EFFICIENCY OF IMAGE VISUALIZATION SIMULATOR TECHNOLOGY FOR PHYSICAL REHABILITATION OF CHILDREN WITH CEREBRAL PALSY THROUGH PLAY

Gorelik VV[1] ✉, Filippova SN[2], Belyaev VS[3], Karlova EV[4]

[1] Togliatti State University, Togliatti, Russia

[2] Russian State Social University, Klin, Russia

[3] Moscow City Pedagogical University, Moscow, Russia

[4] FGBUZ MRTs Sergievsky Mineral Waters of FMBA, Samara Region, Russia

The number of children born with cerebral palsy (CP) remains stably high. Novel approaches for rehabilitation of such patients are being sought. This study aimed to define the efficiency of the image visualization technologies in play activity for the physical rehabilitation of children with cerebral palsy. Sixteen boys with spastic diplegia aged 7–9 participated in the study. They were divided into treatment group (TG) and control group (CG), 8 children each. The TG patients were trained using the virtual reality based Krisaf training simulator twice a week for 40 minutes during 8 months. The child was suspended in the horizontal position and looked at the monitor through the specialised eyeglasses. Under the conditions of the marine environment immersion simulation with reduced gravity children performed motor tasks through play: searched for treasures, competed with dolphins etc. The CG patients attended the physical therapy lessons. Rehabilitation lessons using the virtual reality based Krisaf training simulator for children affected with spastic cerebral palsy led to a significant improvement of motor skills. Various motion tests showed an improvement over baseline, the average indicators increased 1.30–1.48 times. The difference between TG and CG results was statistically significant. In the CG referred to physical therapy the indicators increase was less than 10%, in the TG the increase reached 30–40%. It was concluded that the use of virtual reality based technologies promotes the optimization of neurophysiological processes in the motor analyzer cortical areas and better adaptation to motor loads.

Keywords: cerebral palsy, game situations, virtual reality technologies, motor actions, adaptation

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Compliance with ethical standards: this study was approved by the Ethics Committee of Togliatti State University (protocol № 3 dated September 10, 2018). Parents of the children submitted the informed consent forms allowing their children to participate in the study.

✉ **Correspondence should be addressed:** Viktor V. Gorelik
Belorusskaya 14, Togliatti, 445020; lecgoy@list.ru

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ЭФФЕКТИВНОСТЬ ТРЕНАЖЕРНОЙ ТЕХНОЛОГИИ ВИЗУАЛИЗАЦИИ ОБРАЗОВ В ИГРОВОЙ ДЕЯТЕЛЬНОСТИ ДЛЯ ДВИГАТЕЛЬНОЙ РЕАБИЛИТАЦИИ ДЕТЕЙ С ДЕТСКИМ ЦЕРЕБРАЛЬНЫМ ПАРАЛИЧОМ

В. В. Горелик[1] ✉, С. Н. Филиппова[2], В. С. Беляев[3], Е. В. Карлова[4]

[1] Тольяттинский государственный университет, Тольятти, Россия

[2] Российский государственный социальный университет, Клин, Россия

[3] Московский городской педагогический университет, Москва, Россия

[4] Медицинский реабилитационный центр Сергиевские минеральные воды Федерального медико-биологического агентства, Самарская область, Россия

Число детей, рождающихся с диагнозом «детский церебральный паралич» (ДЦП), остается стабильно высоким. Ведется поиск новых подходов к реабилитации таких пациентов. Целью исследования было определить эффективность использования технологии игровой деятельности на основе визуализации образов в процессе физической реабилитации детей с ДЦП. В исследовании участвовали 16 мальчиков со спастической диплегией в возрасте 7–9 лет, разделенные на две группы: экспериментальную (ЭГ) и контрольную (КГ) — по 8 детей в каждой. В ЭГ занятия проводили на тренажере виртуальной реальности «Крисаф» 2 раза в неделю по 40 мин в течение 8 месяцев. Ребенок при этом находится в подвешенном горизонтальном положении и, используя специальные очки, смотрит на экран. В условиях имитации состояния погружения в морскую среду, при понижении гравитационных воздействий дети выполняют двигательные задания в игровой форме: ищут сокровища, соревнуются с дельфинами и т. д. Дети КГ посещали занятия ЛФК. Реабилитационные занятия детей со спастической формой ДЦП на тренажере «Крисаф» с элементами технологии виртуальной реальности приводили к значительному возрастанию двигательных возможностей. В ЭГ наблюдали рост показателей при проведении разных двигательных тестов, средние тестовые значения улучшились в 1,30–1,48 раза по сравнению с исходными данными. Улучшение результатов в ЭГ статистически достоверно отличалось от результатов КГ. У детей КГ результаты в среднем улучшились менее чем на 10% под влиянием ЛФК, в ЭГ — на 30–40%. Сделан вывод, что применение технологий виртуальной реальности способствует оптимизации нейрофизиологических процессов в корковых зонах двигательного анализатора, повышению адаптации к двигательным нагрузкам.

Ключевые слова: ДЦП, игровая деятельность, технологии виртуальной реальности, двигательные упражнения, адаптация

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✉ **Для корреспонденции:** Виктор Владимирович Горелик
ул. Белорусская, 14, г. Тольятти, Самарская обл., 445020; lecgoy@list.ru

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According to statistics, the overall incidence of newborns is increasing in Russia, against the background of an unstable birth rate in the regions. In 2018, in Russia, cerebral palsy (CP) was diagnosed in ~8 of 1000 newborns. The incidence growth trends were previously recorded by the WHO specialists [1, 2].

Cerebral palsy is a polyetiologic disease, it belongs to the group of neurological diseases and is characterized by a variety of pathogenetic forms. The disease appears as neurological symptoms resulting from lesions of the cortical areas as well as of the the brain cerebellar area. Early onset and ineffective diagnosis lead to the predominance of severe forms of musculoskeletal system structural and functional impairment (upright posture maintenance, balance and muscle tone) [3–6]. Muscle tone (MT) and its regulation are considered the main factors of voluntary motor activity in humans. Various muscle disorders are observed in patients with cerebral palsy: spasticity, muscle hypertonia, rigidity, hypotonia, dystonia, atonia [7–9].

Manifesting as a MT increase the spastic cerebral palsy prevails among the different disease forms. Due to impairment of the pyramidal pathways the muscles of the patients are excessively tense. Together with an increase in MT, limb deformities and flexion contractures (a decrease in the volume of passive movements in the joints) can be observed. Spasticity is characteristic for spastic diplegia and hemiplegic cerebral palsy [10–14]. Despite the morbidity of the cerebral palsy as a severe disease that violates the psychophysical and social adaptation of patients, there is a shortage of methods based on the age-related psychophysical features of an affected patient for the rehabilitation of primary school age children [15–18]. Novel comprehensive and integrative approaches to the rehabilitation of patients are being sought, including treatment of comorbidity (epilepsy, somatic diseases), pharmaceutical and surgical treatment of spasticity and organic muscle damage. Development of methods for influencing the adaptive mechanisms and body reserves of infants and children, activating the psychophysiological regulatory mechanisms of the motor analyzer, optimizing emotional processes taking into account the age-related needs in game activity and motivating motor activity seem promising to us.

To achieve the correction and developmental results, physical rehabilitation of children with cerebral palsy should be based on the effective instruments choice which could influence the affected child [19–21]. It is extremely important to take into account the age-related psychophysical features of the patients in order to create optimal conditions for the formation of motor skills in children with disabilities and to increase the efficiency of their rehabilitation [22, 23].

During ontogenesis in children with cerebral palsy the individual, fundamentally different from normal, hierarchical regulatory systems of the motor analyzer are formed, which ensure the performance of involuntary and voluntary movements [10–17].

It is well known that motor activity is one of the main physiological components of the formation and development of the child's organism. A decrease in motor activity leads to the functional status of the musculoskeletal system impairment, causing changes in the functional status of the vascular and respiratory systems, metabolic disturbances, and decreased performance [8, 18].

Every movement depends on the spatial sense. Brain processes information coming through the sensory system and uses it for the locomotor movement formation. Children with cerebral palsy demonstrate the abnormal sensory system development pattern, which causes the inadequate responce to the incoming information and leads to the locomotor movement development delay [16].

The cerebral palsy associated motor development impairment is a result of the motor analyzer cortical areas regulatory effects disorder. Motor analyzer is the main control center of the entire human body muscle system (MS). In speech activity, the motor component is responsible for the speech and motor acts, therefore patients with cerebral palsy often demonstrate the impaired speech [19].

For patients with musculoskeletal disorders and neurological diseases the formation of altered motor stereotypes and pathologically incorrect movements is typical. These are formed due to the desire of patients to reduce pain or compensate the incorrect work of hypotonic muscles [20]. The altered motor stereotypes lead to the gravity center shift and to improper gait, which enhance the disease severity. Therefore, the main task is to correct the pathological motor stereotypes during rehabilitation. The Krisaf training simulator registers the body pressure force over the entire area (in prone position) and allows one to detect these problems at an early stage and successfully eliminate them. To identify its rehabilitation capability, a pedagogical experiment (PE) was carried out using the Krisaf training simulator at the forming stage.

This study aimed to define the rehabilitation capability of the play methods using the image visualization based Krisaf training simulator during the complex physical rehabilitation of the 7–9 years old children suffering from spastic cerebral palsy.

The goals were: 1) to assess the baseline indicators of motor functions in children with spastic cerebral palsy aged 7–9; 2) to determine the effectiveness of the virtual reality based Krisaf training simulator for the motor functions development in children with spastic cerebral palsy aged 7–9; 3) to evaluate the virtual reality technology rehabilitating capabilities during the play activity and their possible impact on the various types of motor skills in children with cerebral palsy.

METHODS

Study management and methods for diagnosing the functional status of muscle system in 7–9 years old children with cerebral palsy

The study lasted 8 months (September 2018 through April 2019). It was conducted at FGBUZ MRTs Sergievsky Mineral Waters of FMBA, Russia. Sixteen boys with cerebral palsy aged 7–9 participated in the study. Inclusion criteria: children with cerebral palsy (spastic diplegia); children of the same gender; children of a similar age with the same height-weight relationship. The participants were divided into two groups (8 children each): treatment group (TG) and control group (CG). In the TG training was performed using the Krisaf virtual reality based training simulator 2 times a week for 40 minutes during 8 months, the children also practiced physical therapy excercises twice a week. Children of the CG only performed the physical therapy excercises 2 times a week.

Exclusion criteria: acute infectious diseases and other medical contraindications to physical therapy. Physical features of the TG and CG children were similar.

Pedagogical experiment (PE)

The pedagogical experiment lasted September 2018 through April 2019. It included benchmarking, formation and control stages.

1. *Benchmarking stage*: registration of the muscular system functional status baseline indicators in children with cerebral palsy aged 7–9.

2. *Formation stage*: the TG children were trained using the Krisaf virtual reality based training simulator, they also practiced physical therapy excercises twice a week. The CG children were trained by the instructor according to the standard exercise therapy program for the rehabilitation of children with cerebral palsy.

3. *Control stage*: registration of the resulting indicators using the methods applied in the beginning of the pedagogical experiment.

Motion tests

Assessment of motor skills in children with cerebral palsy was performed using the number of motion tests allowing us to evaluate the functional status of the children's musculoskeletal system.

1. Assessment of the back muscles static endurance capability

Head lifting from the back position.

Starting position: lying flat on the back. The trainer takes the child by the wrists and lifts him. The child should raise his head and hold it in this position. Results are measured in seconds.

Head lifting from the stomach position.

Starting position: lying on the stomach, the arms bent at the elbow joints remain at the shoulder level. The child straightens his arms and lifts his head. Results are measured in seconds.

2. Assessment of the abdominal muscles endurance capability

Trunk lifting from the back position.

Starting position: lying flat on the back; the trainer holds the child's legs bent at the knee joints. The child raises the body from the starting position on his own touching the knees by his chest. The result is registered as the number of repeats.

3. Assessment of the hand muscles endurance capability

Wrist flexion and extension.

Starting position: sitting on the chair. The child's wrists are hanging from the armrests. The patient should bend and strengthten the left and right wrists alternately 10 times in a row. Results are measured in seconds. Normally, the result should be within 12–15 s.

Finger flexion.

Starting position: sitting on the chair. The child should alternately touch the thumb with each of the other fingers tips making his fingers to form a ring. Results are measured in seconds.

4. Assessment of the leg muscles endurance capability

Leg raise.

Starting position: lying flat on the back. The child raises his legs alternately and bends them at the knee joints. Results are measured in seconds.

Statistical analysis

The following mathematical statistics methods were applied when processing the data obtained: Kolmogorov–Smirnov test (nonparametric test of the equality of continuous, onedimensional probability distributions) and parametric Student's *t*-test. The differences were considered statistically significant at $p < 0.05$.

Kolmogorov–Smirnov test revealed that the studied variables fall within the limits of normality, which allowed applying the Student's *t*-test for interrelated and independent samples.

The SPSS 17.0 software for Windows was used to process the experimental data.

Forming method based on using the Krisaf training simulator for children with cerebral palsy aged 7–9

During the PE the Krisaf training simulator (Krisaf; Russia) was used to provide the forming effect. Simulator helps to imitate

Table 1. Musculoskeletal system functional status assessment results for children with cerebral palsy aged 7–9 obtained at the benchmarking stage of the PE

№	Tests	TG M ± *m*	CG M ± *m*	Student's *t*-test
1	Head lifting from the back position (s)	19.7 ± 2.7	20.6 ± 2.6	0.7
2	Head lifting from the stomach position (s)	17.4 ± 2.1	16.9 ± 2.04	0.34
3	Trunk lifting from the back position (number of repeats)	7.6 ± 1.4	7.3 ± 1.8	0.13
4	Wrist flexion and extension (s)	18.7 ± 2.8	19.9 ± 2.65	0.4
5	Finger flexion (s)	20.2 ± 3.1	19.6 ± 2.9	0.32
6	Leg raises (s)	15.5 ± 2.4	15.5 ± 2.4	0.12

Note: M — average; *m* — standard error of the mean; *p* — significance of differences between the TG and CG results; no statistically significant differences between the groups ($p > 0.05$).

Table 2. Musculoskeletal system functional status re-assessment results for children with cerebral palsy aged 7–9 obtained at the control stage of the PE

№	Tests	TG M ± *m*	CG M ± *m*	Student's *t*-test
1	Head lifting from the back position (s)	28.7 ± 3.8*	21.4 ± 3.6	2.4
2	Head lifting from the stomach position (s)	25.9 ± 2.76*	18.9 ± 2.5	2.54
3	Trunk lifting from the back position (number of repeats)	14.6 ± 2.1*	8.4 ± 1.5	3.13
4	Wrist flexion and extension (s)	12.4 ± 1.32*	17.7 ± 1.7	3.1
5	Finger flexion (s)	14.4 ± 2.9*	18.6 ± 3.1	2.5
6	Leg raises (s)	22.9 ± 2.36*	16.7 ± 2.4	3.03

Note: M — average; *m* — standard error of the mean; TG — treatment group; CG — control group; * — significant differences between the TG and CG results, $p < 0.05$.

the movements of the affected child in the aquatic environment [4, 21].

The Krisaf training simulator dispays images on the monitor. Audio signals transmitted through headphones help the patient to adjust his motor activity. Thus, the correct execution of excercises can be achieved and the new, close to normal, motor stereotypes can be formed.

Physical rehabilitation of children with cerebral palsy is a labour-intensive and complex process that requires significant efforts of medical personnel and physical therapy trainers. Virtual reality modeling takes place simulating immersion of the child in the gaming aquatic environment. The game situation encourages the child to move more actively. This helps to simulate movements in the aquatic environment, balancing the child's weight by a special pneumatic system, which helps to establish the conditions of reduced gravity. The child with weakened muscle strength and lack of sufficient coordination due to cerebral palsy can perform the movements more accurately. The patient's training using the simulator is based on the execution of wave-like movements that look like the dolphin's movements [22, 23]. Play elements are important, because play activity is essential for little patients. In children

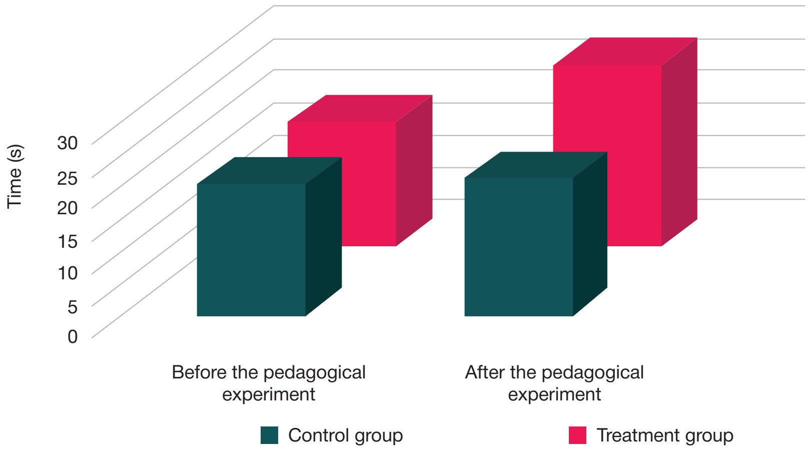

Fig. 1. Comparative data of the "Head lifting from the back position" motion test for children with cerebral palsy aged 7–9 from CG and TG obtained at the control stage of the PE

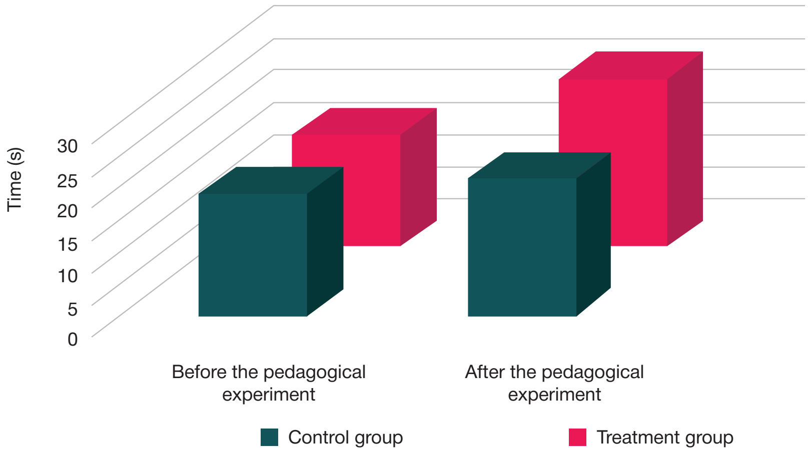

Fig. 2. Comparative data of the "Head lifting from the stomach position" motion test for children with cerebral palsy aged 7–9 from CG and TG obtained at the control stage of the PE

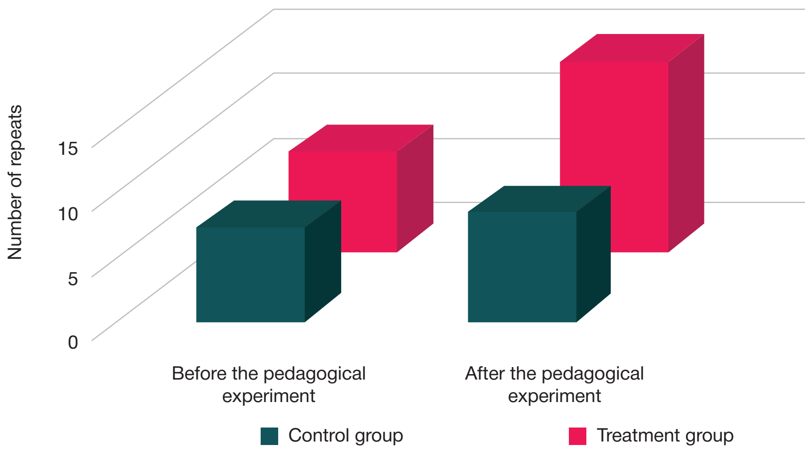

Fig. 3. Results of the "Trunk lifting from the back position" motion test for children with cerebral palsy aged 7–9 from CG and TG obtained at the control stage of the PE

with cerebral palsy the Krisaf training simulator: a) improves the information perception and the quality of the arbitrary movements performance through image visualization; b) activates the right hemisphere by the virtual reality elements and facilitates the movements execution due to the gravity decrease.

RESULTS

At the benchmarking stage of the study preliminary testing was performed to define the baseline of the motor skills development in children with cerebral palsy (Table 1).

According to the results of initial testing, we can conclude that there are no significant differences in the indicators of motor characteristics in children with cerebral palsy of both groups.

After a course of lessons using the virtual reality based Khrisaf training simulator, a control test was conducted in both groups to identify the effectiveness of the method for physical rehabilitation of children with cerebral palsy (Table 2).

Re-examination using the motion tests at the PE control stage revealed a pronounced positive dynamics in the TG and slight changes in the indicators in the CG. Significant differences in the results were found between the control and treatment groups. Figs. 1 and 2 show the “Head lifting from the back position” and “Head lifting from the stomach position” tests results obtained for the CG and TG before and after the experiment.

Head holding time in children in the TG increased by 9 s (back position) and 8.5 s (stomach position), which corresponds to the 32% increase of strength and endurance of the limb girdle muscles in children with cerebral palsy.

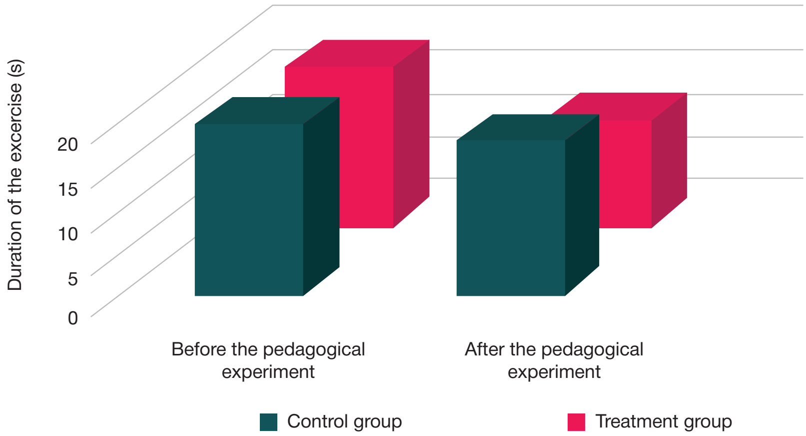

Fig. 4. Results of the “Wrist flexion and extension” motion test for children with cerebral palsy aged 7–9 from CG and TG obtained at the control stage of the PE

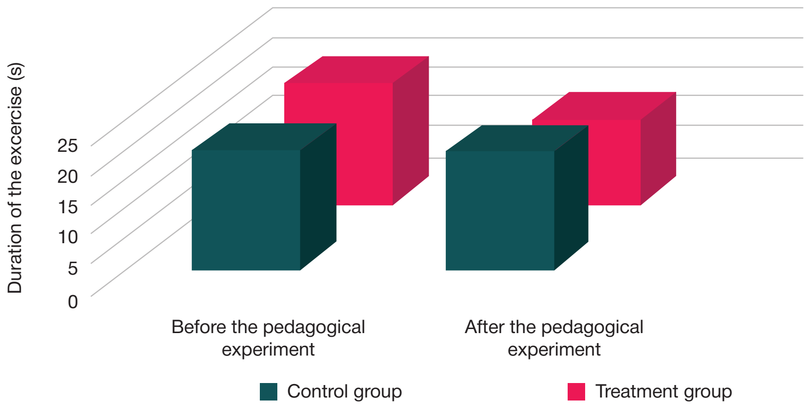

Fig. 5. Results of the “Finger flexion” motion test for children with cerebral palsy aged 7–9 from CG and TG obtained at the control stage of the PE

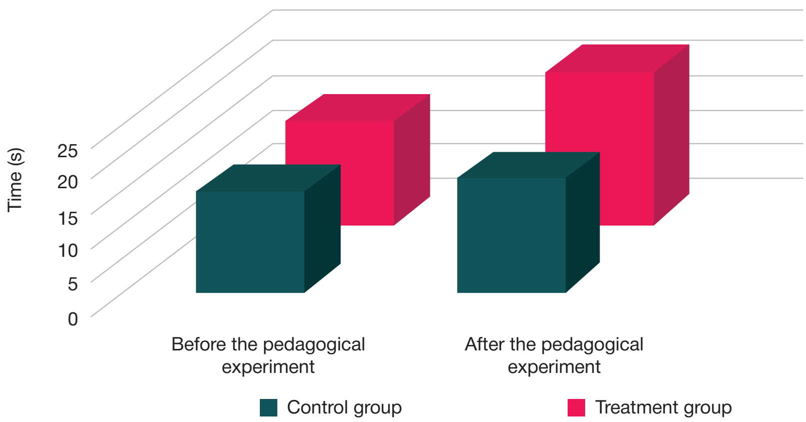

Fig. 6. Results of the “Legs lifting” motion test for children with cerebral palsy aged 7–9 from CG and TG obtained at the control stage of the PE

This is important for the normalization of the upper limbs function, in addition, an increase in the activity of these muscle groups helps to improve the brain blood supply. In the CG, the increase in the muscle strength was 3.8% (back position) and 7% (stomach position), the increase over values was not statistically significant. Thus, it can be said that the use of virtual reality base simulator technologies is effective for rehabilitation of 7–9 years old children with spastic cerebral palsy. The effectiveness of lessons is associated with the activation of the right hemisphere neurophysiological mechanisms and with the increase of the body's adaptive capabilities [14, 17].

Fig. 3 shows the "Trunk lifting from the back position" motion test results.

The "Trunk lifting from the back position" test results demonstrate that after the simulator lessons the back and abdomenal muscle strength significantly increased in the TG children (1.9 times compared to the baseline, i.e. from 7.6 to 14.6 repeats). In the CG the muscle strength remained almost the same. These data serve as an indirect proof of the improvement of motor skills and adaptive mechanisms in children aged 7–9 with spastic cerebral palsy, testify to the good rehabilitation effect of the Krisaf virtual reality based training simulator.

Figs. 4 and 5 show the "Wrist flexion and extension" and "Finger flexion" motion tests results.

The speed qualities of the limb girdle muscles, the flexor-extensors of the upper limbs, as well as the finger muscles of fine motor skills increased in the TG after a series of lessons using the Khrisaf training simulator. For the limb girdle muscles the test execution time was reduced by 6.3 s (35%), and in the CG it was reduced by 2.2 s (11%). In the TG the fine motor skills also improved: test execution time was reduced by 5.8 s (29%). In the CG it was reduced by 0.3 s (1.5%). This suggests that image visualisation during the training lessons helped to establish a friendly environment for children aged 7–9 with delayed verbal function development due to impaired speech and motor functions as compared with the verbal commands and instructions of the physical therapy trainers. Improvement of the fine motor skills in children with cerebral palsy after rehabilitation using the visualization elements was associated with the motor analyzer cortical areas activation. The speed of the small differentiated movements of the fingers also increased.

Fig. 6 shows the "Legs lifting" motion test results for children aged 7–9 with cerebral palsy.

When determining the speed-strength characteristics of the lower limbs muscles, it was clear that the average result improved. In the TG it increased by 7.4 s (33%), and in the CG by 1.2 s (6%). These data indicated the effectiveness of rehabilitation in children with spastic cerebral palsy using the image visualization technology based Krisaf training simulator. An increase in the motor and strength capabilities of the lower extremities in such patients indicated a trend towards the motor analyzer cortical areas neurophysiological processes improvement together with adaptation to motor loads due to the increase in the balance of the right hemisphere functions while using the image visualization method.

Thus, when comparing the TG and CG indicators at the control stage of PE, the significant improvements in the TG indicators were found, which exceeded the results of the CG. These differences arose due to the fact that virtual reality technologies were introduced in the TG, while in the CG the standard exercise therapy program was used.

DISCUSSION

Our study has shown that the virtual reality technologies influence on both the control and executive centers of the motor analyzer is not well understood. It can be assumed that immersion of children in the reduced gravity conditions and in the aquatic environment virtual reality promotes involuntary relaxation of all muscles, as it happens in case of real water immersion. With the help of the simulator complex neurophysiological and sensory effects, muscles start working and somatic and sensory integration improves. This increases the efficiency of lessons and makes the rehabilitation of children with cerebral palsy more effective.

Stimulation of the right hemisphere by visual information facilitates execution of physical exercises. For children with cerebral palsy aged 7–9 the visual information is easier to understand than the trainer's verbal instructions [19]. In addition, the right hemisphere associated adaptive mechanisms of the body can be activated [17]. Positive emotions from training through play promote relaxation of constricted muscles [3]. Thus, the virtual reality based Khrisaf training simulator affecting a number of neurophysiological and sensory mechanisms has an integrative rehabilitative effect on the psychophysical state of 7–9 years old children with spastic cerebral palsy. This indicates that image visualization helps to establish friendly environment for the children with cerebral palsy as compared with the exercise therapy trainer's verbal instructions. Since children with cerebral palsy aged 7–9 often demonstrate the speech development delay and it is difficult for them to understand the meaning of verbal constructions, communication between patient and trainer may be impaired. Image visualization helps to restore mutual understanding and interaction.

Currently the simulator-based methods attract close attention of researchers even in the field of rehabilitation of children with various forms of cerebral palsy. Novel types of simulators are being developed taking into account the latest advances in the understanding of the pathogenesis of diseases, including cerebral palsy. At the same time, application and research using simulator methods provide valuable data for understanding the mechanisms of correction and rehabilitation of the affected person.

Image visualization and virtual reality based training simulator meets the need of a 7–9 years old child in playing. The simulator has an impact both on the regulatory neuropathological, psychopathological, and executive links of the motor analyzer as well as the psychological processes and the quality of life of rehabilitated children.

Improvement in the functional status of the children's musculoskeletal system obtained in this study with the use of virtual reality based technology opens up the prospect of the further research of regulatory mechanisms and recovery processes in children with cerebral palsy.

CONCLUSIONS

1. Rehabilitation using the virtual reality based Krisaf training simulator led to significant (1.3–1.5 times) improvement of the motor capabilities in children with spastic cerebral palsy aged 7–9. 2. Significant increase in the strength and endurance of the limb girdle and lower limbs muscles indicated the effectiveness of rehabilitation using the image visualization technology based Krisaf training simulator. The endurance of the back and abdomen muscles in the TG increased 1.9 times, the adaptation to motor loads improved. In the CG minor changes took place. 3. After training using the image

visualization based training simulator the speed of movements in the upper limbs increased, the fine motor skills of the hands improved. Improvement of the fine motor skills in children with cerebral palsy testified to the better balance of the cortical areas of the motor analyzer neurophysiological processes.

4. The positive dynamics of the motor capabilities in children with cerebral palsy when using novel virtual reality technologies for rehabilitation purposes testified to the optimization of neurophysiological processes in the cortical areas of the motor analyzer and better adaptation to motor loads.

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