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Rehabilitation possibilities for children with cerebral palsy through the use of robotic devices and biofeedback

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ABSTRACT

This article overviews and systemizes published data on the ways of implementing different methods of biofeedback, robotic devices, and brain-computer interfaces (BCI) for rehabilitation of children with cerebral palsy (CP).

Aim. To survey implementation practices and clinical outcomes of rehabilitation technologies and possible neurophysiological mechanisms underlying their efficacy in patients with CP. We searched PubMed, Web of Science and eLIBRARY.ru databases for relevant publications using specified keywords.

Results. The analysis of relevant literature has shown that robotic technologies and BCIs with biofeedback based on electroencephalography and electromyography parameters are rapidly developing and implemented for the rehabilitation of children with CP. The first evidence of effectiveness for such methods and approaches has been found. However, there is a lack of fully developed conventional standards for the use of such rehabilitation methods and protocols in children. Control groups comprising of children with CP are often absent in such studies. In many cases, the variations of neurophysiological and neurochemical parameters before and after a course of rehabilitation are not evaluated. Having such data would help clarify physiological mechanisms underlying effective rehabilitation of motor functions and then design more adequate rehabilitation procedures and medication protocols.

Key words: children, cerebral palsy, biofeedback, robotic exoskeleton, brain-computer interfaces.

Conflict of interest. The authors declare that there are no obvious and potential conflicts of interest associated with the publication of this article.

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Возможности реабилитации детей с синдромом ДЦП с применением роботизированных устройств и биологической обратной связи

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РЕЗЮМЕ

Обзор литературы посвящен систематизации имеющихся данных о применении методики биологической обратной связи, роботизированных устройств и интерфейсов «мозг – компьютер» в реабилитации детей с синдромом детского церебрального паралича (ДЦП).

Цель – изучить опыт применения, клиническую эффективность реабилитационных технологий у пациентов с ДЦП и возможные нейрофизиологические механизмы, лежащие в их основе. Поиск по ключевым словам (дети, ДЦП, биологическая обратная связь, роботизированные устройства, интерфейс «мозг – компьютер», экзоскелеты) был проведен с использованием баз научной литературы Pubmed, Web of Science, eLIBRARY.ru.

Результаты. Проведенный анализ данных литературы показывает, что в настоящее время в реабилитации детей с синдромом ДЦП активно развивается применение роботизированных устройств и интерфейсов «мозг – компьютер» с биологической обратной связью по параметрам электроэнцефалограммы и электромиограммы. Получены первые доказательства эффективности указанных методов и подходов. В то же время не полностью разработаны стандарты использования таких методов в реабилитационной практике и протоколы работы с детьми. Не всегда создавались контрольные группы из детей с ДЦП. Во многих исследованиях не оценивалась динамика нейрофизиологических и нейрохимических показателей до и после курса реабилитации. Такие данные позволили бы уточнить физиологические механизмы восстановления моторных функций и более корректно подходить к назначению реабилитационных процедур и медикаментозного лечения.

Ключевые слова: дети, ДЦП, биологическая обратная связь, роботизированные устройства, интерфейс «мозг – компьютер», экзоскелеты.

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

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INTRODUCTION

Cerebral palsy, among all diseases of the nervous system, is the main cause of disabilities in children [1, 2]. In the Russian Federation, the prevalence of reported cases of cerebral palsy is 2.2–3.3 cases per 1000 newborns [3].

Cerebral palsy is described in modern special literature as a group of non-progressive syndromes caused by impaired development or damage of brain motor centers in antenatal, intranatal or neonatal periods of individual development that vary widely in etiology, clinical manifestations, severity and prognosis [4–6]. Multiple reasons underpinning the emergence of this disorder have been discovered. There are several risk factors for pregnancy, childbirth and the perinatal period, which include premature birth, multiple pregnancy, prenatal development disorders, intrauterine infection, placental pathology, congenital malformations, asphyxia, perinatal infection, perinatal stroke, cervical spine injuries and many others [7].

Cerebral palsy is characterized by impairments in motor functions associated with abnormal development of statokinetic reflexes, muscle tone pathology, and paresis. Secondary changes in nerve and muscle fibers, joints, ligaments, and cartilage develop in the course of a patient's lifetime. Various cognitive and mental disorders are often present in the disease as well [8]. The severity of such disorders can vary from mild emotional abnormalities to severe cognitive impairments. Movement disorders in cerebral palsy are often combined with mental retardation, epileptic seizures, and learning difficulties. Sometimes children have concomitant pathological changes in vision, hearing, sensitivity and various pathologies in internal organs, which exacerbate delays in psychomotor development [9].

Due to the variety of clinical manifestations of cerebral palsy in children, the widely used medical and physiotherapeutic methods of care can sometimes be seen as lacking efficiency. Many authors emphasize the importance of searching for novel recovery techniques and evaluating their efficiency [10]. Of particular relevance are various methods of rehabilitation based on the use of biofeedback (BFB), robotic devices, and brain-computer interfaces, because such methods allow enabling natural physiological resources in a child's brain.

BIOFEEDBACK BASED ON ELECTROMYOGRAM

The technique of electromyographic biofeedback (EMG-BFB), or functional biocontrol, has been used for rehabilitation of patients with cerebral palsy since the 1980s [11]. The method is built up on the principle of training active motor control based on visual and sound information about the produced movements in real time. Using this information, patients are able to deliberately adjust their movement patterns [12, 13]. In early studies, automated devices informing patients of an optimal level of muscle activation or relaxation with sound or color signals were implemented. The EMG in antagonist muscles (flexors and extensors in hand and fingers, shoulder biceps and triceps muscles, tibia and calf muscles, etc.) during movement in children with cerebral palsy was used as signals to control devices. In one of such works [11], an automated device was used in the treatment of 53 patients with spastic diplegia aged 8–14 years. Control group consisted of 15 patients with the same condition. A series of EMG-BFB training sessions (on average, 20 trials, 10–30 minutes long) significantly improved functional properties of affected muscles, their control and coordination. The same improvement was not seen in the control group.

A recent study conducted in the Republic of Korea [14] demonstrated the advantages of using the EMG-BFB technique when the feedback signal is given in a form of a visual image in a virtual reality environment. The study involved 18 children aged 7–15 with a spastic cerebral palsy and 8 healthy children of the same age, whose movement characteristics and EMG activity were used as control values. All children with cerebral palsy first underwent an EMG-BFB session (30 minutes long), with the EMG in biceps and triceps during elbow flexion and extension being represented in the form of a simple graph on a computer screen. In a week, the next EMG-BFB session with the same duration was conducted, with the feedback signal in the form of a video game depicting a character inflating a balloon. The balloon size depended on the EMG power in antagonist muscles when the arms moved. This type of biofeedback led to a significantly greater improvement in movement parameters and ability to achieve neuromuscular balance in the elbow joint, compared to the use of a simple EMG graph as feedback. The authors believe that implementing a video game as a feedback signal improved motivation and provided positive emotions for children, giving more efficiency to the processes of multisensory integration for planning and executing movement.

IMPLEMENTING ROBOTIC DEVICES IN TREATMENT OF GAIT DEVIATIONS

Recently, robotic devices have been widely used for motor function correction and to help patients with social adaptation. Rehabilitation with the use of these devices is based on motor learning [15]. Exoskeletons directly controlling limb joint movements are considered the most physiologically fit mechanism for motor disorders rehabilitation [16]. Such devices facilitate long workouts, improve movement patterns, increase motor activity and endurance. Although movement patterns are produced externally, without biological signals from the patient's body, limb movements provide a flow of reverse afferentation, which positively affects neocortex status.

Wearable leg exoskeletons with built-in electric motors controlled by signals from the child's body have been designed to correct gait deviations in cerebral palsy. They help in correcting crouch-gait in patients with cerebral palsy. Engines are started by means of mechanical sensors due to the child's limb movements. This type of exoskeleton was first tested on a six-year-old subject with spastic diplegia. The results of the study showed that the child's gait parameters improved. The use of exoskeleton entailed no adverse side effects, as the activity of muscles in knee extensors did not decrease [17]. The follow-up study involved six subjects aged 6–19 who had the same condition [18]. After six sessions of 2–4 hours each, half of the participants had improved knee extension parameters. Analysis of brain activity showed that the pattern of electroencephalogram (EEG) changes in the child's neocortex during exoskeleton movements corresponded to that associated with self-initiated movement launch and execution processes. Therefore, it proved that the involvement of the cerebral cortex in organizing movement acts was not reduced. It should be noted that the results of these studies are still of pilot, preliminary nature, and are based on a small sample of children with cerebral palsy.

Recently, Locomat (Switzerland) stationary robotic devices have widely been used. They provide a system for bodyweight support, automated leg orthoses and a treadmill. A group of Italian researchers (University of Verona) used Lokomat in combination with traditional methods of therapy (20 sessions of robotic walking and 20 of physiotherapy, 60 minutes each) in treatment of a small group of children composed of 16 boys and girls 4–18 years old [19]. The treatment resulted in an increase in endurance in a six-minute walking test, but the Gross Motor Function Measure (GMFM) and the modified Ashworth scale did not show a significant improvement in children's condition.

The most representative retrospective study, with the largest sample of patients, was carried out by a group of Italian authors from the IRCCS "E. Medea" Institute (Lecco) and Bambino Gesù Children's Hospital (Rome) [20]. They analyzed the effects of the Locomat-based robotic rehabilitation carried out in 2012–2017, in 72 children with cerebral palsy and 110 with brain injuries acquired postnatally which caused motor disorders (patients aged 4–18). For a month-long period, the children underwent 20 sessions of robotic walking and 20 sessions of physiotherapy lasting 45 minutes each. Assessment of motor functions with the six-minute walk test showed a significant improvement in both groups of children. However, the GMFM test revealed a statistically significant, compared to their initial state, improvement only in a group of children with acquired brain damage.

The most recent version of Lokomat, which displayed motion parameters in a virtual reality environment, was used in a study conducted by researchers from the University of Munich [21]. This allowed increasing the degree of children's involvement in controlling their walk. For 24 months, 20 children with cerebral palsy (mean age being 5.9 years) underwent three stages of treatment including 12 sessions (30–60 minutes duration) of robotic walking each. All types of traditional therapy assigned to them were still preserved. The Gross Motor Function Classification System (GMFCS) test showed a significant improvement in motor functions both after each block and after the entire course of treatment.

It is noteworthy that in each of the studies mentioned above, the use of robotic devices was carried out in combination with other traditional methods of treatment and physiotherapy, in particular. Control groups of children with cerebral palsy were not used. A randomized crossover study is suggested as an evaluation method to measure robotic walking techniques' actual efficiency [22]. The effects of conventional therapy and the use of robotic devices are to be compared, after being studied separately. However, to our knowledge, such studies are yet to be conducted.

IMPLEMENTING ROBOTIC DEVICES IN TREATMENT OF HAND MOVEMENT DEVIATIONS

To help correct deviations in hand motor functions in children with cerebral palsy, a number of robotic devices have been developed. The most popular are the following: InMotion 2 (a commercial version is named MIT MANUS), NJIT-RAVR, and CosmoBot [23].

Implementation of the InMotion 2 system (Fig. 1) helps children with cerebral palsy increase the accuracy of movements in achieving goals with an orthotic robotic arm. Children learn the training technique of the "arm reaches the object" movement in certain directions with a given level of support from the device [24–26]. Several studies [27–29] showed a positive change after a 6-8 week course of using the InMotion 2 system in children with cerebral palsy. A decrease in muscle tone and an improvement of the following kinematic parameters were found: an increase in speed and an improvement in the smoothness of arm movements.

The NJIT-RAVR system combines a robotic arm with virtual reality games to train movements in children with hemiplegia. Similar to InMotion2, the NJIT-RAVR system can both assist and resist movements produced by children. For example, among other virtual reality games, the "Get the mug" game was used in one of the studies [30]. In this game, a three-dimensional room is displayed on the screen with specially designed shelves and a table (Fig. 2). The goal of the game is to perform movements to place mugs on shelves. The study involved four children with cerebral palsy and four healthy children. After a three-week rehabilitation course, one-hour-long sessions three times a week, positive dynamics were found for a duration of time needed to achieve the goal, movement accuracy rate and movement trajectory [30].

Fig. 1. InMotion 2 system (MIT-MANUS commercial version) [26]

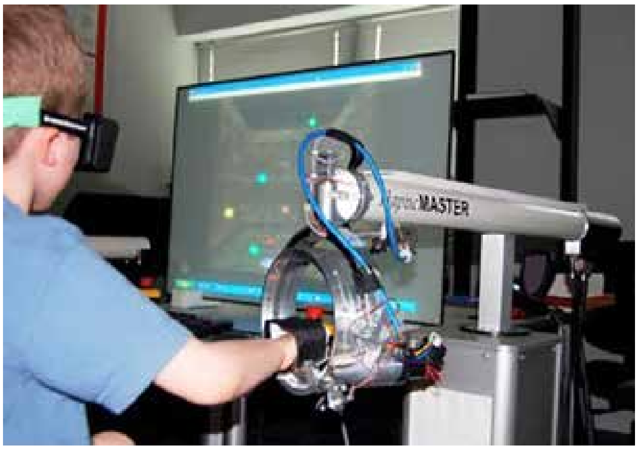
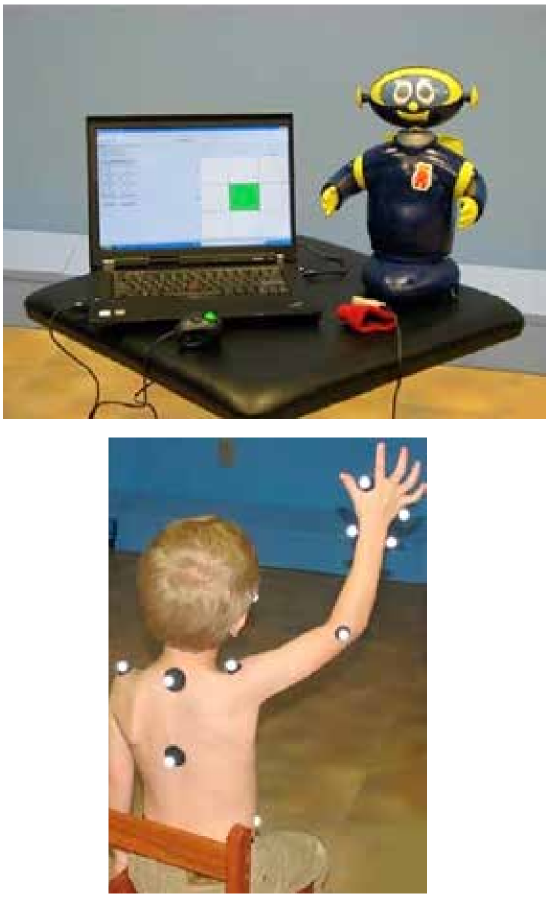


Fig. 2. NJIT-RAVR system [30]

One more version of a robotic rehabilitation system is the CosmoBot system (Fig. 3), developed by AnthroTronix (USA). This remote-control system serves to provide automatic visual and auditory feedback to patients when they try to solve a set of motor tasks. The system evaluates changes in the angle of movement (supination and pronation) in relation to the neutral primary position, which is adjusted individually for each patient.

A study with the CosmoBot system involved six children aged 5–18 with varying degrees of spastic quadriplegia and hemiplegia. Children underwent physiotherapy and robotic rehabilitation (crossover design). The CosmoBot-based rehabilitation was carried out for 20 minutes twice a week for five weeks. After the robotic therapy in children, their movement performance indicators improved to a greater extent in comparison to the traditional treatment [31].



a

b

Fig. 3. CosmoBot feedback system: *a* – graphical user interface allows therapists to set child's motion thresholds required to enable robot's motion; *b* – a child equipped with reflective markers for simultaneous measurement of movements for right shoulder, elbow, forearm and wrist during the "pull up" task [31]

Although positive effects have been identified for each of the mentioned robotic devices, it is not possible to compare them directly in terms of their efficacy. Experimental protocols in each study were different both in session and the entire course duration.

Besides, while some studies were conducted by implementing the InMotion 2 [27–29, 32] or NJIT-RAVR systems with virtual reality games [30, 33, 34], the others combined the InMotion 2 robotic therapy with injections of botulinum toxin type A (BTX-A) [35]. In most studies, children had varied diagnoses, and the sample sizes were extremely small (up to 10 people). These facts impose significant limitations on the possibility of comparing the results of the published studies.

BRAIN-COMPUTER INTERFACES AND THEIR IMPLEMENTATION IN REHABILITATION OF MOTOR FUNCTIONS

The efficiency of rehabilitation procedures, as noted by A.A. Frolov et al. [16], depends on the degree to which they are able to trigger mechanisms of brain plasticity for rebuilding its sensorimotor system. Exoskeleton movements must occur exactly at times when the brain is most susceptible to receiving peripheral signals, or, more precisely, when the patient is trying to make a movement. This approach still cannot be used in completely paralyzed patients or when a normal muscle co-activation process is impaired, which is present in many patients with cerebral palsy. In some studies dedicated to rehabilitation of stroke patients [36–38], brain-computer interfaces (BCIs) based on kinesthetic movement imagery were used to identify patients' intentions.

BCI is a combined hardware and software technology that allows for the control of external technical systems using signals registered in one's brain. A general BCI set includes a system for recording biopotentials and sending them to a computer, tools for filtering signals and selecting activity parameters most indicative of identifying human intentions, and an activity classifier and a tool for its pairing with an external technical device, which may be a prosthesis, exoskeleton or monitor screen [38]. When controlling the BCI, subjects receive feedback from the technical device, allowing them to compare their action with their intention. This approach ensures that the subject is focused on controlling the BCI and reinforces the successful completion of the task. Visual information is typically used as a feedback signal. In case the BCI is designed to control an exoskeleton, proprioceptive afferentation is used as well.

BCIs are classified according to the necessity of surgery procedures to record brain signals (invasive vs non-invasive IMC). Electrocorticogram or neural activity is used as signals of electrophysiological activity for invasive BCIs. For non-invasive BCIs, EEG and magnetoencephalogram are used. According to pattern types, non-invasive BCIs are divided into synchronous and asynchronous [38]. Synchronous BCIs are based on the analysis of EEG activity patterns in response to external stimuli; asynchronous BCIs are based on the analysis of EEG patterns that occur voluntarily following the emergence of subjects' intentions. Most BCIs that control movements of an external technical device are based on fulfilling the task of mental imagery in response to an external command. The practice of controlling such a BCI is an effective procedure promoting the rehabilitation of motor functions in post-stroke and post-traumatic patients [15].

Many present-day BCIs that are parts of systems designed for rehabilitation of motor functions are based on the analysis of the EEG sensorimotor rhythm patterns. This rhythm includes alpha and beta components [39]. The alpha component (10–12 Hz in adults), or the mu-alpha rhythm, is thought to reflect the level of activation of the postcentral somatosensory cortex, while the mu-beta component (peak frequency of about 20 Hz) is indicative of the precentral motor cortex activity. The response of the EEG mu rhythm in the form of desynchronization is considered to be an indicator of activation of corresponding zones of the cerebral cortex. Such a reaction manifests itself when the subject performs movements, imagines them, observes movements performed by others, and hears sounds characteristic of certain movements. The mu rhythm desynchronization starts about 1.5–2 seconds before the start of the movement. The individual frequency of mu rhythm depends on the age of subjects. During the first year of a child's life, the peak frequency of this rhythm increases from 3 to 8 Hz. In subsequent years, the increase in frequency gradually slows down and stabilizes in around 10 Hz by adulthood [40].

The mu-alpha rhythm is considered to have at least two components. The low-frequency component (8–10 Hz) is associated with "non-specific" desynchronization occurring in various motor tasks. The 10–12 Hz desynchronization of the mu-alpha rhythm is focused and specifically localized; it can be clearly identified in the movements of one's fingers and feet [41]. Since the representations of various organs (for example, arms and legs, right and left body parts) are distributed in the cortex over relatively large spans, it appears possible, by means of localizing this component of the mu rhythm, to quite accurately find the organ, the movement of which is being imagined by the subject [38]. The classifier of brain activity, in this case, activates an external robotic device or starts the exoskeleton movement. It has been demonstrated that intentions to make a movement in a stroke patient can be effectively associated with real movements made by an exoskeleton [42].

There are two possible types of BCIs clinical use: neurorehabilitation and social rehabilitation. Neurorehabilitation implies an improvement of motor functions as a result of BCI training, while social rehabilitation helps patients effectively adapt to real life, improving their self-care in everyday life and communication with other people [16, 43].

Despite some authors [44, 45] foreseeing excellent prospects for BCIs in the rehabilitation of children with cerebral palsy, there are only a few experimental works in this area. One of the first research works was a study showing the BCI potential use for patients with cerebral palsy based on the analysis of sensorimotor rhythm patterns and visual EEG-evoked potentials triggered by external stimuli [46]. The mu and beta rhythm modulations, associated with the task of imagining the process of executing certain movements with the subject's upper and lower limbs, were properly estimated by the classifier program.

Researchers from South Korea [47] used the BCI integrated with an electric stimulator of wrist extensor muscles. Electrical stimulation started based on an online analysis of EEG parameters: an increase in beta to theta rhythm powers ratio in frontal leads (an increase of the so-called attention index) when the patient imagined his hand being extended. A series of sessions for children with cerebral palsy resulted in improved parameters of children's hand movements, as well as an enhanced capacity to focus attention. This study proves that the technique of BCI-controlled electrostimulation can be effectively used in the neurorehabilitation of patients with cerebral palsy.

In the context of social rehabilitation, there is evidence of successful use of the BCI, controlled by the P300 potential parameters, when performing cognitive tasks on a computer by children with severe forms of cerebral palsy with both motor and speech disorders [48]. Similar results were collected when using a hybrid BCI system controlled simultaneously by the P300 event-related potential and EMG parameters in subjects with severe motor disorders. This system was developed to control a program designed to assist in writing words [49]. The authors of the work demonstrated that the use of the two-signal processing algorithm improves the accuracy of writing words and reduces the number of errors.

It has already been noted that the use of exoskeletons controlled by BCIs is considered to be the most optimal method for neurorehabilitation [38]. In this way, a central motor command is seconded by afferent kinesthetic signals related to its execution by an exoskeleton, thus, it is complemented by biofeedback. However, to our knowledge, an analogous system was used to help correct motor functions of upper limbs in children with cerebral palsy in only one clinical study so far, which was performed by researchers of the V.I. Vernadsky Crimean Federal University [50]. In this work, the Exokist 2 set was used together with a non-invasive BCI (Fig. 4) collecting data from the EEG in frontal, central, and parietal cortex areas. This set was manufactured by a consortium uniting the Android Technics SPA, N.I. Pirogov Russian National Research Medical University and the Institute of Higher Nervous Activity and Neurophysiology of RAS.

Fig. 4. Rehabilitation session with the use of Exohand-2 set.

The study involved 50 boys and girls with cerebral palsy (30 subjects in the main group and 20 in the control group) who had a level of motor activity not higher than III according to the Gross Motor Function Classification System (GMFCS). All patients underwent a standard course of health resort rehabilitation for 21 days. The patients of the main group were additionally rehabilitated with the help of the Exokist-2 complex paired with a non-invasive BCI. The results of the complex use showed that 70% of the main group patients had a significant decrease in spasticity according to the Ashworth (MAS) and Tardieu (MTS) Scales. In half of the patients, the paretic arm muscle strength significantly increased according to the Medical Research Council Scale for Muscle Strength (MRC-SS). The Modified Franchay Scale (MFS) showed an improvement in the manipulative capabilities of the hand. According to the ABILHAND-Kids Scale, a positive change in patients' ability to perform everyday activities appeared to be the most prominent. Changes in motor functions in the control group of patients with standard therapy were not statistically significant. It should be noted that modulations of the EEG and EMG parameters in children who used the Exokist-2 complex have not been analyzed in this publication.

CONCLUSION

The analysis of available publications shows that there is currently an increased interest in the use of robotic devices in the rehabilitation of children with cerebral palsy. The possibility to control robotic devices based on the analysis of patients' brain activity has been demonstrated. There is evidence of the efficacy of various methods and approaches based on the biofeedback method. On the other hand, standards for the use of such methods in rehabilitation practice and protocols for working with children are yet to be developed. Many studies do not provide data on modulations of neurophysiological indicators (EEG, EMG) and neurochemical parameters before and after a rehabilitation course with the implementation of robotic devices. Such data would help analyze physiological mechanisms underlying rehabilitation of motor functions and approach the assignment of rehabilitation procedures and medical treatment more accurately.

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