Chapter

# Proprioception in Immersive Virtual Reality

*Alexander Vladimirovich Zakharov,*
*Alexander Vladimirovich Kolsanov,*
*Elena Viktorovna Khivintseva, Vasiliy Fedorovich Pyatin*
*and Alexander Vladimirovich Yashkov*

## Abstract

Currently, in connection with the advent of virtual reality (VR) technologies, methods that recreate sensory sensations are rapidly developing. Under the conditions of VR, which is an immersive environment, a variety of multimodal sensory experiences can be obtained. It is urgent to create explicit immersive environments that allow maximizing the full potential of VR technology. Activation of the proprioceptive sensory system, coupled with the activation of the visual analyzer system, allows you to achieve sensations of interaction with VR objects, identical to the sensations of the real physical world. Today, the activation of proprioceptive sensations is achieved using various devices, including robotic ones, which are not available for use in routine medical practice. The immersive multisensory environment makes it possible to significantly personalize the rehabilitation process, ensuring its continuity and effectiveness at various stages of the pathological process and varying degrees of severity of physical disorders, while significantly reducing the burden on the healthcare system by automating the rehabilitation process and objectively assessing the effectiveness. Further development and increased availability of VR technologies and devices that allow achieving an increase in immersion due to sensory immersion will be in great demand as a technology that allows teaching patients motor skills.

**Keywords:** virtual reality, proprioception, neuroplasticity, physical rehabilitation, habilitation

## 1. Introduction

Proprioception is the sensation of the position of body parts relative to each other in space, both in statics and during their movement. The formation of proprioceptive sensation occurs due to the activity of various receptor systems located in the tissues of the human body, the largest number of which is in the muscular system. Proprioception belongs to the somatosensory system and is traditionally defined as sensory sensations of position, movement, or balance [1]. From this position, proprioception is the awareness of the position or movement of our body and its parts in space because of processing information from the receptors of muscles, joints, tendons, and skin. This type of sensory sensation includes two components, the first of which arises in a static position, and the second appears during movement and plays a decisive role in ensuring coordination of movements; both are important in ensuring balance at rest, as well as during movement [2].

The proprioceptive system has a high degree of precision in registering changes recorded by the receptor apparatus, more specifically, a change in the angle in a particular joint or in the mass of a held object. In the process of ontogenesis, the role of proprioception as the dominant receptor system in sensory cognition of the external world goes into second place relative to the visual analyzer, which in humans and mammals acquires a dominant role. However, proprioception continues to be in high demand in building a complete judgment about an external object, providing information about its physical properties necessary to ensure effective interaction with this object, which underlie more complex motor skills that are important for the formation of praxis. Proprioception is actively used as an afferent system for the formation of biofeedback when adjusting the motor system to external conditions in the process of performing a movement and object interaction at the level of the spatial field.

The use of devices for activating proprioceptive sensations as a way to increase sensory immersion in VR or, in another way, to achieve a greater degree of immersion, is one of the unresolved, but actively developing ways to expand the practical application of VR. In VR conditions, sensory perception of reality only through the visual analyzer does not provide the formation of a complete sensory sensation, identical to physical interaction with objects, and cannot be used to implement explicit interaction. It is precisely because of the difficulty of achieving such a quality of proprioceptive sensations, which would be identical to the sensations received in the physical world, that modern VR systems are mostly implicit, and control in them is implemented in surrogate ways that are not identical to the natural richness of object sensations and the complexity of manipulating them.

At the moment, less attention is paid to the study of unimodal proprioceptive information processing in statics or only when performing a movement than the study of multisensory integration processes, with the participation of not only the proprioceptive system, but also other sensory analyzers. Isolated activation of the proprioceptive system is possible only when the visual analyzer is not functioning, which is rarely observed under normal conditions. The close connection between the proprioceptive system and the visual analyzer can be traced through experiments on the formation of proprioceptive sensations, without directly affecting the receptor apparatus. Manipulation of proprioceptive sensations is possible using a visual analyzer, as demonstrated in experiments on the use of mirror therapy in the treatment of phantom pain after limb amputation due to various reasons. In this case, through the information coming through the visual analyzer, it is possible to achieve proprioceptive sensations, sensations of movement, as well as a sense of touch in the complete absence of somatosensory stimuli.

This is evidence that proprioception is a complexly organized bodily sensation, the formation of which can be influenced by the activation of the receptor apparatus of various sensory systems and, of course, primarily the visual analyzer.

## 2. Possibilities of using VR in physical rehabilitation

One of the main and important applications of VR is its use in the medical field to provide various tasks of physical rehabilitation and habilitation.

The main goal of physical rehabilitation is to help a person return to a natural state when performing daily activities by restoring damaged motor skills, as well as if they cannot be completely restored, acquiring new ones that compensate for those lost due to diseases of the musculoskeletal system (trauma, pathology of the muscular system) or the CNS vascular diseases and injuries. Also, significant prospects for the use of VR are traced in patients with impaired formation of the motor system in ontogenesis.

Research on the effectiveness of rehabilitation using VR technology appeared in the mid-1990s.

Currently, there are several systematic reviews evaluating the clinical efficacy of sensorimotor training in VR in restoring the function of the upper limbs and gait after stroke [3–6].

Despite the fact that most often the study of the effectiveness of various methods of motor rehabilitation occurs on the example of such pathologies as acute disorders of cerebral circulation and traumatic brain injury due to their widespread prevalence, the study of the effectiveness of rehabilitation in other pathological conditions using VR technology is also carried out. It should be noted that the nature of movement disorders in various pathologies is accompanied by impairments at various levels of its organization, therefore, modeling various motor tasks under VR conditions allows one to obtain positive results on the restoration of movement in patients with disorders such as infantile cerebral palsy and multiple sclerosis, which are characterized by impaired organization of the motor system at various levels from the cortical to the level of paleokinetic regulation (rubro-spinal) [7]. However, these studies are sporadic and do not allow for a systematic analysis.

Thus, VR technology has significant prospects both in the rehabilitation of patients with various dysfunctions of the CNS and musculoskeletal system in the framework of restoration of function within the framework of physical rehabilitation, and in the development of unformed motor skills in the process of solving the problems of motor habilitation.

The first reason that makes VR a promising environment for solving a complex of problems of physical habilitation and rehabilitation is that VR can be used to ensure interaction with the outside world by patients with pronounced motor or other limitations [8]. The second important factor is that the VR environment and interaction with its objects can be adapted to the patient's existing physical defect, achieving significant personalization, which, accordingly, will contribute to the achievement of a more significant effect of rehabilitation or habilitation.

According to the data obtained when assessing the effectiveness of restoration of the motor function of the upper limb in patients after acute cerebrovascular accident in comparison with the group of patients receiving only traditional methods of motor rehabilitation, the use of VR rehabilitation showed great effects both in the short and relatively long term (for example, 3 months after the onset of pathology) [9].

A significant advantage of using VR is the ability to automate the rehabilitation process, use the autotune of exercises, obtain objective analytics in the rehabilitation process, and reduce the burden on rehabilitators. If we consider VR from this side, then it can be characterized as a technology that is an interface between the user and various technical devices, which makes it possible to simulate a wide variety of rehabilitation or habilitation environments, which is necessary to solve a whole range of tasks, allowing the rehabilitated to interact with objects of the VR environment through a variety of sensory channels.

Thus, the main tasks and prospects of using VR are quite clear, but at the same time they have some limitations in achieving these advantages, relative to traditional methods of physical rehabilitation or habilitation.

New approaches to rehabilitation, habilitation or training emerging on the basis of VR are based on the latest technological advances, including the use of robotic devices, tactile interfaces, and brain-computer interfaces. So, the variety of technical devices allows you to more effectively use the capabilities of VR, as an interface between the patient and the outside world, in which you can simulate various conditions and tasks, thus achieving a personalized approach to solving rehabilitation problems [10]. In addition to restoring motor skills, VR can be considered as a tool in the treatment of cognitive impairments of various origins, in the treatment of post-traumatic stress disorder, as well as various pain syndromes. One of the promising options for the use of VR is its use in the study of the ontogeny of the nervous system, which will be extremely necessary for understanding the formation of a pathological process, since any pathology in the context of ontogeny can be considered as regressive development, i.e. return to earlier stages of the existence and functioning of the CNS as a whole or its individual components [11]. In this regard, it is extremely important to provide neuro-feedback, preferably multisensory, primarily through the visual and proprioceptive sensory channels, because the formation of motor skills without these sensory systems is not possible. In several studies on the adaptation of the motor system after the demonstrated visual inconsistency of movements in VR to movements in the real physical world, it was found that the activity of the visual-motor connection in children is higher than in adolescents and adults, since such adaptation to motor activity in real in the physical world, after such a demonstration in children, it was much slower [12, 13]. Over time, as they grow older, this connection weakens, but obviously, only because of functional restructuring, and not anatomical, therefore, in a saturated immersive environment, you can get the results of visual-motor interaction, which are not always achievable in the physical world. Thus, a separate study of the motor system, as well as its functioning in health and disease, without connection with sensory systems, is inappropriate and incorrect from a physiological point of view.

VR technology can be used to provide a meaningful and effective impact on various human sensory systems; it also provides significant opportunities for modeling their functioning to compensate for lost sensory and motor functions. Now, the most technically simple VR systems are with implicit interaction with VR objects. These VR environments allow the person to be rehabilitated to act as a passive observer of the displayed content, while interaction occurs through the visual and auditory channel. Some expansion of the application of this technology occurs due to the use of various manipulators or joysticks, while the interaction with VR objects acquires the features of explicit interaction, however, the manipulation of VR objects with the use of these VR devices by objects is surrogate in nature, not giving the fullness of physical sensations.

The main problem in this interaction is the absence of physical sensations provided by the proprioceptive system, namely, the feeling of weight, density of an object, position in space. The importance of these sensations in the process of rehabilitation or habilitation lies in the fact that most of the movements performed by a person are the result of the functioning of the proprioceptive system, which ensures all their diversity and successful performance, regardless of external and internal factors. Thus, locomotor activity, devoid of fine tuning, provided by biofeedback based on the proprioceptive system, becomes less effective, and in some situations it is simply impossible, for example, walking at night or interacting with an object in three-dimensional space in the absence of visual control in patients with afferent paresis in the hand. An exception is interaction with objects in three-dimensional space, which is provided by cortical motor centers and the corresponding centers of praxis, in the implementation of which the visual analyzer has an equal or more significant role.

## 3. Prospects for VR in motor rehabilitation

Understanding the importance of ensuring the formation of proprioceptive sensations, when solving a range of physical rehabilitation tasks, is also based on a more intense activation of neuroplasticity processes when performing motor tasks with multisensory and, first of all, proprioceptive reinforcement, demonstrated in a number of experiments both on biological models and in patients with different pathology. The formation of biofeedback stimulates the processes of neurogenesis and neuroplasticity, due to the formation of new interneuronal connections, initially of a functional nature, but subsequently fixed at the structural level due to the activation of latent connections between individual functional structures of the CNS. That is why VR is an ideal immersive environment that makes it possible to maximally activate the processes of neuroplasticity for more effective recovery of not only motor, but also cognitive impairments in patients with damage to the CNS of various origins.

Learning how to perform new skills within the framework of solving motor tasks modeled in VR is of decisive importance for inducing neuroplasticity processes, and as a result, contributes to a more effective restoration of impaired functions due to various injuries of the CNS or the musculoskeletal system. The immersive environment created in VR is a particularly effective tool for carrying out tasks of interacting with objects in three-dimensional space. The restoration of this level of motor function is especially important in increasing the independence of patients with motor defects of varying severity, which is one of the ultimate goals of motor rehabilitation or habilitation. Additional technical capabilities in the form of using various sensors, telemetry during training in VR allow a detailed analysis of the motor activity of the rehabilitated person, which can serve as initial data for the formation of a recommendation system to increase the effectiveness of the rehabilitation process, or to adapt exercises during the rehabilitation process, for example, by gradually complicating them. Implementation, not allowing the rehabilitated person to lose interest and motivation to practice.

For example, today there is many studies that formed the basis of several publications demonstrating the effectiveness of restoration of upper limb functions in patients after acute cerebrovascular accident when using exercises with VR [14].

However, these studies were based only on clinical data carried out in patients in the late rehabilitation period after suffering acute cerebrovascular accident. At the same time, the high safety and effectiveness of such exercises in VR suggests that the use of virtual reality will also be effective in patients in the acute period, after acute cerebrovascular accident. Such results regarding the use of implicit multimodal VR with visual and proprioceptive confirmation of walking have been demonstrated in a study on the restoration of lower limb function in patients in the acute period of stroke **Figures 1** and **2** [15].

One of the reasons underlying the effectiveness of using VR as a method for restoring motor function is the ability to model new motor tasks that make the rehabilitation process more interesting, increasing the motivation of patients for further exercises [16].

VR can be used for multimodal sensory impact on the rehabilitated person. The addition of multimodal sensory reinforcements after performing the required interactions with virtual objects made it possible to use VR in a wide variety of areas, and it also significantly increases the potential for using this immersive environment in motor rehabilitation. Solving the problems of motor rehabilitation, using personalized, motor training, has a more significant impact on the processes of neuroplasticity than implicit or extra-contextual interaction with objects of the VR environment. For example, according to fMRI data, this method demonstrates a higher degree of activation of the motor cortex when performing specific motor tasks and when solving the problem of restoring motor disorders in patients after a stroke [17].

**Figure 1.**
*ReviVR rehabilitation walk simulator.*

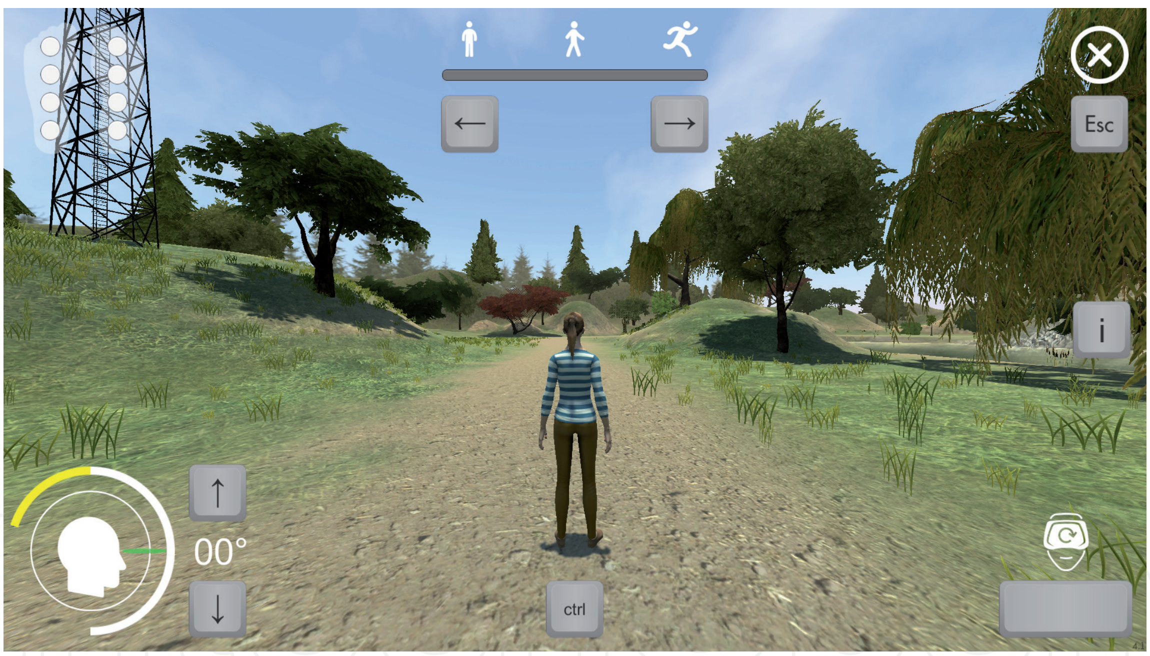


**Figure 2.**
*First-person view in ReviVR rehabilitation walk simulator.*

The data of objective methods for assessing changes in the activity of the cerebral cortex demonstrate the relationship between the specificity of the performed motor task and the degree of activation of neuroplastic changes.

Visual-motor and proprioceptive feedback, implemented in VR, provides realistic, up-to-date information during the rehabilitation exercise. It is realism and maximum proximity to physical sensations that are the most important factors that activate neuroplastic processes in the central nervous system (CNS).

Visual information, which is the most powerful sensory signal that is activated in the immersive environment, is a modeling factor for the reorganization of sensorimotor connections. For example, errors demonstrated during visual accompaniment of motor tasks performed in VR affect the motor and premotor cortex during motor learning, changing the activity of these zones [18–22].

Active and rewarding exercises (by demonstrating the progress of the performed exercise or another method) within the framework of the performed rehabilitation tasks can significantly enhance biofeedback, leading to a significant decrease in the number of errors in the restored movements, i.e. making them more energy efficient and accurate. According to fMRI data, at this moment there is a significant activation of the motor and premotor regions of the frontal cortex of the brain [23].

The very observation and subsequent ideomotor presentation of this movement leads to a significant facilitation of the formation of motor evoked potential and increases intercortical interactions in the motor and premotor regions [24–27].

It should be noted that the implementation of all this activation of the motor areas through exposure, for example, on the visual analyzer, becomes possible due to the proven numerous intrahemispheric corticocortical connections [28, 29]. These connections combine the visual cortex with the motor, premotor, parietal, and frontal lobes into a single functional system [30–34]. At the same time, there is a large number of experimental studies that demonstrate that a significant number of neurons in the motor, premotor and parietal regions can be modulated by the activity of the visual cortex of the brain [35–39].

Moreover, in contrast to proprioception, the activation of which in the physical world is necessarily associated with active or passive movements of the limbs, visual neurofeedback in VR can be provided independently of the fact of movement, for example, by simply demonstrating it. Also, it is interesting that the demonstration of this movement can be significantly changed and, most importantly, it can be completed to its full volume, regardless of the initial motor activity of the person being rehabilitated [40].

Thus, visual biofeedback allows modulation of the motor system, without the need for active or passive movements. The visual system has a high degree of reliability and specificity in the implementation of this biofeedback, because visual afferentation predominates over other sensory modalities, such as proprioceptive or auditory, and is used by a person more effectively in everyday activities [41].

An additional, but important rationale for the advisability of using the visual cortex as a sensory input for modulating motor function is that during an acute cerebrovascular accident, it is not damaged simultaneously with the motor or premotor cortex, due to their location in different blood supply basins of the brain, but namely carotid and vertebrobasilar. For acute cerebrovascular accident, in the first episode, the defeat of two pools is not a common manifestation of the disease. The defeat of the cortical representation of the visual analyzer in the form of hemianopsia and contralateral hemiplegia is observed only in the villous artery syndrome, but the preservation of the opposite visual fields allows using the VR environment for rehabilitation exercises.

Thus, VR allows the user to receive multimodal sensory information, which can cause a real sense of presence and provide cognitive, sensory and emotional immersion in the formed rehabilitation task, which has varying degrees of complexity [42–44].

The use of VR makes it possible to implement various modifications of the displayed object or its movement, highlighting it against the general background, for example, by changing the color, brightness or its shape. This opportunity allows the patient to focus on the target elements of the rehabilitation exercise, enhancing his motivation. With the help of VR, it is possible to achieve modeling of the conditions that in traditional therapy are carried out by limiting the movement of a hand that does not have motor impairments due to stroke, through its fixation to the trunk. To implement this type of therapy in VR, one can ignore the activity of a healthy limb (recorded by telemetry or contact sensors: electromyography, accelerometers, etc.) and not provide visual information regarding its movement [4, 14, 45–47]. Additional opportunities are provided by the use of the "brain-computer" interface based on the motor imagery paradigm and the P300, the use of which allows visualizing the movement of a limb with motor impairments when activity appears according to electroencephalography or functional near-infrared spectroscopy data recorded globally, with all scalp surface of the head, or only in specified areas, which are a projection onto the scalp surface of the head of the motor or premotor areas of the cerebral cortex. For example, the target signal can be used for classification within the brain-computer interface in the contralateral motor or premotor cortex, which may slow down the rate of onset of the "rehabilitation plateau" and increase the rehabilitation potential in patients with CNS pathology.

In the detected functional improvements obtained as a result of motor rehabilitation, sensorimotor activation was observed not only in the contralateral hemisphere, but also in the ipsilateral hemisphere, which indicated the activation of latent connections that were not active before the start of the rehabilitation measures [48–50]. The ongoing rehabilitation in VR and the progress obtained with it in the restoration of motor function are primarily associated not with the compensation of movements, which is the result of maladaptation, but with the restoration of motor function due to the activation of neuroplasticity processes in the motor and premotor cortex of the brain [51].

## 4. The current difficulties of using multisensor VR

Even though VR provides many unique advantages over traditional or new rehabilitation approaches, there are limitations to its widespread practical use as a routine rehabilitation method.

First, there is currently no sufficient evidence base for clinical studies that would demonstrate the unambiguous effectiveness of using VR in sensorimotor rehabilitation in various clinical groups in comparison with various traditional methods of motor rehabilitation. In addition, there is still quite a bit of information regarding the possibility of replacing physical exercises only with classes in virtual reality, namely, how interchangeable, and acceptable it is for short-term and long-term results of motor rehabilitation. That is why it is still impossible to say unambiguously how high the advantages of sensorimotor rehabilitation in VR are relative to those in the real physical world. Thus, all these questions justify the need to continue research in the field of studying the possibility of expanding the use of VR, as well as studying the short-term and long-term effectiveness of using VR in sensorimotor or cognitive rehabilitation, by accumulating a clinical base and obtaining the possibility of conducting a meta-analysis of research data to achieve the maximum high level of evidence. And although nowadays there are several studies in which attempts have been made to solve these problems, rehabilitation using VR technology continues to be considered only as an adjuvant method of sensorimotor and cognitive rehabilitation [5, 52].

The second important reason for the difficulty in the routine use of rehabilitation in VR is the relative high cost of equipment for using these systems as a method of rehabilitation within the framework of the telemedicine concept. A few years ago, the equipment needed to simulate VR, making it difficult to use for more than 40 minutes due to the heavy weight of the VR helmet, has become much more convenient today, because there has been an abrupt growth in the number of manufacturers of these technical devices offering more and more comfortable products for use.

## 5. Neuropasticity and VR

According to data obtained on biological models that allow studying the processes of neuroplasticity, the lack of stimulation of the motor cortex during the "critical period", which usually corresponds to an acute state after damage of any genesis, leads to the loss of corticospinal synaptic connections [53], while stimulation motor cortical networks in the same "critical period" may contribute to the partial restoration of some of these lost connections [54]. Long-term lack of stimulation of the motor cortex in the acute period after injury ultimately leads to the consolidation of existing changes that will prevent further restoration of function.

The key component of the theory of neuroplasticity activation is the dynamic nature of changes in neural connections during motor rehabilitation using VR technology, which can be adapted to the individual needs of the person being rehabilitated, providing a personalized approach to sensorimotor and cognitive rehabilitation.

Some studies demonstrate rich intrahemispheric cortical–cortical connections that link the occipital, parietal and frontal cortex [32, 33, 55]. Moreover, individual studies demonstrate that a significant number of motor neurons in the premotor and motor cortical areas are modulated by visual information [35, 37–39], suggesting that visual information can be a powerful signal for functional reorganization of sensorimotor connections.

The main parameters through which the processes of neuroplasticity can be activated, and which can be influenced when the immersive environment is formed, are visualized movement, biofeedback, motivation and learning through observation.

Rehabilitation measures in VR can also contribute to the process of functional reorganization in the CNS due to the activation of neuroplasticity processes.

The possibility of obtaining a significant rehabilitation result is achievable only with a long training process, because the formation of new skills, which is due to the activation of the processes of synaptogenesis or Hebb learning, as well as other mechanisms of neuroplasticity, does not give an immediate stable result, since stabilization requires subsequent reinforcement in order to stimulate the transition of interneuronal interaction from functional to morphologically fixed changes [56, 57].

Thus, in an immersive environment, it is quite easy to set the proper volume of tasks to be performed and combine them with secondary cognitive tasks, making the performance of a motor task interesting due to diversity, increasing the motivation of the person being rehabilitated for a long rehabilitation process [58].

Studies on biological models have demonstrated that the intensity and duration of physical exercise is one of the determining factors that have a significant impact on neuroplastic changes during rehabilitation [59]. For example, changes at the synaptic level in a biological experiment occurred after the animal was exposed to thousands of repetitions of a given task over a short period of time, i.e. 12,000 repetitions over 2–3 days [60, 61].

Also, it was noted that patients with CNS disease receiving rehabilitation on this occasion require more and more intensity of physical exercises in order to achieve positive results in restoring physical function, in comparison with the process of developing new motor skills in healthy people [62]. The duration of rehabilitation sessions to achieve positive effects in the restoration of function, for example, the upper limb, after a stroke also depends on the stage of stroke: from 1–2 hours in the acute stage [63] and up to 10–20 repetitions per training in the chronic stage of stroke [64]. At the same time, it is implied that during the entire time of the training, it is required to maintain a high level of motivation to achieve a positive result and maintain it throughout the entire course of rehabilitation.

The flexibility of most VR applications suggests that learning in a meaningful, enriched environment can be started earlier in recovery from an emerging CNS disease, such as a traumatic brain injury, compared to conventional exercise. An early start increases the rehabilitation potential by influencing neuroplastic processes and ensuring the activation of latent connections and cortical structures, which is also necessary to prevent the onset and progression of functional maladaptive processes. The same statement is relevant for patients with acute cerebrovascular accident, where verticalization in the first days after a stroke is limited due to pronounced concomitant pathology, which is usually the cause of the stroke, or the severity of the patient's movement disorders.

The possibility of automating the rehabilitation process in VR makes training more accessible for patients, and in the future can be used in telemedicine [65].

The hypothesis underlying the substantiation of the effectiveness of motor rehabilitation says that the success of motor learning occurs only at the moment of the maximum approximation of the rehabilitation exercise to real motor skills, which the rehabilitated person will use in the future in the real physical world, as well as when using neuro-feedback [57, 66].

In addition to using a simulated VR environment to restore basic movements or simple functions necessary to perform everyday household tasks, VR can become a training platform for developing patients' skills in using various means of individual rehabilitation, for example, for teaching the use of a motorized wheelchair or driving a car, etc. [67].

## 6. Implementation of neurofeedback in VR

Optimization of training and an increase in its effectiveness arises with the meaningfulness of the exercises performed and their optimal complication [58]. As a rule, only one repetition for training is not enough, since the formation of a motor skill occurs because of multiple repetitions with their use in solving real physical motion problems [68, 69]. For this, it is necessary to achieve an optimal combination of cognitive efforts required by the patient to solve motor problems during repetition of movements, and the complexity of the rehabilitation task.

The use of neuro-feedback contributes to an increase in the activation of structures that are usually not involved in the implementation of the performed movement in the norm. For example, in experiments on healthy subjects, it was demonstrated that the addition of neuro-feedback when performing a movement in VR leads to a more significant activation of the contrateral sensorimotor cortex according to the motor evoked potential [40]. In studies conducted in patients with hemiplegic infantile cerebral palsy, VR rehabilitation has demonstrated bilateral activation of the sensorimotor cortex and ipsilateral activation of the premotor cortex. After the completion of rehabilitation, bilateral activation disappeared, and the contralateral sensorimotor cortex continued to maintain a high level of activity [70].

Increasing the efficiency of neuro-feedback through the use of sensory channels is the most promising way to increase the possibility of motor learning using VR and ensure sufficient cognitive immersion in the VR environment.

The effectiveness of neuro-feedback can be assessed by such a parameter as productivity, which characterizes the quality of the movement performed by a person. The neural feedback obtained directly in the process of performing a rehabilitation exercise to restore motor function, after the completed rehabilitation task, can act as a criterion for evaluating the effectiveness. Some studies demonstrate that the enhancement of neurofeedback has an additional value in increasing the effectiveness of motor rehabilitation in patients after acute cerebrovascular accident [71]. At the same time, the direct implementation of neuro-feedback in the process of performing the rehabilitation task will be more promising, because on the basis of this approach, it is possible not only to visualize the performed movement and its quality, but also to carry out additional motivation of the patient by, for example, completing the construction of the full range of motion with a pronounced motor deficit in paralyzed limbs, or visualizing such a movement, which is the patient's in principle unable to perform (such as walking or running).

Perhaps, in some cases, this will cause a certain dissonance between real proprioceptive sensations and visual information provided to the rehabilitated person. However, in the end it will be perceived by the subject only from the positive side, since will allow him to demonstrate his independence and the ability to perform all the same actions without taking into account the existing disabling state. Such additional motivation will lead to the fact that the person being rehabilitated will be more motivationally involved in the process of restoring motor function, which will lead to better results in restoring motor function both in the short and long term.

As a complement to neuro-feedback, mainly implemented through the visual analyzer, VR provides the ability to use auditory and proprioceptive feedback, which are intuitively interpreted and implemented in real time, but with increased accuracy and consistency compared to the stimuli available in the physical world [4, 72].

The use of this technology as a supplement to visual information in an immersive environment through the activation of additional sensory systems also makes it possible to increase the degree of cognitive and emotional immersion in the VR environment and the task performed in it. This is especially in demand in patients with a certain damage to one or another sensory system at a different level from the peripheral part of the sensory analyzer to the cortical representation. It does not matter whether this damage arose because of a real disease, was acquired by the patient earlier, or was congenital. Thus, it is possible to achieve a more complete sensory saturation and get the maximum effect on the motor and premotor regions of the frontal and parietal lobes of the cerebral cortex.

These effects make it possible to neutralize sensory deprivation, which is observed in a patient after a pathological condition has arisen with gross damage to the CNS and manifests itself in pronounced motor disorders. Such patients are usually bedridden or wheelchair-bound and do not receive in full all those sensory sensations that a person experiences while freely moving in the physical world without physical limitations. Long-term sensory deprivation ultimately leads to neurotransmitter rearrangements, the clinical manifestation of which may be not only difficulty in restoring stato-locomotor function, but also the development of cognitive and emotional-volitional disorders.

Thus, rehabilitation measures, which are based on the activation of neuroplastic processes in the CNS after its damage, can be sufficiently fully modeled in an immersive environment, and multisensory neuro-feedback allows us to model the process of interaction with the VR environment as realistic and efficient as possible, which will contribute to solving most tasks.

## 7. Additional prospects for using VR

Also, it should be noted that the concept of motor learning forms the basis for the scientific substantiation of the integration of vocational training into rehabilitation practice, which will expand the possibilities of social adaptation of patients with a disabling disease, will contribute to their subsequent professional integration through training in professional activities, taking into account the existing motor or sensory deficit. This concept makes it possible to use VR to model specific conditions for teaching patients with movement disorders for their subsequent professional integration into society.

Today this problem is quite urgent, since any professional training is primarily focused on patients with intact motor impairments or their minimal severity.

In the context of the wide possibilities of VR for modeling a wide variety of conditions and tasks using various sensory channels, it can be assumed that its use will be in demand for the rapid formation of the necessary environment, which allows to restore not only any lost skill due to the developed disease, but also for the training of professional skills in patients with pre-existing movement or other disabilities.

An important factor influencing the improvement of the effectiveness of rehabilitation in VR is the possibility of its use as remote rehabilitation within the framework of the telemedicine concept.

Such a combination is possible only in conditions where a clear assessment of biometrics is available, which of course is possible in VR. The use of artificial intelligence algorithms will allow automating the process of motor rehabilitation, taking into account the initial personified clinical data.

Effective approaches to rehabilitation should include targeted training, individual feedback based on multisensory interaction, an individual exercise schedule, a fairly long and frequent repetition of motor exercises, exciting game scenarios, individual rehabilitation programs taking into account the characteristics of motor deficits and individual preferences of the person being rehabilitated [73].

Attention should be paid to the need to further form the evidence base for assessing the effects of rehabilitation in VR and the contribution of individual elements that form neuro-feedback through various sensory channels and primarily through the proprioceptive channel, which allows the formation of explicit interaction with VR objects, identical to the interaction with physical objects [74–76].

## 8. Conclusion

The spread of the use of VR in rehabilitation practice is determined by numerous factors, including the technical availability of equipment and software, the possibility of creating personalized rehabilitation exercises to achieve a higher rehabilitation effect.

The use of a multisensory component in the implementation of neuro-feedback allows one to achieve potentially better results in motor rehabilitation. Proprioception, as one of the components of such neuro-feedback, is the most promising way of forming sensations that are as close as possible to natural sensations obtained during physical contact with objects of the real world.

It is possible to single out the factors that determine the more effective use of VR for solving various rehabilitation tasks: immersivity, neuro-feedback, the possibility of multiple repetition of a motor task with visualization of such a movement, the use of artificial intelligence and mathematical models on the basis of which the movement is visualized, taking into account all the richness of kinematics and synergy of such movements, as well as the possibility of objective continuous monitoring of the entire rehabilitation process.

The use of devices that create proprioceptive sensations upon contact with VR objects make it possible to count on obtaining explicit VR environments, which will have a much wider range of users. This gives reason to count on achieving maximum efficiency in the restoration of motor functions during the rehabilitation and habilitation of patients with various functional disorders, both as a result of acquired pathology and as a result of disorders that have arisen at various stages of ontogenesis.

It is extremely important today to form a complete understanding of how different sensory and tactile manipulations in VR affect the dynamics of various processes in the CNS, since the study of this issue will reveal the full potential of rehabilitation through VR.

One of the important, unsolved problem, possibly allowing to reveal the full potential of rehabilitation, is the formation of a complete understanding of how different sensory influences in VR affect the dynamics of various processes in the central nervous system, including the dynamics of sensorimotor connections. Understanding of this effect will make it possible to achieve greater personalization of the rehabilitation process, not only based on the severity of a motor defect, but also considering functional disorders in a complex, multicomponent, hierarchically arranged motor system.

## Acknowledgements

SamSMU students, and staff Samara regional hospital after D.V. Seredavin.

## Conflict of interest

The results were obtained in Leading Research Centre supported by RF Ministry of Communications and RVC JSC fund (Grant No. 003/20 03-17-2020, Grant ID - 0000000007119P190002).

## Notes/thanks/other declarations

We thank management Samara Medical University for the opportunity to conduct scientific work.

## Author details

Alexander Vladimirovich Zakharov[1*], Alexander Vladimirovich Kolsanov[2], Elena Viktorovna Khivintseva[1], Vasiliy Fedorovich Pyatin[3] and Alexander Vladimirovich Yashkov[4]

1 Department of Neurology and Neurosurgery, Samara Medical University, Samara, Russia

2 Department Operative Surgery and Clinical Anatomy with Innovative Technology Course, Samara Medical University, Samara, Russia

3 Department of Physiology with a Course on Life Safety and Disaster Medicine, Samara Medical University, Samara, Russia

4 Department of Medical Rehabilitation, Sports Medicine, Physiotherapy and Balneology, Samara Medical University, Samara, Russia

*Address all correspondence to: zakharov1977@mail.ru

## References

[1] Stillman BC. Making Sense of Proprioception: The Meaning of Proprioception, Kinaesthesia and Related Terms. Physiotherapy. 2002;88(11):667-676. DOI: 10.1016/S0031-9406(05)60109-5

[2] Pereira EM, Rueda FM, Diego IA, De La Cuerda RC, De Mauro A, Page JM. Use of Virtual Reality Systems as Proprioception Method in Cerebral Palsy: Clinical Practice Guideline. Neurologı'a (English Edition). 2014;29(9):550-559. DOI:10.1016/j.nrleng.2011.12.011.

[3] Weiss PL, Rand D, Katz N, Kizony R. Video capture virtual reality as a flexible and effective rehabilitation tool. J Neuroeng Rehabil. 2004;1:12. DOI: 10.1186/1743-0003-1-12.

[4] Holden MK. Virtual environments for motor rehabilitation: review. Cyberpsychol Behav 2005;8:187-211. discussion 212-189. DOI: 10.1089/cpb.2005.8.187.

[5] Laver KE, Lange B, George S, Deutsch JE, Saposnik G, Crotty M. Virtual reality for stroke rehabilitation. Cochrane Database of Systematic Reviews. 2017;11(11):CD008349. DOI: 10.1002/14651858.CD008349.pub4

[6] Maier M, Ballester BR, Duff A, Oller ED, Verschure PFMJ. Effect of Specific Over Nonspecific VR-Based Rehabilitation on Poststroke Motor Recovery: A Systematic Meta-analysis. Neurorehabilitation and Neural Repair. 2019;33:112-129. DOI: 10.1177/1545968318820169.

[7] Fulk GD. Locomotor training and virtual reality-based balance training for an individual with multiple sclerosis: a case report. J Neurol Phys Ther. 2005;29(1):34-42. DOI: 10.1097 / 01.npt.0000282260.59078.e4.

[8] Rose FD, Brooks BM, Rizzo AA. Virtual reality in brain damage rehabilitation: Review. CyberPsychology & Behaviour. 2005;8(3):241-271. DOI: 10.1089 / cpb.2005.8.241.

[9] Piron L, Tombolini P, Turolla P, Zucconi C, Agostini M, Dam M, et al. Reinforced feedback in virtual environment facilitates the arm motor recovery in patients after a recent stroke. Virtual Rehabilitation. 2007; 2007:121-123. DOI: 10.1109/ICVR.2007.4362151.

[10] Merians AS, Fluet GG, Qiu Q, Lafond I, Adamovich SV. Learning in a virtual environment using haptic systems for movement re-education: Can this medium be used from remodeling other behaviors and actions? Journal of Diabetes Science and Technology. 2011;5(2):301-308. DOI:10.1177/193229681100500215.

[11] Bohil CJ, Alicea B, Biocca FA. Virtual reality in neuroscience research and therapy. Nature Reviews. Neuroscience. 2011;12(12):752-762. DOI: 10.1038 / nrn3122.

[12] Adams H, Narasimham G, Rieser J, Creem-Regehr S, Stefanucci J, Bodenheimer B. Recalibration and Prism Adaptation of Children and Teens in Immersive Virtual Environments. IEEE Transactions on Visualization & Computer Graphics. 2018;24(4):1408-1417. DOI: 10.1109/ TVCG.2018.2794072.

[13] Bodenheimer B, Creem-Regehr S, Stefanucci J, Shemetova E, Thompson WB. Prism Aftereffects for Throwing with a Self-Avatar in an Immersive Virtual Environment. In: Rosenberg ES. (eds.) 2017 IEEE Virtual Reality (VR) Proceedings: March 18-22, 2017, Los Angeles, CA, USA. Piscataway, NJ: IEEE; 2017. p. 141-147.

[14] Merians AS, Poizner H, Boian R, Burdea G, Adamovich S. Sensorimotor

training in a virtual reality environment: Does it improve functional recovery poststroke. Neurorehabilitation and Neural Repair. 2006;20(2):252-267. DOI: 10.1177/1545968306286914.

[15] Zakharov AV, Bulanov VA, Khivintseva EV, Kolsanov AV, Bushkova YV, Ivanova GE. Stroke Affected Lower Limbs Rehabilitation Combining Virtual Reality With Tactile Feedback. Frontiers in robotics and AI. 2020; 7:81. DOI: 10.3389/frobt.2020.00081.

[16] You SH, Jang SH, Kim YH, Hallet M, Ahn SH, Kwon YH, et al. Virtual reality-induced cortical reorganization and associated locomotor recovery in chronic stroke: an experimenter-blind randomized study. Stroke. 2005;36(6):1166-1171. DOI: 10.1161 / 01.STR.0000162715.43417.91.

[17] Boyd LA, Randhawa B, Vidoni ED, Wessel BD. Motor learning after stroke: Is skill acquisition a prerequisite for contralesional neuroplastic change? Neuroscience Letters. 2010;482(1):21-25. DOI: 10.1016 / j.neulet.2010.06.082.

[18] Bray S, Shimojo S, O'Doherty JP. Direct instrumental conditioning of neural activity using functional magnetic resonance imaging-derived reward feedback. Journal of Neuroscience. 2007;27(28):7498-7507. DOI: 10.1523/JNEUROSCI.2118-07.2007.

[19] Hadipour-Niktarash A, Lee CK, Desmond JE, Shadmehret R. Impairment of retention but not acquisition of a visuomotor skill through time-dependent disruption of primary motor cortex. Journal of Neuroscience. 2007;27(49):13413-13419. DOI:10.1523/JNEUROSCI.2570-07.2007.

[20] Muellbacher W, Ziemann U, Boroojerdi B, Cohen L, Hallett M. Role of the human cortex in rapid motor learning. Experimental Brain Research. 2001;136(4):431-438. DOI: 10.1007/s002210000614.

[21] Muellbacher W, Ziemann U, Wissel J, Dang N, Kofl er M, Facchini S, et al. Early consolidation in human primary motor cortex. Nature. 2002;415(6872):640-644. DOI: 10.1038/nature712.

[22] Richardson AG, Overduin SA, Valero-Cabré A, Padoa-Schioppa C, Pascual-Leone A, Bizzi E, et al. Disruption of primary motor cortex before learning impairs memory of movement dynamics. Journal of Neuroscience. 2006;26(48):12466-12470. DOI: 10.1523/JNEUROSCI.1139-06.2006.

[23] Wise SP, Moody SL., Blomstrom KJ, Mitz AR. Changes in motor cortical activity during visuomotor adaptation. Experimental Brain Research. 1998;121(3):285-299. DOI: 10.1007 / s002210050462.

[24] Leonard G, Tremblay F. Corticomotor facilitation associated with observation, imagery and imitation of hand actions: A comparative study in young and old adults. Experimental Brain Research. 2007;177(2):167-175. DOI: 10.1007 / s00221-006-0657-6.

[25] Patuzzo S, Fiaschi A, Manganotti P. Modulation of motor cortex excitability in the left hemisphere during action observation: A single- and paired-pulse transcranial magnetic stimulation study of self- and non-self-action observation. Neuropsychologia. 2003;41 (9):1272-1278. DOI: 10.1016/s0028-3932(02)00293-2.

[26] Stefan K, Cohen LG, Duque J, Mazzocchio R, Celnik P, Sawaki L, et al. Formation of a motor memory by action observation. Journal of Neuroscience. 2005;25(41):9339-9346. DOI: 10.1523/JNEUROSCI.2282-05.2005.

[27] Strafella AP, Paus T. Modulation of cortical excitability during action observation: A transcranial magnetic stimulation study. Neuroreport.

2000;11(10):2289-2292. DOI: 10.1097 / 00001756-200007140-00044.

[28] Bulanov VA, Zakharov AV, Chaplygin SS. Solving classification problems of visual evoked potentials for the brain-computer interfaces. 2020 IOP Conf. Ser.: Mater. Sci. Eng. 2020; 862: 052051. DOI:10.1088/1757-899X/862/5/052051.

[29] Bulanov VA, Zakharov AV, Khivintseva EV. Wavelet transform for the identification of P300. 2020 IOP Conf. Ser.: Mater. Sci. Eng. 2020;862:052049. DOI:10.1088/1757-899X/862/5/052049.

[30] Dum RP, Strick PL. Frontal lobe inputs to the digit representations of the motor areas on the lateral surface of the hemisphere. Journal of Neuroscience. 2005;25(6):1375-1386. DOI: 10.1523 / JNEUROSCI.3902-04.2005.

[31] Fang PC, Stepniewska I, Kass JH. Ipsilateral cortical connections of motor, premotor, frontal eye, and posterior parietal fields in a prosimian primate, Otolemur garnetti. The Journal of Comparative Neuroscience. 2005;490(3):305-333. DOI:10.1002/ cne.20665.

[32] Lewis SJG, Slabosz A, Robbins TW, Barker RA, Owen AM. Dopaminergic basis for deficits in working memory but not attentioanl set-shifting in Parkinson's disease. Neuropsychologia. 2005;43(6):823-832. DOI: 10.1016 / j.neu ropsychologia.2004.10.001

[33] Lewis JW, Van Essen DC. Corticocortical connections of visual, sensorimotor, and multimodal processing areas in the parietal lobe of the macaque monkey. The Journal of Comparative Neurology. 2000;428(1):112-137. DOI: 10.1002 / 1096-9861 (20001204) 428: 1 <112 :: aid-cne8> 3.0.co; 2-9.

[34] Lewis JW, Van Essen DC. Mapping of architectonic subdivisions in the macaque monkey, with emphasis on parieto-occipital cortex. The Journal of Comparative Neurology. 2000;428(1):79-111. DOI: 10.1002/ 1096-9861(20001204)428:1<79::aid-cne7>3.0.co;2-q.

[35] Graziano MS. Where is my arm? The relative role of vision and proprioception in the neuronal representation of limb position. Proceedings of the National Academy of Science. 1999;96(18): 10418-10421. DOI: 10.1073 / pnas.96.18.10418.

[36] Graziano MS, Gandhi S. Location of the polysensory zone in the precentral gyrus of anesthetized monkeys. Experimental Brain Research. 2000;135(2): 259-266. DOI: 10.1007 / s002210000518.

[37] Graziano MS, Gross CG. Spatial maps for the control of movement. Current Opinion in Neurobiology. 1998; 8(2):195-201. DOI: 10.1016 / s0959-4388 (98) 80140-2.

[38] Graziano MS, Gross CG. Visual responses with and without fixation: Neurons in premotor cortex encode spatial locations independently of eye position. Experimental Brain Research. 1998;118 (3):373-380. DOI: 10.1007/ s002210050291.

[39] Kakei S, Hoffman DS, Strick PL. Sensorimotor transformations in cortical motor areas. Neuroscience Research. 2003; 46(1): 1-10. DOI: 10.1016 / s0168-0102 (03) 00031-2.

[40] Adamovich SV, August K, Merians A, Tunik E. A virtual reality-based system integrated with fmri to study neural mechanisms of action observation-execution: A proof of concept study. Restorative Neurology and Neuroscience. 2009;27(3): 209-223. DOI: 10.3233 / RNN-2009-0471.

[41] Snijders HJ, Holmes NP, Spence C. Direction-dependent integration

of vision and proprioception in reaching under the infl uence of the mirror illusion. Neuropsychologia. 2007;45(3):496-505. DOI: 10.1016 / j.neuropsychologia.2006.01.003.

[42] Riva G. Virtual environments in neuroscience. IEEE Transactions of Information Technology of Biomedicine. 1998;2(4):275-281. DOI: 10.1109/4233.737583.

[43] Riva G, Castelnuovo G, Mantovani F. Transformation of flow in rehabilitation: The role of advanced communication technologies. Behavioural Research Methods. 2006;38(2):237-244. DOI: 10.3758 / BF03192775.

[44] Zakharov AV, Khivintseva EV, Pytin VF, Kolsanov AV, Kalinin VA, Osadchuk MA, et al. Restoration of motive function of the lower extremities using virtual reality technique. Journal of Advanced Pharmacy Education & Research. 2019;9(2):102-107.

[45] Deutsch JE, Merians AS, Adamovich S, Poizner H, Budrea GC. Development and application of virtual reality technology to improve hand use and gait of individuals poststroke. Restorative Neurology Neuroscience. 2004;22(3-5):371-386.

[46] Kenyon RV, Afenya MB. Training in virtual and real environments. Annals of Biomedical Engineering. 1995;23(4):445-455. DOI: 10.1007 / BF02584444.

[47] Merians AS, Jack D, Boian R, Tremaine M, Burdea GC, Adamovich SV, et al. Virtual reality-augmented rehabilitation for patients following stroke. Physical Therapy. 2002;82(9): 898-915. DOI:10.1093/ptj/82.9.898.

[48] Carey LM, Abbott DF, Puce A, Jackson GD, Syngeniotis A, Donnan GA. Reemergence of activation with poststroke somatosensory recovery: A serial fMRI case study. Neurology. 2002;59(5):749-752. DOI: 10.1212/wnl.59.5.749.

[49] Carey LM, Abbott DF, Egan GF, O'Keefe GJ, Jackson GD, Bernhardt J, et al. Evolution of brain activation with good and poor motor recovery after stroke. Neurorehabilitation and Neural Repair.2006;20(1):24-41. DOI: 10.1177 / 1545968305283053.

[50] Small SL, Hlustik P, Noll DC, Genovese C, Solodkin A. Cerellar hemispheric activation ipsilateral to the paretic hand correlated with functional recovery after stroke. Brain. 2002;125(7):1544-1557. DOI: 10.1093 / brain / awf148.

[51] Subramanian SK, Lourenço CB, Chilingaryan G, Sveistrup H, Levin MF. Arm motor recovery using a virtual reality intervention in chronic stroke: Randomized control trial. Neurorehabilitation and Neural Repair. 2013;27(1):13-23. DOI: 10.1177 / 1545968312449695.

[52] Gibbons EM, Thomson AN, Noronha MD, Joseph S. Are virtual reality technologies effective in improving lower limb outcomes for patients following stroke–a systematic review with metaanalysis. Top. Stroke Rehabil. 2016;23(6):440-457. DOI: 10.1080/10749357.2016.11 83349.

[53] Friel KM, Barbay S, Frost SB, Plautz EJ, Stowe AM, Dancause N, et al. Effects of a rostral motor cortex lesion on primary motor cortex hand representation topography in primates. Neurorehabil Neural Repair. 2007;21:51-61. DOI: 10.1177/1545968306291851.

[54] Salimi I, Friel KM, Martin JH. Pyramidal tract stimulation restores normal corticospinal tract connections and visuomotor skill after early postnatal motor cortex activity blockade. J Neurosci.

2008;28(29):7426-7434. DOI: 10.1523 / JNEUROSCI.1078-08.2008.

[55] Stepniewska I, Fang PC, Kaas JH. Microstimulation reveals specialized subregions for different complex movements in posterior parietal cortex of prosimian galagos. Proc Natl Acad Sci U S A. 2005;102(13):4878-4883. DOI: 10.1073/pnas.0501048102.

[56] Adamovich SV, Fluet GG, Tunik E, Merians AS. Sensorimotor training in virtual reality: A review. Neurorehabilitation. 2009;25(1):29-44. DOI: 10.3233 / NRE-2009-0497.

[57] Schmidt RA, Lee TD. Motor control and learning: A behavioral emphasis (5th ed.). Champaign, IL: Human Kinetics; 2011.

[58] Kleim J, Jones T. Principles of experience-dependent neural plasticity: Implications for rehabilitation after brain damage. Journal of Speech, Language & Hearing Research. 2008;51(1):S225–S239. DOI: 10.1044/1092-4388(2008/018).

[59] Krakauer JW, Carmichael ST, Corbett D, Wittenberg GF. Getting neurorehabilitation right: What can be learned from animal models? Neurorehabilitation and Neural Repair. 2012;26(8):923-931. DOI: 10.1177/1545968312440745.

[60] Nudo RJ, Milliken GW. Reorganization of movement representations in primary motor cortex following focal ischemic infarcts in adult squirrel monkeys. Journal Neurophysiol. 1996;75(5):2144-2149. DOI: 10.1152 / jn.1996.75.5.2144.

[61] Plautz EJ, Milliken GW, Nudo RJ. Effects of repetitive motor training on movement representations in adult squirrel monkeys: role of use versus learning. Neurobiol Learn Mem. 2000;74(1):27-55. DOI: 10.1006/ nlme.1999.3934.

[62] Cirstea MC, Ptito A, Levin MF. Arm reaching improvements with short-term practice depend on the severity of the motor deficit in stroke. Experimental Brain Research. 2003;152(4):476-488. DOI: 10.1007/s00221-003-1568-4.

[63] Bernhardt J, Dewey H, Thrift A, Donnan G. Inactive and alone: physical activity within the first 14 days of acute stroke unit care. Stroke. 2004;35(4):1005-1009. DOI: 10.1161/01. STR.0000120727.40792.40.

[64] Lang C, Macdonald J, Gnip C. Counting repetitions: an observational study of outpatient therapy for people with hemiparesis post-stroke. J Neurol Phys Ther. 2007;31(1):3-11. DOI: 10.1097/01.npt.0000260568.31746.34.

[65] Holden M, Todorov E, Callahan J, Bizzi E. Virtual environment training improves motor performance in two patients with stroke: Case report. Neurology Report. 1999;23(2):57-67. DOI: 10.1097/01253086-199923020-00013.

[66] Barnett ML, Ross D, Schmidt RA, Todd B. Motor skills learning and the specificity of training principle. Research Quarterly. 1973;44(4):440-447. DOI: 10.1080/10671188.1973.10615224.

[67] Kizony R, Levin MF, Hughey L, Perez C, Fung J. Cognitive load and dual-task performance during locomotion poststroke: A feasibility study using a functional virtual environment. Physical Therapy. 2010;90(2):252-260. DOI: 10.2522/ ptj.20090061.

[68] Lee TD, Swinnen SP, Serrien DJ. Cognitive effort and motor learning. QUEST. 1994;46: 328-344. DOI: 10.1080/00336297.1994.10484130.

[69] Lehto NK, Marley TL, Ezekiel HJ, Wishart LR, Lee TD, Jarus T. Application of motor learning

principles: The physiotherapy client as a problem-solver. IV. Future directions. Physiotherapy Canad. 2001;53(2):109-114.

[70] You SH, Jang SH, Kim YH, Kwon YH, Barrow I, Hallett M. Cortical reorganization induced by virtual reality therapy in a child with hemiparetic cerebral palsy. Developmental Medicine & Child Neurology. 2005;47:628-635. DOI: 10.1111/j.1469-8749.2005.tb01216.x.

[71] Molier BI, Van Asseldonk EH, Hermens HJ, Jannink MJ. Nature, timing, frequency and type of augmented feedback; does it influence motor relearning of the hemiparetic arm after stroke? A systematic review. Disability and Rehabilitation. 2010;32(22):1799-1809. DOI: 10.3109/09638281003734359.

[72] Subramanian SK, Massie CL, Malcolm MP, Levin MF. Does provision of extrinsic feedback result in improved motor learning in the upper limb poststroke? A systematic review of the evidence. Neurorehabilitation Neural Repair. 2010;24(2):113-124. DOI: 10.1177/1545968309349941.

[73] Timmermans AA, Seelen HA, Willmann RD, Kingma H. Technology-assisted training of arm-hand skills in stroke: Concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. Journal of Neuroengineering & Rehabilitation. 2009;6:1. DOI: 10.1186/1743-0003-6-1.

[74] Rose FD, Attree EA, Brooks BM, Johnson DA. Virtual environments in brain damage rehabilitation: A rationale from basic neuroscience. In Riva G, Wiederhold BK, Molinari M. (eds.). Virtual environments in clinical psychology and neuroscience. Amsterdam, The Netherlands: Ios Press; 1998. p. 233-242.

[75] Rose FD, Attree EA, Brooks BM, Parslow DM, Penn PR, Ambihaipahan N. Training in virtual environments: Transfer to real world tasks and equivalence to real task training. Ergonomics. 2000;43(4):494-511. DOI: 10.1080/001401300184378.

[76] Sandlund M, McDonough S, Hager-Ross C. Interactive computer play in rehabilitation of children with sensorimotor disorders: A systematic review. Developmental Medicine & Child Neurology. 2009;51(3):173-179. DOI: 10.1111 / j.1469-8749.2008.03184.x.