REHABILITATION OF PATIENTS WITH CEREBRAL PALSY USING HAND EXOSKELETON CONTROLLED BY BRAIN-COMPUTER INTERFACE

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Cerebral palsy (CP) is one of the most severe central nervous system diseases in childhood associated with motor impairment. The study was aimed to assess the efficiency of the complex comprising brain-computer interface (BCI) and hand exoskeleton as an instrument for the motor function recovery in patients with CP complementing the essential therapy. The Fugl-Meyer Assessment scale, ARAT test and Jebsen–Taylor function test were used in 14 children and adolescents for the motor function improvement assessment after the therapy complemented by 7–10 BCI-exoskeleton based procedures. The EEG mu-rhythm sources properties during the motor imagery BCI control were studied. After the procedures completion, the significant improvement of the Fugl-Meyer Assessment scale score (7 (2; 11) for hand active movements; 4.5 (1; 6) for proximal arm and 2.5 (0; 5) for hand), ARAT test score (7.5 (1; 31) for total score, 1.5 (0; 12) for grasp movement and 1.5 (0; 8) for grip movement), as well as significantly different from the zero execution time reduction in three out of seven Jabsen–Taylor function test items (–1 (–4.13; 0.25) for simulated feeding; –1 (–2; 0) for moving light and heavy cans) were identified. The average BCI detection level was 0.51 (0.45; 0.54) (max = 0.70). In most EEG recordings the mu-rhythm sources were detected, both for intact and affected hemispheres. The mu-rhythm desynchronization associated with motor imagery was observed, significantly affecting the BCI accuracy. The results obtained indicate that the use of BCI-exoskeleton complex effectively complements the standard rehabilitation methods for children with CP, and suggest that its clinical effectiveness in individuals with CP may be proven by enrollment of more patients.

Keywords: cerebral palsy, rehabilitation, brain-computer interface, hand exoskeleton, EEG

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Compliance with ethical standards: the study was approved by the Ethics Committee of Pirogov Russian National Research Medical University (protocol № 184 dated April 15, 2019). The informed consent was submitted by all patients' parents, adolescents aged over 14 submitted the additional informed consent.

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РЕАБИЛИТАЦИЯ БОЛЬНЫХ С ДЕТСКИМ ЦЕРЕБРАЛЬНЫМ ПАРАЛИЧОМ С ПОМОЩЬЮ ЭКЗОСКЕЛЕТА КИСТИ, УПРАВЛЯЕМОГО ИНТЕРФЕЙСОМ «МОЗГ–КОМПЬЮТЕР»

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Детский церебральный паралич — одно из тяжелых заболеваний центральной нервной системы у детей, сопровождающееся двигательными нарушениями. Целью работы было определить эффективность применения комплекса, объединяющего интерфейс «мозг–компьютер» (ИМК) и экзоскелет кисти, в качестве средства восстановления двигательной функции у пациентов с ДЦП в дополнении к основной терапии. У 14 детей и подростков по шкалам ARAT, Fugl-Meyer, Jebsen–Taylor оценивали изменение двигательной функции в результате терапии, дополненной 7–10 процедурами с комплексом ИМК–экзоскелет, а также исследовали свойства источников μ-ритма ЭЭГ при воображении движений во время управления ИМК. После процедур были выявлены достоверно положительный прирост баллов по шкалам Fugl-Meyer (7 (2; 11) — для активных движений руки; 4,5 (1; 6) — для проксимальных отделов и 2,5 (0; 5) — для кисти), ARAT (7,5 (1; 31) — для общей суммы баллов, 1,5 (0; 12) — для шарового и 1,5 (0; 8) — для цилиндрического захвата) и достоверно отличное от нуля снижение времени выполнения трех из семи задач теста Jabsen–Taylor (–1 (–4,13; 0,25) — для имитации кормления; –1 (–2; 0) — для перестановки легких и тяжелых банок). Средняя вероятность правильного распознавания ИМК составила 0,51 (0,45; 0,54) (max = 0,70). В большинстве записей ЭЭГ были выделены источники μ-ритма, как в сохранном, так и в пораженном полушарии. Показано наличие десинхронизации μ-ритма при воображении движений, от степени которой достоверно зависит точность работы ИМК. Результаты показывают, что применение комплекса ИМК–экзоскелет эффективно дополняет стандартную реабилитацию детей с ДЦП, а также дают основания предполагать, что ее клиническая эффективность в случае ДЦП может быть доказана с привлечением большего числа пациентов.

Ключевые слова: ДЦП, реабилитация, интерфейс «мозг–компьютер», экзоскелет кисти, электроэнцефалограмма

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Cerebral palsy (CP) is one of the most severe central nervous system (CNS) diseases in childhood associated with organic brain lesions. The prevalence of cerebral palsy in the developed world is 2–3 per 1000 live births [1]. CP is not only the most prevalent CNS pathology in childhood, but is also one of the most common causes of disability.

CP is associated with motor impairments of varying degrees found in patients with all common types of the disorder: spastic diplegia — 69.3%, hemiplegic cerebral palsy — 16.3%, atonic-astatic type — 9.2%, hyperkinetic type — 3.3%, double hemiplegia — 1.9% [2]. The traditional physical rehabilitation methods are as follows: massage, exercise therapy, instrumental kinesiotherapy, as well as physical therapy and electrophysiology helping to decrease spasticity. However, spasticity reduction is just the first step towards increasing the patients' functional activity. There is an urgent need in using the goal-directed functional therapy for further rehabilitation. Methods based on the brain plasticity stimulation are considered promising, particularly those using motor imagery [3]. Fundamental is the idea of successful attempt to imagine movement positive reinforcement using visual and proprioceptive feedback provided by brain-computer interface (BCI)-controlled exoskeleton. BCI classifies the acquired electroencephalogram (EEG) parts and in case the required motor imagery is detected turns on the exoskeleton which executes the appropriate movement providing the proprioceptive feedback. EEG classification is possible due to specific motor imagery patterns, especially the mu-rhythm desynchronization in the primary sensorimotor cortex during the limb imaginary movement detected in healthy individuals [4]. Rehabilitation approach based on the BCI-controlled hand exoskeleton use is considered the efficient method of motor function recovery well-proven in the post-stroke patients' rehabilitation [5, 6]. The method implements the principles of modern neurorehabilitation: patient's active involvement, training intensity and regularity, biofeedback. The technique was validated in randomized controlled trials of post-stroke motor function recovery [7–10].

It is to be hoped that rehabilitation using the BCI-exoskeleton complex would be also effective for children with CP, since the specific brain disorders occur during the period of maximum adaptability and brain plasticity, when the projections from the affected areas of the central nervous system have not yet reached their targets. Such disorders can interfere with the neuron maturation processes [11]. High brain plasticity patterns adaptivity typical for early development plays a positive role in healthy individuals contributing to the formation of motor skills. However, in patients with brain disorders the same patterns may provoke the normal development threatening atypical compensatory motor synergies formation, which often occurs in children with CP [12]. The underlying factor is inadequate plasticity, for example when plastic changes in neuronal circuits during the focused use of the intact limb lead to reduced neuronal activation in the remaining cortex (representing the affected limb) [13].

Motor imagery with kinesthetic feedback activates the brain plasticity pattern and thus teaches the child to perform hand flexion, as well as facilitates execution of atypical but functionally significant movements. That is the whole purpose of rehabilitation using the BCI-exoskeleton complex in patients with CP.

According to studies of kinesthetic imagination, in children with CP, motor imagery activates the same brain regions as in post-stroke patients [14]. It has been also shown that in healthy children the motor imagery ability develops between 5 and 12 years of age and contributes to the motor skills improvement [15]. In children with CP, the described ability is relatively preserved, though reduced compared to normal [16]. Moreover, the motor imagery ability does not depend on the lesion lateralization [17].

Thus, the kinesthetic motor imagery training is of high potential for motor function recovery in children with CP [17, 18]. The study was aimed to assess the efficiency of BCI-exoskeleton complex for rehabilitation of patients with CP. The motor imagery ability was assessed based on the the BCI accuracy and the mu-rhythm desynchronization level in the primary sensorimotor cortex of the hemisphere opposite to the hand used during the motor imagery procedure.

METHODS

The study was carried out at the Russian Children's Clinical Hospital of Pirogov Russian National Research Medical University from May 2019 to February 2020. The total of 14 patients underwent the motor imagery based rehabilitation course using the BCI-controlled hand exoskeleton (Table 1).

Inclusion criteria: age 7–19; patients with central paralysis of the upper extremities, including those diagnosed with cerebral palsy, acute cerebrovascular disease, traumatic brain injury; structural brain lesion identified using neuroimaging techniques. Exclusion criteria: inability to perform the procedures during the study; refusal of patient or his legal representative to participate in the study; extreme aphasia preventing understanding the instructions; severe visual impairment making it impossible to follow the instructions on the computer screen; hand spasticity score 5 according to the Modified Ashworth Scale. The withdrawal criteria were as follows: patient's refusal to continue participating in the study; acute or decompensated chronic disorder potentially affecting the research results; prescription of muscle relaxants (changing the dosage after the patient's inclusion to the study); botulinum toxin preparation injected into the paretic hand muscles after the patient's inclusion to the study.

The procedures were carried out using the Exohand-2 robotic hand complex comprising the BCI-controlled hand exoskeletons. The patient was seated in the medical chair. His hands were put in the hand exoskeletons fixed on the armrests of the chair. In front of the patient at a distance of 1–1.5 m a monitor was placed with a circle for gaze fixation and the visual instructions to perform the following mental tasks: either kinesthetic imagination of the left or right hand opening, or sitting still and relaxed. Neuropsychologist was called upon in the following situations: 1) child's lack of motivation to participate in the procedure; 2) difficulty in understanding the instructions to imagine the movement; 3) pronounced attention problems; 4) phobias and/or panic attacks experienced during the procedure. In the described situations the causes of trouble were diagnosed, and the kinesthetic motor imagery training was carried out.

In order to facilitate the difficult kinesthetic motor imagery task and to make it easier to understand, the clues were used that simplified the imaginary motion initiation (Table 2). The age of the child, his interests, as well as the cognitive functions development level were taken into account.

In children with cognitive deficit, it was recommended to use metaphors proposed for the younger age group. In children with pronounced tendency towards absent-mindedness, increased toggling between associations, as well as violation of purposeful activity, the explanations were simplified and reduced as much as possible, using precise language.

Table 1. Study participants' characteristics

Participant	Gender	Age	Diagnosis	Lateralization
1	Female	11	Consequences of traumatic brain injury	Left-sided hemiparesis
2	Female	16	Spastic hemiplegia. Spastic hemiparesis on the right side	Right sided hemiparesis
			Condition after osteoplastic trepanation, functional hemispherotomy on the left side	
3	Male	17	Spastic cerebral palsy, tetraplegia	Left-sided dominant tetraparesis
4	Female	17	Unspecified cerebral palsy	Left-sided hemiparesis
			Spastic hemiplegia	
			Localization-related (focal) (partial) symptomatic epilepsy and epileptic syndromes with complex partial seizures. Focal structural epilepsy, remission	
5	Male	11	Spastic hemiplegia	Left-sided hemiparesis
			Other disorders of psychological development	
			Hypermetropia	
6	Female	10	Spastic hemiplegia	Left-sided hemiparesis
			Unspecified disorder of psychological development	
			Other types of generalized epilepsy and epileptic syndromes, electrical status epilepticus in slow wave sleep	
7	Male	16	Spastic cerebral palsy	Right sided hemiparesis
8	Male	12	Childhood hemiplegia	Right sided hemiparesis
			Focal structural epilepsy, remission. Condition after the left frontal-central-parietal region cortical dysplasia resection performed in 09.2017. Focal cortical dysplasia, type IIb (ILAE).	
			Inherited epilepsy. Intellectual disability	
			Condition after Coleman's surgical procedure on the left side	
9	Male	10	Consequences of traumatic brain injury	Right sided hemiparesis
10	Female	12	Cerebral palsy	Spastic diplegia
11	Male	12	Cerebral palsy	Right sided hemiparesis
			Focal structural epilepsy	
			Regional cortical dysplasia. Condition after functional hemispherotomy on the left side	
			Mild cognitive impairment due to epilepsy	
			Optic nerve atrophy	
12	Female	16	Spastic cerebral palsy	Left-sided hemiparesis
13	Male	13	Cerebral palsy	Spastic diplegia
14	Female	19	Cerebral palsy	Spastic diplegia

During the tasks execution electroencephalogram (EEG) was acquired, which allowed the classifier to detect the currently executed task. Classification result was presented in the form of visual and proprioceptive feedback: if the detected task corresponded to the instructions, then the color of the circle on the monitor screen changed from white to green, and the exoskeleton performed opening of the hand.

EEG acquisition was performed using the NVX52 unit (Medical Computer Systems; Russia) being a part of the Exohand-2 complex. The total of 32 electrodes located at F3, Fz, F4, Fc5, Fc3, Fc1, Fcz, Fc2, Fc4, Fc6, C5, C3, C1, Cz, C2, C4, C6, Cp5, Cp3, Cp1, Cpz, Cp2, Cp4, Cp6, P3, Pz, P4, Po3, Poz, Po4, O1, O2 was used. The signal processing was performed using the Butterworth filter (passband 5–30 Hz), and the notch filter to filter out the mains hum from the 50 Hz power line. The Bayesian classifier based on the EEG signal covariance matrices analysis was used for the currently performed task detection [19].

The motor imagery training had been carried out for 7–10 days (2–3 daily procedures). The duration of the procedure was 6.5 min, which was about 1.5 times shorter than the procedure conducted in adult post-stroke patients [8]. The duration of the breaks between the procedures was 5 min.

The BCI control accuracy was evaluated based on the answers of the system classifier. The answers made it possible to obtain the confusion matrix G for each session. The number of rows and the number of columns in each matrix were equal to the number of detected tasks (three in this study). Element $g_{i,j}$ (i = 1, 2, 3; j = 1, 2, 3) was used for evaluation of task i detection level in a case when instruction j was presented. The average value of the matrix diagonal elements was an estimate of the average detection level, i.e. the BCI control accuracy.

The filtered EEG recordings were further processed in order to estimate level of the mu-rhythm desynchronization associated with motor imagery. Each recording was analyzed using the Adaptive Mixture Independent Component Analysis (AMICA) [20], which was chosen as the most informative physiologically significant EEG sources search method [21, 22].

For the signal decomposition into independent components two statistical models were used, which made it possible to automatically select the recording parts containing artifacts occurred due to child's moving in the chair. These parts were excluded from the analysis. For the remaining parts, the detected independent components topographic maps were examined in order to select the components corresponding to the mu-rhythm sources in the left and right hemispheres. The mu-rhythm desynchronization level was calculated using the following formula: $100\% \cdot (v_{base} - v_{act})/v_{base}$, where vact was a component activity variance when imagining the contralateral hand movement, and v_{base} was a component activity variance at rest.

If the mu-rhythm source identification was impossible, the activity evaluated by LCMV beamforming was taken instead of the source activity [23] based on the averaged topographic map obtained during other sessions for the mu-rhythm source of the appropriate localization.

The motor function assessment was performed using the following standard scales: Fugl-Meyer Assessment scale, Action Research Arm Test (ARAT) and Jebsen–Taylor function test. The Fugl-Meyer Assessment scale was used for analysis of total scores needed for assessment of proximal arm and hand motor function, as well as the total score for all active hand movements. The ARAT test was used for analysis of grasp, grip, pinch and gross movements. The Jebsen–Taylor function test was used to analyze the execution time in seven motion tests: writing a simple sentence, cards turning over, picking up small objects, simulated feeding, stacking checkers, moving light cans, moving large weighted cans. All seven items of the Jebsen–Taylor test were executed with both left and right hand.

Goniometer was used for measurement of the maximum angles in hand joints when performing active movements of the wrist joint, as well as of the metacarpophalangeal and interphalangeal joints of all fingers. All patients passed the clinical tests before the start of the procedure and after its completion.

The assessment scales scores statistical analysis included the comparison of values obtained before and after the procedures using the Wilcoxon test, ANOVA, Student's *t*-test, and the comparison of clinical scales score improvement according to the signed-rank test with a zero median.

RESULTS

BCI control

The average imaginary movements and resting state detection level during the session was 0.51 (0.45; 0.54) (max = 0.70). The mu-rhythm sources in the hemisphere opposite to the intact hand were identified during 72.0% (61; 84) of sessions, and the mu-rhythm sources in the hemisphere opposite to paretic hand were detected during 64% (45; 80) of sessions. In patients with biparesis and tetraparesis, the hand with better Jebsen–Taylor test score was considered intact. Fig. 1A and 1B present the mu-rhythm sources topographic maps averaged for all participants and all acquired recordings (those in which the mu-rhythm sources were identified).

The correlation between the BCI control accuracy and the average source occurrence was significant (Fig. 1C). The high proportion of sessions in which the sources of mu-rhythm were identified was typical for participants most successful in BCI management.

The mu-rhythm suppression value for the hemisphere opposite to the intact hand was 12% (7; 23) (max = 51%), and for the hemisphere opposite to the paretic hand it was 11% (6.5; 17) (max = 31%). The corresponding average values were 18.6% and 13.4%, the difference was significant (ANOVA: $p = 0.0018$; *t*-test: $p < 10^{-4}$). Thus, the imaginary movement of the paretic hand caused the weaker mu-rhythm desynchronization in the contralateral hemisphere.

The significant correlation between the BCI control accuracy and the mu-rhythm desynchronization level was revealed, both for the hemisphere opposite to the intact hand (Fig. 1D), and the hemisphere opposite to the paretic hand (Fig. 1E). The greater was the rhythm suppression associated with imaginary movement of both intact and paretic hands, the higher was the BCI control accuracy.

Motor function improvement

According to the signed-rank test with zero median, the significant increments indicating the motor function improvement after the procedures' completion were obtained for all sections of the Fugl-Meyer Assessment scale, for proximal arm, hand and for the total score for all active movements (Table 3). According to the ARAT test, the significant improvement was observed in the grasp and grip movement tests score, as well as in the total score. In the pinch movement and gross hand movements tests the improvement detected after the procedures completion was not significant (see Table 3).

The Jebsen–Taylor test items execution using the paretic hand was very difficult: before the start of the procedures the execution time exceeded 2 min in all patients. After the procedures completion only two children were able to finish one test, and three children were able to finish two tests out of seven in less than 2 min. All patients successfully executed the tasks by intact hand, after the procedures completion the execution time was reduced in all functional tests, except the “Writing a simple sentence” test. The “Moving light cans”, “Moving large weighted cans” and “Simulated feeding” tests execution time reduction after the procedures completion was significantly different from zero according to the signed-rank test (Table 4).

Of all studied paretic hand active movements only the dorsal extension amplitude increased from 30° (25°; 41.25°) to 40° (40°; 58.75°). The amplitude increase turned out to be significantly greater than zero ($p = 0.016$ according to the signed-rank test).

DISCUSSION

The kinesthetic motor imagery methods are considered an effective instrument for the motor function recovery, and

Table 2. Examples of clues simplifying the initiation of motor imagery

Age	7–10 years	10–13 years	13–18 years
Instruction example	Imagine that you are trying to reach for the flower to pick it/want to take a toy car/ want to catch a butterfly/want to grasp your favourite toy	Imagine that you control the robot with the power of thought/open the treasure chest/ open the jewelry box	Imagine that you are trying to reach for the doorknob to open the door/hold out your hand for someone to shake/pick an apple from the tree
			The use of specific kinesthetic images is accepted: "Your hand is clenched into a fist. Gradually, the fingers begin to come off the palm, feel them straighten, relax and form a straight line"

therefore are increasingly used in clinical practice for regaining movements after a stroke [5, 6]. There are few papers on the motor imagery in children, both healthy and affected by CP. The papers report that the motor imagery ability develops between 5 and 12 years of age and is peculiar not only to children with typical development [15, 24], but also to children with CP [16–18]. Our evidence confirmed these results: the average detection level of the proposed states (opening the right or left hand, rest) by the EEG classifier during the procedure was 0.51, and the maximum value was 0.70, which exceeded 0.33 (the three states detection random expectation value). However, the detection level 0.51 was lower than the average detection level in adults (0.6 according to the study of 37 healthy individuals and 32 post-stroke patients) [8].

The age of children with CP included in the motor imagery study was the same as in our study: 11–16 years [17], 9–14 years [18], or even younger (5–9 years) [16]. The exclusion criteria in the discussed study were much more stringent: patients with severe paresis, dystonia and cognitive impairment were excluded. In our study, the participants demonstrated severe motor function impairment (see Table 1). However, all of them were successful in the BCI management: the mu-rhythm sources in the hemisphere opposite to the intact hand were identified during most sessions. Our results were in line with the previously obtained data on the successful motor imagery in children with left- and right-sided CP [17].

It is important to note that the observed correlation between the BCI control accuracy and the mu-rhythm desynchronization level is not a trivial matter, since the classifier uses the signal covariance matrices and the response may be affected by various electric activity sources (including artifacts) [25]. The results obtained indicate that BCI-based training really cause the primary sensorimotor cortex activation specific to the task being performed, which is one of the main goals of the procedure.

The significant motor function impairment in children with CP is associated with muscular weakness, increased muscle tone, spasticity, and sensory deficit [26]. Motor imagery training in children with CP aimed at brain plasticity stimulation promotes the motor function recovery both as individual therapy [16, 18] and being combined with other rehabilitation methods [17]. During our study, the Fugl-Meyer Assessment scale and the ARAT test scores improved which indicated the motor function improvement. Despite the patients group heterogeneity according to age, diagnosis, and lesion lateralization (see Table 1) the score improvement in some function tests was significant (see Table 3). Despite the inevitable subjective nature, the Fugl-Meyer Assessment scale and the ARAT test are widely used in clinical practice for the motor function impairment assessment. Their total scores reliability is based on a large number of motion tests that have been developed for adult patients [27]. The observations of the medical specialists who have performed testing of our patients confirm that such testing can be tedious for children with CP, and thus reduce the motor function assessment reliability.

Unlike the Fugl-Meyer Assessment scale and the ARAT test, the Jebsen–Taylor function test is based on the objective task execution time measurement. Severe motor function impairments in the study participants made in impossible for them to execute the ARAT test tasks prior to the procedures.

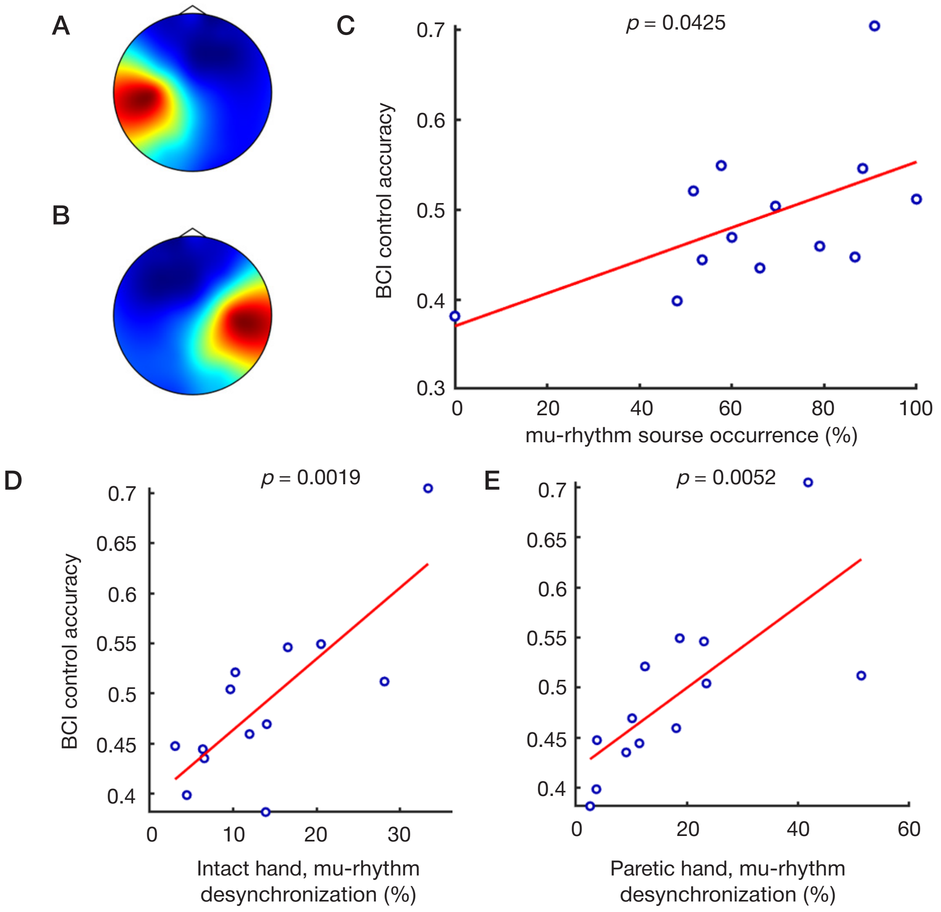

Fig. 1. Topography of mu-rhythm sources and BCI control accuracy. **A**. Average topography of mu-rhythm sources in the left hemisphere. **B**. Average topography of mu-rhythm sources in the right hemisphere. **C**. Correlation between BCI control accuracy and mu-rhythm sources occurrence in all study participants. **D**. Correlation between BCI control accuracy and mu-rhythm desynchronization in the hemisphere opposite to the intact hand. **E**. Correlation between BCI control accuracy and mu-rhythm desynchronization in the hemisphere opposite to the paretic hand

Table 3. Motor function median, quartile and significance level values according to Fugl-Meyer Assessment scale and ARAT test (obtained before and after the procedures)

Scale (motion tests)	Before	After	Difference	$p_{wilcoxon}$	p_{anova}	p_{diff}
Fugl-Meyer (Proximal arm)	20.5 (15; 25)	26 (22; 27)	4.5 (1; 6)	0.13	0.27	**0.032***
Fugl-Meyer (Hand)	6 (2; 12)	9.5 (5; 17)	2.5 (0; 5)	0.24	0.28	**0.031***
Fugl-Meyer (Total score for all active movements)	27 (18; 32)	34.5 (26; 43)	7 (2; 11)	0.19	0.25	**0.022***
ARAT (Grasp movement)	11 (3; 24)	13 (3; 36)	1.5 (0; 12)	0.62	0.34	**0.008***
ARAT (Grip movement)	8 (3; 13)	9.5 (6; 21)	1.5 (0; 8)	0.43	0.34	**0.018***
ARAT (Pinch movement)	0.5 (0; 13)	3.5 (0; 18)	0 (0; 3)	0.63	0.56568	0.16
ARAT (Gross hand movement)	7 (4; 16)	9 (4; 16)	0 (0; 1)	0.63	0.63	0.063
ARAT (Total score)	31.5 (12; 76)	42 (15; 110)	7.5 (1; 31)	0.33	0.37	**$< 10^{-3}$***

Table 4. Motor function median, quartile (seconds) and significance level values according to Jebsen–Taylor function test (obtained before and after the procedures)

Motion test	Before	After	Difference	$p_{wilcoxon}$	p_{anova}	p_{diff}
Writing a simple sentence	18 (11.25; 29.75)	24 (14.10; 48.25)	0 (–1.50; 3.70)	0.45	0.41	0.36
Cards turning over	6 (4.00; 8.50)	5 (3.00; 7.75)	0 (–1.25; 0.86)	0.44	0.97	0.40
Picking up small objects	9 (6.00; 11.00)	7 (6.50; 13.75)	–0.06 (–2.00; 1.25)	0.88	1.00	0.90
Simulated feeding	11 (8.50; 15.25)	10 (6.50; 13.00)	–1 (–5.66; 0.00)	0.41	0.27	**0.0469***
Stacking checkers	9 (7.75; 16.25)	9 (6.75; 15.75)	–1 (–4.13; 0.25)	0.57	0.91	0.21
Moving light cans	5 (4.50; 9.25)	4 (3.00; 7.25)	–1 (–2.00; 0.00)	0.38	0.44	**0.0039***
Moving large weighted cans	6 (4.00; 9.25)	5 (4.00; 7.50)	–1 (–2.00; 0.00)	0.43	0.45	**0.0117***

After the procedures completion only five patients out of 14 were able to pass some function tests. However, the execution time for intact hand reduced in all tests except one, and in four tests out of seven the differences were significant (see Table 4). As is known, the motor deficit is typical not only for paretic hand, but also for intact hand [28]. Despite the fact that motor impairment of the intact hand is significantly lower than the motor impairment of the paretic hand, it can significantly limit the patient's functional activity, especially in the case of severe lesions. During the BCI-exoskeleton based training the voluntary activation is observed in both affected and intact hemispheres. The described bilateral activation contributes to the procedures' effectiveness affecting the function of both hands.

For more accurate and fair motor function assessment, the biomechanical analysis of movements registered before and after rehabilitation is used. The described analysis is widely used in clinical trials for post-stroke patients [29]. In children with CP, the possible movement detection protocols as well as sets of biomechanical parameters for motor function assessment are still being developed [30].

CONCLUSION

BCI-hand exoskeleton procedure is an effective and promising instrument for motor function recovery in children with CP, which may complement the essential therapy. All study participants were successful in the BCI management despite the differences in age, lesion lateralization and motor function impairment severity. It has been shown, that BCI management triggers the specific primary sensorimotor cortex activation, even in the affected hemisphere.

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