Virtual Reality Technology in Complex Medical Rehabilitation of Patients with Disabilities (Review)

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M.G. Volovik, DSc, Leading Researcher, Department of Functional Diagnostics, University Clinic;
V.V. Borzikov, Junior Researcher, Department of Functional Diagnostics, University Clinic;
A.N. Kuznetsov, Junior Researcher, Department of Functional Diagnostics, University Clinic;
D.I. Bazarov, Junior Researcher, Counseling and Rehabilitative Department, University Clinic;
A.G. Polyakova, MD, DSc, Senior Researcher, Counseling and Rehabilitation Department, University Clinic

Privolzhsky Research Medical University, 10/1 Minin and Pozharsky Square, Nizhny Novgorod, 603950, Russia

The review is devoted to integration of innovative virtual reality technologies in the complex of medical rehabilitation of patients with disabilities. The analysis of data presented in modern domestic and foreign literature proves the effectiveness of using these technologies for recovery of impaired motor functions in patients of various ages with nervous and musculoskeletal system pathologies and gives evidence of their corrective effect on neurophysiological motor deficiency. Evaluation of the achieved results from the perspective of evidence-based medicine confirms the feasibility of using a personalized approach to targeting and controlling the dosage of virtual technologies in the complex of rehabilitation measures.

Key words: virtual reality; rehabilitation; motor functions.

Introduction

The problem of rehabilitation of people with disabilities is relevant worldwide. According to the UN, there are about 450 million people with physical and mental disabilities. Among the Russian population, there are 7.8% of individuals with motor and cognitive disabilities due to injuries, musculoskeletal system and nervous system diseases, most of whom are working-age people [1]. This harms the country's economy, the loss measuring in tens of billions of rubles per year, and urges to seek and develop innovative multidisciplinary technologies able to improve effectiveness of complex rehabilitation measures [2].

Today, technologies that influence the brain through virtual reality (VR) are being actively developed. According to numerous data, their use increases medical rehabilitation efficacy in terms of both time and quality of the achieved results [3–10].

The notion of virtual reality. VR technology development

Virtual reality is a computer-generated simulation of real-world environment, reproduction of any situation through sensations (visual, auditory, olfactory, haptic etc.) in order to induce responses [11]. American computer artist Myron Krueger was the first to introduce the concept of artificial reality in the late 1960s. Immersion in VR is achieved through a coding language known as VRML (Virtual Reality Modeling Language). VR technologies use interactive simulation with VR headsets or glasses, projectors and sensor gloves. Moreover, there is multisensory stimulation (visual, auditory or haptic) in different variants: passive (watching videos) or active (the user manipulates the image of his own body — "avatar" or specific objects within the virtual scenario) using feedback from the computer calculating the results of user actions [12–16]. Multisensory training

Corresponding author: Mikhail G. Volovik, e-mail: afanassy@mail.ru

in the virtual environment for physical rehabilitation was proposed by Australian physiotherapists Carr and Shepherd in 1982 [17].

In the late 1960s, VR was reported to be capable of reconstructing and training alpha-activity of the brain in order to enhance relaxation, which was used to assist patients with uncontrolled epilepsy [18]. In 1993, psychiatrist Lemson put forward the idea of using VR in rehabilitation of patients with various phobias and anxiety disorders [19]. At about the same time, the group of Williford described the decrease in acrophobia manifestations when using VR [20, 21]. Later, this approach was used in treatment of itching [22], pain syndromes [23, 24], depression, insomnia, post-traumatic stress disorder in the military [25, 26]. The potential of VR technology is highly appreciated in children with autism spectrum disorders [27–30] and in patients with Parkinson's disease [31], Alzheimer's disease [32], multiple sclerosis [33], etc. Nowadays, VR is increasingly used for rehabilitation after stroke [34–38]. The entertaining effect of immersion in VR distracts the patient's attention from painful procedures, reduces anxiety, discomfort or dissatisfaction with treatment [39].

In Russia, VR therapy in rehabilitation treatment of patients with motor disorders developed alongside with the methods of robotic mechanotherapy [40–42]. This approach is based on the fundamental mechanisms of motion physiology established by classics of national physiology Bernstein and Anokhin. When studied from the standpoint of evidence-based medicine, VR technologies proved to be highly effective in recovery of walking function [9, 43] and upper limb motor function [44–46]. Movements recover more successfully and physical activity increases in such patients due to training in a VR environment that is very close to the real world, higher motivation and active participation of patients in rehabilitation [47–49].

Traditional physiotherapeutic methods (therapeutic gymnastics and mechanotherapy) do not always involve active training of the patient's motor skills, while VR with its unique ability to reproduce almost any environment and provide feedback involves the patient in the training process with similar movement parameters, the patient being able to realize and correct his mistakes when performing movements [50–53]. VR creates an opportunity to improve motor skills more effectively in the same context as in real life owing to three key elements necessary for training motor functions (repeated stimulation, sensory feedback, patient motivation) [54, 55].

The use of VR in neurorehabilitation showed that recovery of motor deficits depends on activation of brain plasticity mechanisms, including changes in the primary sensorimotor cortex and in the additional motor area [53, 56, 57]. This knowledge allows us to expand the range of nosologies in which VR helps achieve significant results.

VR neurorehabilitation for motor functional recovery in patients after stroke

One of the most promising areas of integrating VR in the rehabilitation complex is elimination of stroke consequences [58–60]. Most often, VR therapy is used in the long-term rehabilitation period of post-stroke patients [61–63], although the literature data show the advantages of early VR rehabilitation using interactive games that increase motivation for therapy and programs with tactile feedback contributing to the recovery of sensory functions and preventing the development of potential complications [64, 65].

The results of including VR in the complex of rehabilitation measures for motor disorders in post-stroke patients are often ambivalent from the perspective of evidence-based medicine. For example, there were no statistically significant differences between treatment outcomes in the group of patients undergoing rehabilitation with the YouGrabber VR system (YouRehab, Switzerland) — game software simulating training in the gym — and in the control group with traditional therapy, although the results were slightly worse in the latter [66]. Functional contribution to motor deficit compensation similar to traditional rehabilitation methods was observed when using the Reh@City VR system (NeuroRehabLab, Portugal). It is a virtual simulation of a city where memory, attention, and solution of visual-spatial tasks are integrated to perform various daily activities [52]. As described in the study [67], in the early post-stroke period, patients used the Sixense VR system (USA) and rehabilitation game software with an avatar on the screen synchronized with the patient's movements. The authors reported improvement in sensorimotor function, but the differences between the main and control groups of patients appeared to be insignificant.

At the same time, a number of studies have demonstrated progressive improvement in quality and increase in the range of movements (for example, using VR in combination with rehabilitation exoskeleton for shoulder, elbow and wrist joints, enabling movements with seven degrees of freedom, support of the paretic arm, registration of movement kinematics and grip strength for feedback control) [49]. Promising results have been obtained in the work of Kiper et al. [68] where enhanced feedback in a virtual environment was used to restore upper limb dysfunction after stroke. Gesture-controlled VR game consoles (Nintendo Wii; Nintendo, Japan; Xbox Kinect; Microsoft, USA) have demonstrated high efficiency in motor rehabilitation [69], especially for improving upper limb functions [70].

In general, interaction combining visual and tactile (haptic) stimulation appeared to be the most effective. For example, Yin et al. [71] investigated the effect of cycling exercises using VR on improving the balance in patients after stroke. The VR system used included bilateral pedal force sensors and a dynamometer platform, analyzed the collected data to provide the patient with feedback in the form of a virtual car, thereby training the affected side. The authors showed that strength increased by 22% and the balance improved by 29% after a cycle of such exercises. Similar rehabilitation principle is described in the work of Flowers et al. [72].

Gross data on present-day use of VR technologies for targeted motor rehabilitation of the upper limb functions after cerebral circulation disorders are given in a number of domestic articles [73–75]. Such basic motor functions of the hand as the ability to accurately reach the object, manipulate it, and coordinate the movements of both hands are primarily impaired in patients with motor disorders of central origin. The use of VR technologies can partially compensate for these disorders: difficulties in dosing muscle effort, for example, in finger flexion and extension [73] as well as muscle weakness, inter-articular coordination disorders and the sequence of activation of different muscle groups [74].

A great number of recent studies have shown the efficacy of applying VR technologies for rehabilitation of patients with post-stroke motor disorders in the upper limbs, whereas the sources available provide no works focusing on the use of VR for rehabilitation of patients with the consequences of frequent limb injuries complicated by developing peripheral neuropathies (complex regional pain syndrome, etc.). Besides, as we have already mentioned, in a number of studies where such commercial VR systems as Sixense [67] or YouGrabber [66] were used in complex rehabilitation therapy of patients with motor disorders, the results showed no significant differences as compared to groups of patients undergoing conventional rehabilitation. The reason for this may be inaccurate selection of visual stimuli applied through 3D glasses or a panoramic screen, while neurorehabilitation requires the whole range of afferent stimuli [25]. This suggests that further research and development in this area remain relevant and search for more effective VR technologies as well as new evidence-based methods of verifying and predicting their application results should continue.

VR technology in rehabilitation of children

One of the promising directions in correcting the coordination and accuracy of limb movements is the use of VR as an additional method of rehabilitation in children with cerebral palsy [4]. Numerous works focusing on the use of VR technologies in such children are devoted to both technological and medical aspects of rehabilitation [5, 6, 76]. The most common system used in treatment of cerebral palsy is Virtual Rehab (USA), a rehabilitation platform designed to restore motor function of the limbs using commercially available sensors Microsoft Kinect (USA) and Leap Motion (USA) as well as video game technology for telerehabilitation. For example, a virtual environment has been developed on the basis of open source platform Unity 3D. A child with cerebral palsy can interact with the environment in real time using the Leap Motion sensor that detects and tracks hand and finger movements. At the same time, combined EEG recording with MindWave device (NeuroSky, USA) allows monitoring the patient's clinical progress in real time taking into account the differences in the levels of attention and relaxation [77].

Virtual reality in Microsoft Kinect sensor therapy proved to be effective in improving exercise performance and physical activity [5]. VR rehabilitation was found to have potentially positive effect on the manner of walking, balance, muscle strength and general motor skills in children with cerebral palsy [78]. Turning treatment into a game increases the child's attention when performing certain exercises in rehabilitation compared to conventional treatment [79, 80] and, most importantly, it is possible to use VR technologies at home [8, 81, 82]. The authors of these and other studies (for example, [83]) are optimistic about enhancing the conventional treatment with VR as an alternative play tool for cognitive and motor rehabilitation of children including those with multiple disorders. In literature, we have found no reports on the methods of remote instructor-assisted online sessions with the use of VR headsets for motor-disabled children, whereas similar systems for adult patients are being developed [84].

The study of Nikolenko et al. [85] presents developed by the authors complex for rehabilitation of children with progressive muscular dystrophy based on modern technologies of VR gaming, the efficacy of which was scientifically grounded and proved taking into consideration the existing principles of rehabilitation in children with this severe pathology. The technique can significantly improve motor functions, quality of life and ensure rehabilitation availability.

VR technologies in rehabilitation of patients with consequences of injuries to the musculoskeletal system and the nervous system

One of the most difficult problems of rehabilitation in patients with motor disorders is recovery of lost functions after spinal cord injury. The results of the latest studies [86–88] suggest the feasibility of using VR for rehabilitation of these patients. Evaluation of visual feedback effect in exercises with interactively controlled avatar on gait improvement in patients with spinal cord injury [89] showed that movement speed was significantly higher with fewer attempts compared to tests where only static scenes were demonstrated. Dimbwadyo-Terrer et al. [48] studied effectiveness of the VR system Toyra (Spain) in recovery of the upper limb function in people with tetraplegia caused by spinal cord injury. The course of rehabilitation involved VR games based on performing daily activities (eating, combing hair, or washing the face) with three difficulty levels.

Despite the absence of statistically significant differences in rehabilitation results between these patients and the control group that underwent conventional rehabilitation treatment, they were more motivated and expressed willingness to carry on using the system Toyra.

Other researchers also remarked on positive dynamics when using VR technologies in patients after spinal injury [90–93]. For example, when studying VR effect on improving the driving ability in patients with spinal cord injury, it was observed that rehabilitation of driving skills in VR conditions made significant progress even when the consequences of spinal injury were severe [94].

Introducing VR technologies in the complex of rehabilitation measures in patients with loss of upper limb movements due to brain injuries is a very important factor in the process of retraining motor skills [95]. Conventional approaches in such cases are unable to solve the problem of neuroplasticity completely, while rehabilitation methods with the use of VR providing feedback can improve these processes [96–98].

Different task complexity levels can be the key factor for effective rehabilitation using VR, when the situation is modeled motivating patients to surpass their own results. For example, when developing movements using the Nintendo Wii game console (Japan) with a peripheral device that tracks the body position and movements (Balance Board, Nintendo of Korea), it was found that the effect of using the VR system in patients after knee surgery did not depend on knee injury severity, but was determined by consistent complication of tasks [99].

The use of wearable sensors contributed to successful integration of VR into the rehabilitation system of patients with frozen shoulder syndrome [100]. Rehabilitation treatment including a set of exercises, hot compresses, interference therapy consisted of sessions with VR for 40 min twice a week during 4 weeks. As a result, the authors of the study revealed a significant increase in the range of shoulder joint movements and strength of the upper limb muscles.

Recently, there have been published a few works focusing on the benefits of using VR technology in rehabilitation of patients with consequences of sports injuries (for example, the knee joint in the postoperative period) [101].

Conclusion

Technologies based on the use of virtual environment provide optimal conditions for recovery of motor deficits in patients with motor disorders, haptic feedback contributes to the recovery of sensory functions and interactive games increase motivation for therapy. However, to ensure safety of patients, especially children, there should be requirements for thorough evaluation of possible complications resulting from the use of VR technologies. A personalized approach is required in each case taking into account individual adaptive and compensatory capabilities of the body, assessing the adequacy of mental responses and controlling physiological functions of patients in their interaction with the virtual environment.

There are currently available software variants providing the possibility to include monitoring registration of various physiological parameters in mobile VR solutions, wearable devices connected to a smartphone. Muñoz et al. [102] have developed a mobile complex of virtual reality with built-in biological feedback based on the use of signals from the patient: heart rate, EEG and electromyography obtained through wearable sensors and transmitted to the smartphone via Bluetooth. These signals are used to control real-time virtual environment created on the basis of Unity 3D, while the EmoCat Rescue game developed by the authors based on the PhysioVR framework facilitates acquisition, streaming and recording of physiological signals. In this case, the smartphone is used as a screen for screenless virtual reality glasses and as a personal server for data transmission [102, 103]. Making virtual reality a mobile and economically accessible technology, such approaches represent the trends in development of VR rehabilitation in the near future and provide the basis for its large-scale introduction into medical practice.

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