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Virtual reality technologies in complex medical rehabilitation of patients with cerebral palsy

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ABSTRACT

The review highlights the issue of applying virtual reality (VR) technologies in medical rehabilitation of patients with cerebral palsy (CP). This review generalizes the current evidence on the use of virtual reality in restoration of motor and coordination functions, as well as in correction of other diseases associated with motor disorders in patients with CP. The analysis of national and international research shows that at present it is impossible to speak unambiguously about the efficiency of VR in rehabilitation of patients with CP. This is explained by some methodological shortcomings of the analyzed works (small size of the studied samples, lack of control over the results in the long term). However, the use of VR technologies for improving various functions in patients with CP is a promising method of medical rehabilitation.

Key words: virtual reality, rehabilitation, cerebral palsy.

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Технологии виртуальной реальности в комплексной медицинской реабилитации пациентов с детским церебральным параличом

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РЕЗЮМЕ

Обзор посвящен вопросам применения технологий виртуальной реальности (ВР) в медицинской реабилитации пациентов с детским церебральным параличом (ДЦП). Обобщены современные данные касательно использования ВР в восстановлении двигательных, координаторных функций, а также коррекции других расстройств, сопутствующих двигательным нарушениям у пациентов с ДЦП. Анализ

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работ, представленных в отечественной и зарубежной литературе, показывает, что в настоящее время нельзя однозначно говорить об эффективности ВР в реабилитации пациентов с ДЦП. Это связано с рядом методологических недостатков проанализированных работ (небольшой размер изучаемой выборки, отсутствие контроля результатов в отдаленный период). Тем не менее использование технологий ВР с целью улучшения различных функций у пациентов с ДЦП является перспективным методом медицинской реабилитации.

Ключевые слова: виртуальная реальность, реабилитация, детский церебральный паралич.

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INTRODUCTION

Cerebral palsy (CP) refers to a group of stable disorders of movement and posture maintenance that lead to motor defects due to non-progressive damage and / or abnormalities of the developing brain in a fetus or a newborn child [1–3]. CP is an urgent problem of modern medicine, as it is the main neurological cause of childhood disability worldwide, which affects families, education, and social life of the child [4]. The prevalence of CP is 2–3.6 cases per 1,000 children [5]. Competent choice of methods and terms of rehabilitation allows for social adaptation of children with this pathology, improving the prognosis of their motor and mental development [2].

There are many methods of medical rehabilitation of patients with CP at the moment. Their effectiveness depends on the patient's rehabilitation potential and a set of procedures [6]. The following rehabilitation measures are currently used: orthosis; physical rehabilitation (massage, therapeutic gymnastics, hardware kinesiotherapy, robotic mechanotherapy), including rehabilitation based on the principle of biofeedback; surgical orthopedic interventions on the extremities; surgical correction of spinal deformities in children with CP; botulinum therapy [7]. The main goal in the rehabilitation of patients with CP is to help the child achieve the highest possible level of physical, cognitive, psychological, and social independence [2].

Nevertheless, it remains relevant to develop and implement new effective and safe methods of rehabilitation of patients with CP, aimed at restoring their motor activity. At the same time, it is extremely important to use treatment methods that will be not only effective, but also interesting for children, and will result in patient's involvement in the rehabilitation process, which should affect the treatment outcome [8]. Motivation and active participation of children in the rehabilitation process play a key role [9].

Currently, virtual reality (VR) technologies are becoming more popular. VR technologies can significantly improve the results of rehabilitation treatment [10, 11]. VR is a computer simulation of a real environment which is able to evoke a sense of presence through 3D images and animations. VR provides interaction with various objects in this environment [12, 13]. VR technologies were initially used in the 50s of the XX century, usually for entertainment purposes. In the mid-60s, the potential for using VR was recognized by researchers from a variety of fields, including medicine [14]. VR technologies have shown positive results in the treatment of acrophobia [15], itching [16], pain syndromes [17], post-traumatic stress disorder, depression, and insomnia [18]. A high potential of VR was found in the rehabilitation of patients with CP [19], children with autism spectrum disorder [20–22], and patients with Parkinson's disease [23], Alzheimer's disease [24], and multiple sclerosis [25]. High efficiency of VR in medical rehabilitation is explained by achievement of the immersion effect, which allows to distract the patient's attention from pain and discomfort and reduce anxiety or dissatisfaction with treatment [26]. A sense of immersion in VR is provided by virtual reality glasses, special helmets, projectors, gloves with sensors, as well as the VRML (Virtual Reality Modeling Language) encoding language for describing three-dimensional images. The patient's participation or immersion in VR can be implemented in the following ways: active, when the user controls a virtual image (avatar) or a specific VR object and passive, when videos are viewed without active control [27]. Virtual reality allows a person to interact with various objects in real time, unlike other forms of visualization (video games, television) [28]. A user in an artificially created virtual environment can have an experience similar to events and actions in real life [29]. The patient can see, feel, manipulate, move objects, and manage events in virtual space. This creates a "presence effect" [30]. The greatest effectiveness of using VR from the standpoint of evidence-based medicine was revealed when restoring the function of walking [31] and manipulative function of the upper limb [32], which was achieved by creating a virtual environment as close to the real one as possible, as well as by creating motivation for active participation of the patient in rehabilitation activities [32, 33]. It is the active involvement of the patient in the training process in the virtual environment, during which you can realize and correct your mistakes when performing movements, that allows to achieve high results in teaching the patient motor skills [34, 35]. VR training helps to effectively hone movements due to three key elements necessary for improving motor functions: repetition of stimulation, sensory feedback, and patient motivation [26, 35].

Restoration of motor disorders using VR is associated with activation of brain plasticity mechanisms, including changes in the primary sensorimotor cortex and supplementary motor area [35, 36]. This knowledge allows to expand the range of nosologies in which significant results can be achieved using VR [37, 38].

USING VR TECHNOLOGIES IN NEUROREHABILITATION IN PATIENTS WITH CP

The use of virtual reality as an additional method of rehabilitation is one of the promising directions in the correction of motor and concomitant disorders in patients with CP [39]. The use of virtual reality in children with CP is very popular, since computer technologies are motivating for children and young people [40]. It is worth noting that insufficient motivation may prevent the patient from reaching their functional potential [9, 41]. Virtual reality allows to perform complex movements in a safe environment and provides an opportunity for active learning [2, 9]. Some studies point to the positive impact of virtual reality on the reorganization of brain structures, neuroplasticity, motor abilities of the patient, visual perception, social behavior, and personal qualities [2, 19, 42]. A positive feature of using virtual reality is that the actual daily activity of the patient is taken into account [43].

There are many different VR systems, including Virtual Rehab, Caren, Nirvana, Tyromotion, MiTii, and others. One of the most commonly used systems is VirtualRehab, which is a rehabilitation platform that uses Microsoft Kinect and Leap Motion sensors, as well as video game technology. The VirtualRehab system is designed to restore the motor functions of the limbs. VR therapy using Microsoft Kinect and Nintendo Wii sensors has proven to be effective in improving exercise performance and increasing physical activity [44].

VR equipment is characterized by high cost and complexity, which determines the use of these systems only in the clinical setting. However, game systems are being developed for home use as well: TyromotionPablo for hand and finger training; Tymo for balance and strength training; the Interactive Rehabilitation Exercise System (IREX) with immersion and gesture control technology; YouGrabber and YouKicker systems for training upper and lower limb movements. The game form of treatment increases child's attention to performing certain exercises in comparison with conventional treatment [45, 46] and, most importantly, makes it possible to use VR technologies at home [47]. Currently, VR games for patients with CP are being actively developed and implemented in rehabilitation practice. These games will be therapeutically relevant and at the same time interesting for patients themselves [48]. In many studies on the use of VR in rehabilitation of children with CP, the effectiveness of the method is evaluated depending on the established goal: restoring the function of the upper and/or lower extremity, postural control and balance; improving physical fitness, and training the cardiovascular system [42, 49].

USING VR TECHNOLOGIES TO RESTORE UPPER LIMB FUNCTIONS IN PATIENTS WITH CP

One of the top priority tasks of restoring household and social activity of patients with CP is to improve the basic motor skills of the upper limb, such as the ability to coordinate movements of two hands, reach an object, and manipulate it [50].

J.W. Yoo et al. analyzed in their study the effectiveness of VR-based biofeedback using electromyography (EMG-biofeedback) in patients ($n = 18$) with various forms of CP (average age 9.5 ± 1.9 years) to improve the upper limb functions. All patients with cerebral palsy had one 30-minute EMG biofeedback session, followed one week later by another 30-minute VR-based EMG biofeedback session. The results were evaluated by the following tests: the range of motion of the elbow joint, the box and block test, and the biceps muscle strength test. Statistically significant improvement in all the tests was detected after the application of EMG biofeedback in conjunction with VR ($p < 0.05$). This study is the first clinical trial that demonstrated the effectiveness of using VR-based EMG biofeedback in patients with cerebral palsy to improve the upper limb functions [51].

G. Acar et al. studied the effectiveness of using VR (Nintendo Wii) to improve the upper limb functions in patients with hemiparetic form of CP ($n = 30$) with level I–II motor disorders according to the Global Motor Function Classification System (GMFCS). The patients were divided into two groups of 15 people depending on the complex of rehabilitation measures received. In the first group (average age 9.5 ± 3.0 years), traditional neurological treatment using VR was performed (30 minutes) (tennis, boxing, baseball – 5 minutes each); in the second group (average age 9.7 ± 2.9 years), only traditional neurological treatment was performed (45 minute-session). All patients received 45-minute treatment 2 times a week for 6 weeks. The upper limb function was evaluated before and after treatment using the Quality of Upper Extremity Skills Test (QUEST), the Jebsen – Taylor Hand Function Test, the ABILHAND test, and the Pediatric Functional Independence Measure (self-care). The results of the study demonstrated a more pronounced improvement in the upper limb function in patients with hemiplegic CP who were treated with traditional neurological treatment in conjunction with VR [52].

In addition, pilot studies were conducted that determined high efficiency of using VR systems to improve upper limb functions in patients with hemiplegic CP [47, 53].

One of the most popular systems for restoring upper limb functions and planning movements is the MiTii program ("move it to improve it"), which uses an interactive computer game that is controlled by hand and body movements. The system has remote configuration and progress check, as well as an opportunity to add personalized features to a series of games. Currently, randomized clinical trials of the MiTii VR system are being conducted at the University of Queensland (Australia) in order to evaluate the effectiveness of improving the upper limb function and to better understand the central neurovascular mechanisms that cause changes in the upper limb function, movement planning, and executive function [54].

Despite the positive results of using VR to improve the upper limb function in patients with CP, the data are controversial. In a systematic review of S. Rathinam and colleagues, only 4 out of 6 studies showed improvement. In 2 other studies, no changes were observed after the inclusion of VR in rehabilitation measures [55].

Thus, at the moment, it is impossible to claim high efficiency of using VR to restore the upper limb function in the rehabilitation of patients with CP. It is extremely important to monitor long-term results, in particular, to evaluate the application of skills acquired in the process of VR-based rehabilitation in real life situations and actions.

USING VR TECHNOLOGIES TO RESTORE LOWER LIMB FUNCTIONS (WALKING) IN PATIENTS WITH CP

Restoring lower limb functions in patients with CP is the key and most difficult task of medical rehabilitation. The aim of studies related to correction of motor disorders of the lower extremities in cerebral palsy is usually to improve walking [9].

S. Gagliardi and colleagues conducted a pilot study to evaluate the effectiveness of immersive VR used to improve walking in patients with CP. 16 children with spastic tetraplegia were included in the study (average age 11 ± 2.4 years). The rehabilitation was aimed at restoring walking and endurance skills using the Gait Real-time Analysis Interactive Lab (GRAIL). 18 sessions of therapy were conducted for all patients within 4 weeks. The effectiveness of the GRAIL VR system was evaluated using functional and instrumental methods, including gait analysis and Gross Motor Function Measure 88 (GMFM-88). Improved walking behavior (left and right step length ($p = 0.001$ and 0.003, respectively); walking speed ($p = 0.001$), endurance (6-minute walk test ($p = 0.026$)), gross motor functions (GMFM-88 ($p = 0.041$)), and other kinematic and kinetic parameters were observed 4 weeks after the start of rehabilitation activities using VR [56].

A.T.C. Booth et al. conducted a systematic review and meta-analysis of studies (from 1980 to 2017) evaluating the effectiveness of using VR to improve gait in children with CP. The meta-analysis contained 41 studies, including 11 controlled randomized trials. It was determined that the use of VR for functional gait training in patients with CP leads to clinically significant positive outcomes. It was found that functional gait training has moderate positive effects on walking speed compared to standard physical therapy ($p = 0.04$). There is weaker evidence that functional gait training using VR can improve walking and motor functions. The authors argue that functional gait training using VR is a safe, feasible, and effective method for improving walking in children with CP. Besides, adding virtual reality and biofeedback to rehabilitation activities in patients with CP can increase patient motivation and improve treatment outcomes [57].

However, there are also conflicting data regarding the effectiveness of virtual reality technologies in improving walking in patients with CP. D. Levac et al. conducted a pilot non-randomized controlled trial that included two groups of patients with different forms of CP. In the first group ($n = 5$), patients with CP had one VR session per day for 5 days in the hospital setting. After that, active video games were used at home for 6 weeks. In the second group ($n = 6$), only active video games at home for 6 weeks were used. Walking was evaluated in all patients using the 6-minute walk test (6MWT) and the global motor function scale (GMFM-88).

No differences were found between the groups based on the results of the study. In the group that used active video games at home for 6 weeks, a statistically significant improvement according to GMFM-88 ($p = 0.042$) was observed. In the first group, where VR was used in the clinical setting and active video games were used at home, better 6MWT values were found ($p = 0.043$). Despite this, all 6MWT values returned to their original level after 2 months. Thus, the authors concluded that neither VR nor active video games improved motor functions in patients with CP [58].

However, the use of VR to restore the lower limb function remains relevant. Currently, protocols have already been developed for clinical studies of the effectiveness of VR technologies for restoring lower limb functions (walking) in patients with CP [59, 60]. It's worth noting that these protocols allow to evaluate long-term results of rehabilitation measures.

USING VR TECHNOLOGIES IN RESTORING POSTURAL CONTROL AND MAINTAINING BALANCE (BALANCE, COORDINATION) IN PATIENTS WITH CP

Postural control, movement coordination, and balance are the key factors that provide most functional skills, especially walking and maintaining body position in space. The main reason for impairment of postural control is increased co-activation of agonist and antagonist muscles, as well as a decrease in the regulation of postural muscle contraction in a specific situation [61]. In recent years, some VR trials have focused on evaluating improvements in postural control and movement coordination in patients with CP [62, 63].

The first study using VR to restore postural control is the work by J.E. Deutsch et al., which presents a clinical example with retro- and prospective observation. The study included a 13-year-old child with spastic diplegia who was treated using the Nintendo Wii gaming system for 11 sessions of 60–90 minutes over 4 weeks. According to the results of observation, there was an improvement in postural control, visual perception, and functional mobility [64].

The study by S. Gordon et al. used the Nintendo Wii system as a method of rehabilitation of children with dyskinetic CP. 6 patients aged 6 to 12 years were included in the study. Two rehabilitation sessions a week for 6 weeks were performed. All children had improved postural control and motor functions as a result of using the virtual reality system [8].

16 subjects were included in the study by D. Sharan et al. A study group included 8 patients with CP (average age 8.9 ± 3.2 years), and a control group contained 8 children without pathology (average age 10.4 ± 4.4 years). The Nintendo Wii Sports and Wii Fit VR systems were used for rehabilitation. Motor activity was evaluated using the Manual Ability Classification System (MACS) and the Pediatric Balance Score (PBS). The positive effect was detected according to the PBS. There were no differences in manual skills compared to the control group. Thus, researchers showed that the use of Nintendo Wii Sports and Wii Fit VR systems had a positive effect on the function of balance control in the CP patient [29].

There are also other studies in which the use of technologies demonstrated high efficiency in improving postural control and balance maintenance in children with CP [65, 66].

In 2018, D. Cano Porras et al. presented a systematic review of 97 articles, 68 of which were published in 2013 and later. This review concludes that VR has a positive effect in restoring balance and gait, and also has advantages in combination with traditional rehabilitation methods [67]. VR together with transcranial magnetic stimulation has a positive effect on maintaining balance [68].

Thus, the inclusion of VR technologies in rehabilitation activities has positive prospects for improving postural control and balance in patients with CP.

USING VR TECHNOLOGIES TO IMPROVE PHYSICAL DEVELOPMENT AND CARDIOVASCULAR TRAINING IN PATIENTS WITH CP

Active video games are an optimal alternative to passive computer games and have recently become very popular among children and teenagers. Physical activity and physical fitness are reduced in children with CP compared to their healthy peers. Patients with CP spend most of their time sitting, also in front of a monitor screen [69].

Several studies evaluated the impact of active VR games on physical activity of children with CP when used at home. These studies showed that active games moderately improve physical activity, as well as reduce the time spent sitting in front of the monitor screen [70, 71].

INFLUENCE OF VR TECHNOLOGIES ON CONCOMITANT CP SYNDROMES

Most children with CP have comorbidities in addition to motor disorders. These disorders include behavioral, cognitive, and learning disabilities that affect general motor functions. 40% of patients with CP have attention deficit hyperactivity disorder [2]. Some studies exhibited a positive effect of VR-based methods on cognitive functions and behavioral disorders of patients with CP [72, 73].

M. Pourazar et al. presented the results of a randomized controlled trial on evaluating the effectiveness of VR in order to improve reaction time in children with CP. 30 boys aged 7–12 years were included in the study and divided into 2 groups (a study group and a control group). Measurement of reaction time (SRT, simple reaction time) and evaluation of discriminative reaction time (DRT) were performed in all patients initially and after day 1. A VR session between two dimensions was performed in the study group using the Xbox console. According to the results of the study, the reaction time decreased in patients with CP after using VR. The authors believe that VR systems are a promising tool in the rehabilitation process for improving reaction time in children with CP [74].

The possibilities of using VR to correct oral and facial disorders in children with CP are being studied. M. L. Martín-Ruiz et al. believe that performing rehabilitation activities using the VR-based SONRIE method on facial muscles can improve swallowing, facial muscle function, and speech in children with CP. All future studies will focus on SONRIE validation for correction of functional insufficiency of maxillofacial muscles in children with CP [75].

J.W. Shin et al. studied the effect of traditional neurological treatment and VR training programs on eye and hand coordination in children with CP. The study included 16 patients with diplegic CP. In the control group (n = 8), patients performed physical therapy exercises 2 times a week for 45 minutes for 8 weeks. In the study group (n = 8), patients performed physical therapy exercises (30 minutes) and VR training (15 minutes) 2 times a week. The results of the study showed a significant improvement in the coordination of eye and upper extremity movements in the study group. The authors claim that a properly planned training program using VR can improve eye and upper limb coordination in children with CP [76].

Thus, the use of VR technologies can improve limb function, walking, postural control, and balance in patients with CP. In addition, virtual reality technologies have a positive impact on such socially important functions of patients with CP as behavior, facial expressions, reaction time, hand-eye coordination, etc.

THE DISADVANTAGES OF USING VR TECHNOLOGIES

Despite the positive results of research on assessing the effectiveness of virtual reality in the rehabilitation of patients with CP, there are disadvantages associated with the use of VR. Until now, many VR systems have not been adapted for patients with CP with severe spasticity (the degree of spasticity is 2–4 according to the Ashworth scale). Here, games that require the use of a remote control are implied. Currently, games that can individually adapt to the reduced functions of a patient with CP are being developed [77]. For example, Sony has created a touch glove for the Sony PlayStation 3 game console, as well as several VR games for patients with cerebral palsy with upper limb dysfunction [78]. There is also an Interactive Rehabilitation and Exercise System (IREX) that uses motion detection and capture technology, which facilitates the interaction of the patient with the game system [79].

In addition, most of the available virtual reality games may be too complex for patients with cerebral palsy. Special programs require the purchase of additional technical devices, and also have a high cost [9].

It is worth noting that virtual reality technologies contain a limited number of games. This reduces the motivation for long-term training. A study by S.G. Owners et al. noted a reduction in the time spent playing the game after 6 weeks of use. Besides, the duration of training using the Nintendo Wii Fit decreased by 82% in the first 6 weeks of use [80].

In addition, there are factors that limit the use of VR technologies. D. Levac et al. conducted a survey among Canadian physical and occupational therapists on the clinical use of VR in rehabilitation activities, as well as on the factors that prevent the use of VR. A total of 1,071 respondents were surveyed. Factors impeding the use of VR were a lack of funds, premises with the necessary space, time, staff, and patients with the necessary pathology [81].

It should be noted that the disadvantage of many works related to the use of VR technologies in the rehabilitation of children with CP is the small number of patients included in the study. This is explained by a number of limitations, such as the ethical aspect of using VR and parents' distrusting new rehabilitation methods [46, 81].

CONCLUSION

Currently, the inclusion of VR in the complex of rehabilitation measures for patients with CP is being studied. VR technologies create a three-dimensional virtual environment and are able to provide visual, audio, and tactile feedback for complete patient immersion. Thus, VR opens up new opportunities in the medical rehabilitation of patients with CP. The virtual environment provides optimal conditions for improving motor functions, postural control, balance, general motor activity, and associated syndromes. Interactive games increase motivation for therapy.

The potential role of virtual motor rehabilitation is promising. However, more information is required about its effectiveness and safety. At the moment, there are conflicting data regarding the use of VR technologies in the rehabilitation of patients with CP. This may be related to the size of the samples being studied, the timing of observation, and the estimated outcome indicators. Further development of VR technologies is necessary along with a detailed study of the effectiveness and safety of this rehabilitation method and its impact on the daily functional activity of patients with CP.

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