure 1. The main rhythms of the brain.](image)

Delta rhythm. The delta rhythm includes EEG waves in the frequency range of 0.5-3.5 Hz. The delta rhythm is the main rhythm of slow-wave sleep, when its amplitude reaches 300 μV or more.

Theta rhythm. According to the data of different studies, the boundaries of the theta rhythm differ somewhat, but on average we are talking about oscillations with a frequency of 4 to 8 Hz. Normally, the amplitude of the waves does not exceed 40 μV. An increase in the theta rhythm index can, on the one hand, indicate pathology, and on the other, reflect certain functional states associated either with a decrease in the level of brain activity, or, on the contrary, with concentration, cognitive and emotional activation.

Alpha rhythm. The alpha rhythm includes well-modulated, high-amplitude (average amplitude 60-80 μV) rhythmic activity with a frequency in the range from 7.5 to 13 Hz. It is registered in more than 85% of healthy adults. The alpha rhythm is best expressed in healthy adult subjects in a state of calm wakefulness with their eyes closed, mainly in the parieto-occipital regions of the brain. Depression of the alpha rhythm indicates a general activation of the cerebral cortex. Opening of the eyes or mental activity is usually accompanied by depression of the alpha rhythm. An important feature of alpha activity is its functional asymmetry under various cognitive and emotional stress.

Beta rhythm - frequency 14-35 Hz, amplitude up to 15 μV (low-frequency - 14-25 Hz and high-frequency beta rhythms - 26-35 Hz are distinguished). These rhythms are well expressed in the frontal and temporal regions. Both synchronization and desynchronization of beta activity are associated by many authors with various types of emotions and cognitive processes. Synchronization of the beta rhythm in the frontal areas is associated with the processes of attention.
2.2. Evoked potentials

Evoked potentials (EP) are bioelectric signals that appear at constant time intervals after certain external influences. Richard Caton in 1875 first showed that electrical potentials arise in the brain in response to stimulation of a sensory organ. The study of the EP of the brain is based on the registration of electrical responses of the brain to exogenous stimuli (visual, auditory, sensory), as well as endogenous events associated with expectation, recognition, decision-making, and initiation of a motor response. EP is recorded from electrodes located on the surface of the patient's head. The IP method appeared almost 20 years later than electroencephalography. The use of highly sensitive amplifiers for EP recording makes it possible to isolate weak signals from the central nervous system (CNS), which are 5–100 times less in amplitude than the usual spontaneous brain activity. The electrical responses of the brain to visual, auditory, or sensory stimuli are assessed by changes in the main EP parameters - the amplitude and latency of various response components. The main method for identifying endogenous events, which has significantly advanced the analysis of cognitive processes, is the study of the cognitive potential of P300, in the implementation of which the temporomandibular and brainstem- reticular structures are actively involved in humans. P300 is only part of the complex potential that arises in the directed attention model when performing a cognitive task. The selection process for a significant stimulus includes a purely sensory part associated with physical parameters, mainly reflected in the indicators of early EP components. The next stage is the primary recognition and classification of stimuli, which is most clearly reflected in the negative deviation in the region of 96-250 ms after the onset of the stimulus, which is designated as N2 (N200). This is followed by the final identification of the stimulus, which requires comparing it with a pattern in memory and making a decision regarding the action associated with it. The potential P3 (P300) itself is associated with these events (Figure 2).

![Figure 2. CVL (P300) in healthy subjects of different ages. A - the sensory part of the response (N-P complex) - averaging the response to an insignificant stimulus; B - sensory (N1-P2) and cognitive (N2-P3-N3) parts of the response when averaging responses to a significant stimulus; 1 - healthy subject A., 25 years old, latent period P300 - 331 ms, amplitude - 12 μV; 2 - healthy subject L., 55 years old, P300 latency - 363 ms, amplitude - 6.8 μV.]

There is a clear dependence of P300 indices on age. Starting from the age of 7, there is a tendency to a decrease in the latency period of the P300 peak up to 18–20 years, that is, the latency period is inversely related to age, reflecting such processes as cognitive development. After this moment, the actual "aging curve" begins, since then the latent period of P300 increases at a rate of 1.25 ms per year, and its amplitude decreases at a rate of about 0.1 μV per year. These changes in the amplitude-temporal parameters of cognitive EP (CEP) are associated with the normal aging process, accompanied by a
decrease in the number of dendritic spines and a decrease in the density of synaptic contacts at the level of cerebral neurons. The essential advantages of this technique are the objectification of the data obtained, as well as the ability to detect early cognitive impairments. The method is useful not only for the diagnosis of the latter, but also for the differential diagnosis between cognitive impairment, dementia, and functional disorders, including depression.

2.3. Readiness potential
Movement-related cortex potentials (MRCP) are endogenous evoked potentials released in connection with the initiation of voluntary movement. MRCP was first described by Kornhuber H. and Deecke L. in 1964. From this moment on, the potentials associated with movement are the subject of discussion in the field of the study of voluntary motor action. The brain potentials associated with movement are subdivided into several subcomponents. The earliest, called Bereitschaftspotential, BP, or readiness potential, occurs on average 2,000 ms before the start of the movement. This slowly increasing negative wave is most pronounced in the mid-central parietal area and is bilaterally symmetrical. Approximately 400 ms before movement, as determined by an electromyogram, the BP gradient rises quite sharply. The amplitude of this wave is maximum in the central and parietal area, contralateral to the movement. Due to the different distribution over the scalp, the described BP segments are designated differently: (1) early BP and (2) late BP or negative slope (NS). The readiness potential ends approximately 150-500 ms before the start of movement with a short positive oscillation (premotor, or premotional, positivity, PMP; P-50). Subsequent negativity (motor potential, motor potential, MP; N-10) coincides in time with the beginning of movement and is most pronounced in the central region, the contralateral moving part of the body. After the movement, 4 more components are distinguished: N + 50 - negative frontal peak; P + 90 and N + 160, predominant in the contralateral parietal region. The fourth component, expressed approximately 300 ms after movement, is a positive potential widely distributed in the precentral and somatosensory areas contralateral to the movement. A positive post-motion wave is sometimes referred to as a reafferent potential (response after potential, RAP).

Readiness potentials in the study of cognitive processes. As mentioned above, the readiness potentials have an asymmetric distribution just before the movement (late readiness potentials). It is believed that the onset of readiness potential lateralization reflects the moment of making a decision in a situation of choice - for example, pressing a button with the right or left hand, depending on the presented stimulus. It is caused by differentiated activation of the motor cortex of the left and right hemispheres during the preparation and initiation of a unilateral motor response.

The electrophysiological indicator of the central activation of motor responses is the lateralized readiness potential (LRP) obtained by the double subtraction method of the amplitudes of the potentials recorded separately above the right and left hemispheres from the corresponding electrodes. Lateralized readiness potentials are used in psychophysiology and neuropsychology to assess the central mechanisms of choice reactions, the characteristics of reaction time intervals, and in the study of learning mechanisms.

3. Technologies used in BCI

3.1. Electroencephalography
Electroencephalography (EEG) is a method for examining the brain based on recording its electrical potentials.

The concept of "electroencephalography" is dualistic, it combines, in fact, two terms: methodology and technique.

Electroencephalography is a branch of electrophysiology that studies the mechanisms of generating the total bioelectric activity of the brain, as well as a neurophysiological technique for recording the bioelectrical activity of the brain from the convexital surface of the head.

The subject of EEG research in the clinic is the bioelectric activity of the brain in diseases (lesions) of the brain. Such studies can be defined as a clinical EEG. Clinical EEG, in turn, has long ceased to be
homogeneous. At least three relatively independent areas can be distinguished: epileptological, nonepileptological, and EEG of critical conditions (EEG studies performed in the intensive care unit for acute cerebral failure).

Research is carried out in psychology and psychophysiology, in which the subject of consideration is the neurodynamics of the brain of a healthy person. This type of EEG can be defined as a physiological (psychophysiological) EEG. Understanding the specific tasks of each of the directions and correlating them with the methodological capabilities of the EEG make it possible to effectively carry out research and receive deep satisfaction from the results obtained.

Disadvantages and limitations of electroencephalography:

EEG registration makes it possible to assess the state of the system for generating the total bioelectric activity of the brain. The "efficiency" of the mechanisms of bioelectrogenesis is a reliable neurophysiological correlate of the functional state of the central nervous system (CNS). EEG, like any functional technique, cannot localize structural lesions. EEG cannot, according to the parameters of neurodynamics, invariantly state disorders of mental functions and assess their severity. The amplitude-frequency parameters of the EEG correlate weakly with the course of mental functions.

Method advantages:

Unlike EEG, such neuroimaging methods as "functional neuroimaging" in a large number of cases are insufficiently sensitive and specific, especially at the initial stages of brain diseases or when metabolic disorders prevail over structural and morphological disorders, as in some forms of sclerosing and necrotizing encephalitis, degenerative and dynamic ischemic disorders.

3.2. Magnetoencephalography

MEG technology is based on the measurement of the magnetic fields in the brain that arise from the electrical activity of the brain. This method allows you to work with a signal time resolution of the order of 1 ms and is able to penetrate 5 mm in depth. For comparison, the EEG has a resolution of 4 ms and is capable of picking up potential from the surface of the cerebral cortex. The devices for recording MEG are based on superconducting sensors cooled by liquid helium. The number of recording sensors in one device can reach half a thousand. Most often, magnetoencephalographs measure the magnetic field gradient and can be operated outside a shielded chamber. When registering MEG, superconducting gradiometers located in a special fiberglass Dewar vessel are located at a distance of about 1–2 cm from the surface of the head. The MEG was registered for the first time in 1968.

The technical difficulties of MEG are associated with the fact that the magnetic fields generated by the brain are very weak compared to the permanent magnetic field of the Earth and the fields generated by electrical devices and skeletal muscles of the body. In recent years, the improvement of MEG registration has been achieved with the use of highly sensitive magnetic sensors based on a superconducting quantum mechanical interference device (SQUID). By choosing the appropriate configuration of the SQUID coils, it is possible to achieve relative protection of the magnetometer from external magnetic fields. The time resolution of the MEG is 1 ms.

MEG is widely used in a neurosurgical clinic for localization of an epileptic focus, in monitoring post-traumatic and post-stroke conditions. The complex use of MEG with the method of evoked potentials makes it possible to identify with high accuracy in the cortex GMs involved in the processing of sensory information and the organization of motor acts.

At the moment, devices based on MEG technology are stationary equipment. But at the moment, developments are underway related to reducing the size of this equipment and the implementation of wearable options. such a development is OPM-MEG, developed by researchers from the University of Nottingham (UK), University College London and QuSpin.

3.3. Functional near infrared spectroscopy

fNIRS is a brain imaging technology that uses optical techniques to detect changes in hemodynamic activity in the cerebral cortex in response to sensory, motor, or cognitive activation [15], [16]. fNIRS depends on the location of near-infrared light sources and detectors on the scalp. Oxygenated (HbO2)
and deoxygenated (HHb) hemoglobin are the dominant light-absorbing elements in the brain at near infrared wavelengths and have different light absorption patterns. Thus, fNIRS can record changes in HbO2 and HHb concentrations that occur during brain activation [17]. FNIRS technology can achieve a resolution of 10 ms and a penetration depth of up to 40 mm. Like other hemodynamic-based neuroimaging techniques, fNIRS can provide information on the specific location of recorded hemodynamic activity. However, compared to fMRI or PET, fNIRS is affordable and easy to implement in a portable system, allowing for a wider range of uses. By linking fNIRS to MEG, we can additionally take advantage of the good temporal resolution provided by the latter. After all, MEG can collect information about rapid cortical-cortical or thalamocortical oscillations, which play a crucial role in the development and integration of information in cognitive networks. Therefore, based on the additional benefits offered by MEG and fNIRS, their integration can provide higher spatial-temporal resolution than any other method.

4. Conclusions
The fNIRS technology, due to its compactness, the type of data obtained and the possibility of contactless data acquisition, is promising for use in neurointerfaces for monitoring the physical state and the possibility of creating control systems when used in conjunction with faster methods such as EEG or MEG.

Developments related to reducing the size of equipment for MEG will allow us to create more comfortable wearable devices with a resolution higher than that of EEG and combine with methods such as fNIRS to expand the range of possible applications of these devices.

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