The application of virtual reality in neuro-rehabilitation: motor re-learning supported by innovative technologies

Zastosowanie rzeczywistości wirtualnej w neurorehabilitacji; innowacyjne technologie wspomagające ponowne uczenie się ruchu

Paweł Kiper 1,2(A,B,D,E,F), **Andrzej Szczudlik** 2(A,D,E,F), **Elżbieta Mirek** 3(D,E), **Roman Nowobilski** 2(A,E), **Józef Opara** 4(A,E), **Michela Agostini** 1(B,F), **Paolo Tonin** 1(B,F), **Andrea Turolla** 1,5(B,F)

[1] San Camillo Hospital IRCCS Foundation, Venice, Italy
[2] Jagiellonian University Medical College, Krakow, Poland
[3] University of Physical Education, Krakow, Poland
[4] Academy of Physical Education, Katowice, Poland
[5] The University of Sheffield, Sheffield, United Kingdom

Key words
Virtual reality, Robot-aided therapy, Motor learning, Rehabilitation

Abstract

The motor function impairment resulting from a stroke injury has a negative impact on autonomy, the activities of daily living thus the individuals affected by a stroke need long-term rehabilitation. Several studies have demonstrated that learning new motor skills is important to induce neuroplasticity and functional recovery. Innovative technologies used in rehabilitation allow one the possibility to enhance training throughout generated feedback. It seems advantageous to combine traditional motor rehabilitation with innovative technology in order to promote motor re-learning and skill re-acquisition by means of enhanced training. An environment enriched by feedback involves multiple sensory modalities and could promote active patient participation. Exercises in a virtual environment contain elements necessary to maximize motor learning, such as repetitive and diffe-rentiated task practice and feedback on the performance and results. The recovery of the limbs motor function in post-stroke subjects is one of the main therapeutic aims for patients and physiotherapist alike. Virtual reality as well as robotic devices allow one to provide specific treatment based on the reinforced feedback in a virtual environment (RFVE), artificially augmenting the sensory information coherent with the real-world objects and events. Motor training based on RFVE is emerging as an effective motor learning based techniques for the treatment of the extremities.

Słowa kluczowe
rzeczywistość wirtualna, terapia wspomagana przez robota, uczenie się ruchu, rehabilitacja

Streszczenie

Upośledzenie funkcji ruchowych po udarze mózgu u wielu chorych ma negatywny wpływ na samodzielność i czynności życia codziennego oraz wymaga długotrwałej rehabilitacji. Liczne badania wykazały, że uczenie się nowych umiejętności motorycznych pobudza neuroplastyczność mózgu i umożliwia poprawę funkcjonalną. Innowacyjne technologie wykorzystywane w rehabilitacji wzmacniają możliwości treningu ruchowego poprzez dostarczanie informacji zwrotnej. Łączenie tradycyjnej rehabilitacji ruchowej z innowacyjną technologią poprzez wzmocniony trening umożliwia przyspieszenie ponownego uczenia się ruchu i nabywania umiejętności funkcjonalnych. Otoczenie wzbogacone przez informacje zwrotną angażuje wiele zmysłów i stymuluje pacjenta do aktywnej pracy. Ćwiczenia w otoczeniu wirtualnym maksymalizują efekt uczenia się ruchu poprzez powtarzające się i zróżnicowane zadania oraz dostarczenie informacji zwrotnej w odniesieniu do działania i jego efektu. Innowacyjne technologie rehabilitacyjne, zarówno terapia wirtualna, jak i urządzenia - roboty, pozwalają na specyficzne leczenie oparte na treningu z wykorzystaniem wzmocnionego sprzężenia zwrotnego w środowisku wirtualnym (*Reinforced Feedback in Virtual Environment*

The individual division on this paper was as follows: A – research work project; B – data collection; C – statistical analysis; D – data interpretation; E – manuscript compilation; F – publication search

Article received: 31.03.2014; accepted: 22.04.2014

Please cited: Kiper P., Szczudlik A., Mirek E., Nowobilski R., Opara J., Agostini M., Tonin P., Turolla A. The application of virtual reality in neuro-rehabilitation: motor re-learning supported by innovative technologies. Med Rehabil 2013; 17(4): 29-36

– RFVE), zwiększając informacje czuciowe odpowiadające rzeczywistym zadaniom i przedmiotom. Trening ruchowy oparty na RFVE daje także możliwość poszerzenia wiedzy na temat technik wykorzystywanych do poprawy czynności ruchowych niedowładnej kończyny.

INTRODUCTION

Rehabilitation of people with central nervous system (CNS) injury is difficult and requires involvement of different specialists, the patient and their family as well and the effect of the rehabilitation are not always fully satisfactory for both. This is due to the complex and diverse nature of rehabilitating function of the nervous system. Which include various physiological phenomena, from simple reflex regulation of internal organs through a complex reflex action, to complex processes of thinking and other mental functions.

Stroke is a common disease of the nervous system. In Poland, there are about 75 000 new strokes per year, mostly among people over 65 years old[1]. Approximately 15% of patients with ischemic stroke and up to 50% of patients with hemorrhagic stroke die within a month, usually during the first two weeks of hospitalization. Such a high mortality rate means stroke is the 3rd highest causes of death in adults, both in the world and Poland[2]. Only 10% of patients after a stroke do not have significant impairment of mobility, sensory disorders or cognitive disorders, and 40-75% of patients after stroke are completely dependent[3].

Both ischemic and hemorrhagic strokes often affect regions of the brain responsible for planning and execution of movements. This means that various movement disorders are common and long-persisting symptoms of a stroke. Most are hemiparesis (75% of patients), aphasia and apraxia. For this reason, patients with stroke in many rehabilitation centers represent the largest population of patients[2].

Rehabilitation, both in acute and in chronic stage of stroke are often not fully effective due to the insufficient frequency and duration of rehabilitation. Intensification of the rehabilitation process in order to improve the function of self-care, social activity and the ability to work is now becoming a priority.

A recent study on motor learning and control provide new neurophysiological information that can be transferred into functional therapy. Scientific studies have shown that repetitive, intense and random task practice lead to the modification of neuronal structures[4]. In order to facilitate the activation of brain areas and, consequently, to improve motor control, it could be beneficial to combine classical rehabilitation with innovative computer technologies. Using the adaptive capabilities of the nervous system exercises should involve different senses and promote active patient participation. Besides the concept of classical rehabilitation, which we can understand as the direct work of physiotherapists or rehabilitation team with a patient, there are also different rehabilitation techniques, where the work of physiotherapists mirrors certain technology, such as a computer in a virtual therapy or robotic devices. Innovative technologies such as robotics and virtual reality (VR) are being tested in neurorehabilitation especially for hemiparesis treatment.

Virtual reality through enhanced feedback in virtual environment (RFVE) contains the components needed to maximize motor learning, such as the practice of repeated and varied tasks, feedback of performance and its effect which can increase motivation.

Neuro-rehabilitation and motor learning through methods and robotic devices

Difficulties in fully understanding the pathological phenomena after brain damage leads to the emergence of a variety of therapeutic methods associated with various theoretical models of rehabilitation. Some of these techniques are already used in clinical practice, while others are still in the research phases.

One of the techniques developed, based on the principles of motor learning, is the Arm Ability Training. This technique was developed for motor rehabilitation of patients with minor hemiplegia, characterized by impaired coordination and precision of motion[5] in which the deficit can be determined by a precise kinematic assessment[6]. Arm Ability Training has been described on the basis various functions in healthy subjects, such as grip, reaching, stability and speed of movement. In a randomized clinical trial Platz et al. showed greater benefits with this training method when compared to classical physiotherapy, and the result was an improvement in performing activities of daily living with the affected limb[5]. Arm Ability Training is more focused on functional disorders than on disability in accordance with the principles of motor learning which states that motor control and learning are modular[7].

Another technique is Electromyogram-triggered Neuromuscular Stimulation arising from the theory of sensorimotor integration, which assumes that the undamaged areas of movement can be recruited and trained, in order to achieve efficient movement according to two learning principles of movement: repetition and sensorimotor integration[8]. Some studies have shown the effectiveness of this method in the treatment of stroke in the acute, subacute and chronic stage[9].

Another technique is Constraint-Induced Movement Therapy (CIMT) including the temporary immobilisation of the unaffected limb (6-10 hrs. / Day) and requirement to use the affected limb. Rehabilitation through CIMT is a method that can be used for patients after stroke and chronic cerebrovascular disease. For the upper limb the methods includes using induction of the affected limb for the majority of day whilst at the same time immobilizing the unaffected limb for a period of two to three weeks. For the lower limb there are different techniques which do not require immobilization of the unaffected limb, but these are based on intense training enriched with functional elements of positive feedback. The method is based on the assumption of restoring the inter-hemispheric balance by reducing the somatosensory stimuli coming from the unaffected limb and increasing the stimuli coming from the affected hemisphere[10,11]. The theory is based on the fact that the CNS has plasticity and in response to stimulation it could stimulate intensive creation of new neuronal connections[12-14]. Numerous studies have reported changes in cortical brain excitability[12,14,15] and have shown significant improvement and effects in patients in the chronic phase following stroke[16,17].

Another therapy is Mirror Box Therapy, which involves placing the paretic limb inside a 'mirror box', and the unaffected limb in front of the mirror. Seeing a reflection of movement through the mirror means that visual feedback is provided and the brain reads them as an image of properly functioning limbs. In this way, cortical maps are again remodeled. Observation of physiological movement increases excitability of the brain areas responsible for movement of the affected limb and induces subjective impression of the biologically correct movement. Due to the motor activation caused by the mirror neurons system, it is assumed that they represent internal models as examples of planning movements. Studies have shown that patients with stroke who used mirror therapy presented significantly greater improvements in motor activity compared to the control group. The improvement persisted even six months after therapy[2,18,19].

For relearning movement there are also mechanical or electronic devices that can help in the reeducation of motor function. The following devices have found wide application in the treatment of motor impairment. Robot-Aided Therapy is based on the theory of sensory integration combined with multisensory feedback (visual, sensory, auditory)[20,21]. It is based on the enhanced stimulus coming from the paretic side of the body as a result of intensive repetitive exercises both active and passive. Most of these devices are based on a passive exercise helping to achieve the movement initiated by the patient. In order to perform robot-aided therapy several types of devices have been developed such as:

- The robot called the MIT-Manus, which provides visual, tactile and auditory feedback. The device has shown in numerous studies beneficial effects in upper limb motor function in patients during the acute and chronic phases[22]. MIT-Manus uses two ranges of motion allowing for intense exercise for the upper limb.
- The Rutgers Master II-ND Force Feedback Glove allows patients to exercise finger movements. The patient undergoing therapy receive feedback (visual, sensory, auditory) during the execution of motor tasks. Besides the feedback a computer system provides real time information on the speed, range of movement and force of the movement performed. In clinical studies, the authors concluded that this devices could improve the quality, speed and fine dexterity movement and that the use of this therapy can complement classical rehabilitation[23].
- The Assisted Rehabilitation and Measurement (ARM) Guide allows the patient to perform exercises in four ranges of movement. In addition it can control the position of the patient's limb, which is placed on the handle. The patient moves the handle in order to perform the specified task and receives real-time visual feedback on movement and force generation on the monitor, and information about the position of the limb, range of motion and the following motor task. The authors suggest that the primary stimulus for recovery of functional movement is based on repeated movements[24].
- Mirror Image Movement Enhancer (MIME) is a robotic device that allows the execution of movements in six ranges of movement, helping or hindering the performance of motor activity depending on the task. The efficacy of therapy using this robot has been confirmed in clinical studies[25].
- ARMin is a half-exo-skeleton supporting movements of the upper or lower extremities. The position and force of the movement is adjusted to the current capacity of the patient and the tasks are displayed on the screen placed in front of subject[26].
- The Phantom 3.0 robot was tested on adult healthy subjects in order to study the function of the musculoskeletal system. This robot can provide feedback (visual, auditory, sensory) and generate forces which resist movement performance (Figure 1 a, b)[27].
- The prototype robot Tino is able to provide feedback, both sensory and visual, generated as a virtual image and provide resistance to assist the patient with the correct performance of the movement. The robot is used to improve the function of the fingers and the wrist. A pilot study showed significant improvement in hand function (Figure 2 a, b)[28].

Similar types of robotic devices allow patients to perform exercises bilaterally. Usually, they generate only sensory feedback. The use of these kind of robots is to reeducate lost automatisms e.g. during walking.

Bilateral Arm Training involves the use of the same exercise in real time for both affected and unaffected limbs. Clinical studies on bilateral upper limb training carried out using fMRI (functional Magnetic Resonance Imaging) point to facilitate interhemispheric balance and reduction of intracortical inhibition between hemispheres, which takes place probably through connections of the commissural fibres[29,30]. To perform bilateral exercise different devices are used such as:

- BI-MANU-TRACK, which is a system that allows exercises for forearm supination and pronation and wrist flexion and extension. The movements are performed bilaterally and the patient does not receive feedback at any stage[31].
- BATRAC is a device that allows the patient to perform rhythmic movements and again it does not provide any feedback. Patients undergoing

therapy with this robot can perform flexion and extension of the shoulder and elbow. The effectiveness of BATRAC device has been tested in clinical trials and shows improvements of movement activity[32].

The most commonly used devices to exercise the lower limbs are Lokomat and Gait Trainer. Lokomat is an automated gait orthosis supporting movement re-education. It generates a simulated gait pattern for any segments of the lower extremities. The use of a robot allows precise performance of repetitive movements required for normal gait pattern. Gait re-education helps to prevent the formation of compensatory and pathological patterns. Krishnan et al. tested the device with patients after stroke, showing a significant improvement with gait[33]. Gait Trainer is, however, intended for people who are not able to reach an upright position and do not have the required movements within the limb or limbs. The patient is placed in a harness, onto a platform, which eliminates the risk of falling and reduces the degree of difficulty. This device does not provide feedback and perform only passive movements based on the phases of the gait cycle (Figure 3 a, b)[34].

Using the techniques described above in order to relearn movement are characterized by certain general principles according to which the improvement is dependent on the amount of exercise performed. The acquisition of new motor skills is only possible though obtaining feedback from the environment and depends on the amount of exercise[35]. The first principle states that learning is more effective when performed exercises are separated by periods of rest between repetitions (distributed practice) compared to the situation when repetitions are performed in one block (massed practice)[36]. Despite the fatigue, the effectiveness of the training was increased linearly because of the interruptions between exercises[37]. The second principle states that the introduction of differentiated tasks (variable practice) improves the remembrance of performs in relation to the tasks always performed repetitively (constant practice)[38]. Another principle demonstrates the importance of randomly choosing the quantity and type of tasks (contextual interference) to be tested in the random ordering of n trials of x tasks (random practice). This leads to a better performance of each of the tasks than if a single task were practiced alone.

The continuous interaction with the external environment unconsciously determines the efficiency of education of many of our behaviors and habits. The basis of this process is procedural memory (motor memory), which is produced in the form of the likelihood of responses for specific stimuli. Procedural memory is located in the structures associated with the motor system, especially in the cerebellum, and basal ganglia (caudate nucleus), which is the starting point cognitive and perceptual learning and motor efficiency[39]. Motor learning can be

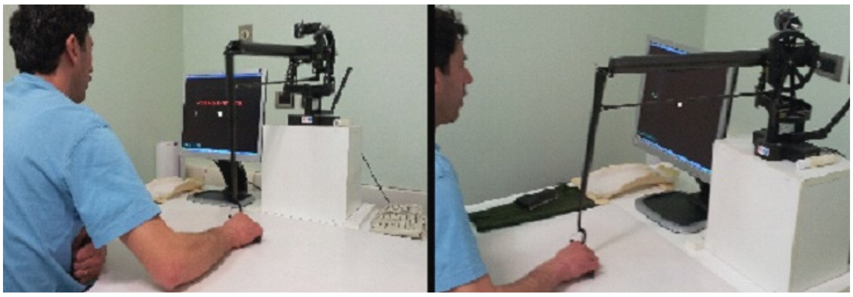

Figure 1 a and b

A patient moves the arm over a slippery flat surface with the aim of completing the set motor task

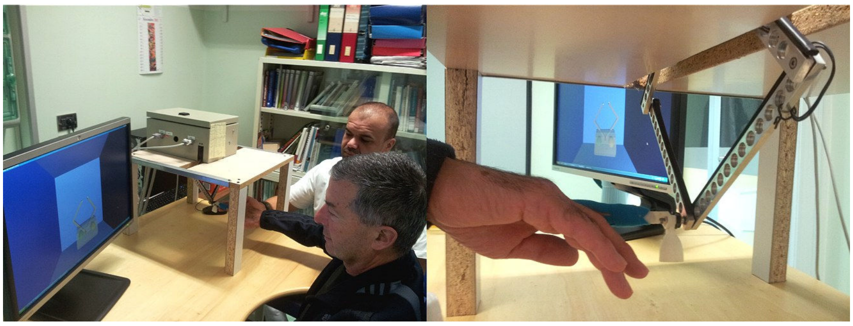

Figure 2 a and b

A robot-Tino prototype serves in the rehabilitation of the fingers and wrists

Figure 3 a and b

A patient in the course of re-education by means of the Gait Trainer device

defined as the ability to improve individual movements or sequences of movements through repetition and interaction with the environment.

It remains to determine how the above-mentioned techniques affect the reeducation of motor function in stroke patients. Studies of random practice and massed practice, which included a group of patients in the chronic phase post stroke showed better improvement of motor function in the random practice[40]. Many different sensorimotor exercise strategies can be added to the rehabilitation program. It was shown that some forms of feedback improve the efficiency of simple movement learning. Winstein et al. observed this when testing the phases (acquisition, maintenance and re-acquisition of motor tasks) of the learning process by performing simple movements with enhanced feedback. Comparing a group of stroke patients with a control group of healthy subjects did not show any difference in the acquisition of motor functions related to the learning process. However, individuals after stroke (regardless of the delivery of the feedback) committed more errors in each phase than those in the control group[41]. The authors concluded that a stroke in the sensorimotor area alters the ability to control and correct movement execution, but not the ability to relearn motor tasks.

Virtual therapy and the process of motor re-learning

Virtual reality is an innovative technology consisting of a high-end user-computer interface that involves real-time simulation and interactions through multiple sensorial channels. These sensorial modalities are visual, auditory, tactile, smell and taste. The computer based environment represents artificially generated sensory information and allows individuals to experience and interact with or within three-dimensional (3-D) environments[42]. The first virtual reality video arcade was the "Sensorama Simulator" invented by Morton Heiling in 1962. This early virtual reality workstation had 3-D video feedback, motion, color, stereo sound, aromas, wind effect and a seat that vibrated. The term Virtual Reality was introduced by Jaron Lamier in 1986, describing it as a set of technological tools (PC software for 3-D interactive display) and tracking devices for the recognition of the position and orientation of a subject, linked to a PC that updates the image in real time on the display[43]. Virtual reality has a history of use in military training, entertainment simulations, surgical training, training in spatial awareness and in psychology for phobias therapeutic intervention[44]. Several systems have shown the advantage of hand and arm motor skills training for stroke patients, and also showed benefits in cognitive enhancements[20,45-48].

Virtual Reality refers to the use of innovative technology, with enhanced feedback (auditory, visual, tactile) and provides sensory information in a form similar to those received from real world objects and events[49,50]. Rehabilitation in a virtual environment is carried out with a physiotherapist, where the person supervising the exercises controls the movements and posture of the patient.

Performing the exercises in a virtual environment patients try to follow optimal movement patterns which are demonstrated in real time in a virtual scenario. This approach is conducive to learning by imitation, and the complexity of motor tasks can be gradually increased to facilitate the transfer into the real world the movement patterns learned in the virtual one [51]. Patients following a stroke can improve the ability of movement through systematic and intensive exercises in the virtual environment[52,53]. The use of therapy using virtual reality in clinical practice is a relatively new approach for rehabilitation developed about a decade ago and is still under assessment. Conducted studies have shown that virtual reality has a major impact on improving mobility[54-57]. It was shown that motor relearning can be more effective in an environment with enhanced feedback. This technology allows the creation of special settings where human-computer interaction is optimized.

There are several ways to realize the visual interaction, with varying degrees of immersion (i.e., virtual reality interaction level). What determines the sense of presence is the level of immersion provided, which in turn depends on the system used. According to the differing levels of immersion it is possible to specify two types of virtual reality: immersive and non-immersive. Immersive virtual reality is able to create a high level of real world simulation by producing a three-dimensional computer-generated environment. This high level of immersion is possible by using a display device (e.g. Head Mounted Display, HMD) and completely isolates the user from the external environment. These devices are equipped with one or more electromagnetic sensors determining the body position, motion detection and continuously transmit this information to a computer which changes the three-dimensional image within real time[58]. One of the systems providing the highest level of immersion is a Cave Automatic Virtual Environment (CAVE), which displays the images on the walls cubic room. The person in the room wears glasses with an electromagnetic sensor and these determine position within the three-dimensional space and with appropriate software the image changes in real time according to the position of the patient's head[59].

Non-immersive virtual reality uses monitor displays or wall projections to produce a three-dimensional image. Therefore the external environment is not completely eliminated and the person receives the impression of a three-dimensional virtual world. This can be likened to looking through the windscreen of the car. One type of non-immersive system is the Virtual Reality Rehabilitation System (VRRS), in which the movement is recorded and presented in a virtual scenario on the monitor or on a wall projection (Figure 4 a, b)[42,53,55].

The current performance of these technologies has allowed one to minimize the latency in the exchange of signals, which have provoked discomforts due to interaction with the virtual world, such as cybersickness (nausea, vomiting, dizziness, headache, disorientation)[59].

The rehabilitation in virtual reality is a human-machine interaction in a 3-D virtual-world created by means of a computer in real time. Within

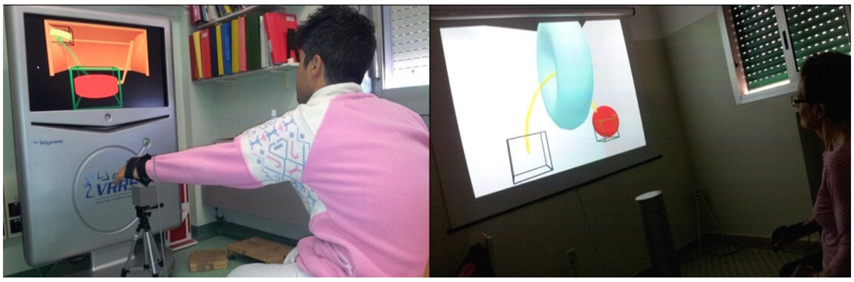

Figure 4 a and b

VRRS – non-immersive virtual reality presented on a monitor (on the left) and by means of a wall projection (on the right)

this virtual world, the patient learns to manage problematic situations related to his disorder. The possibility of the sense of presence in a real world through virtual reality is offered to the patient, which should permit one to transfer the acquired skills from the virtual environment into the real world. In fact, the aim is not to recreate mechanically the same physical reality, but to provide the better information necessary to realize tasks with the same confidence level as used in the physical environment.

Virtual reality therapy used for rehabilitation provides high quality care. The advantage of using a virtual environment in rehabilitation is undoubtedly the possibility to automatically record the results which allows monitoring of treatment progress. The ability to capture motor tasks helps to analyze the results. In addition, virtual reality systems allow you to create scenarios similar to the patient's real environment and generate real-time feedback in various forms depending on the motor task. Furthermore it generates stimuli to facilitate the movement re-learning without error. Virtual reality as a presented in the form of a game can motivate patients to increase participation.

CONCLUSION

This review paper indicates that innovative technologies, both virtual therapy and robotic devices, are beneficial for the treatment of post stroke patients. Virtual Therapy and robotics are relatively new approaches to rehabilitation, developed to provide a higher level of task simulation than conventional physiotherapy.

Previous studies have shown that virtual reality training in the form of RFVE can be used as a technique for movement re-learning[45]. It has been shown that treatment within a virtual environment can be beneficial for both the subacute and chronic phase following a stroke [60]. It seems that the capacity of the recovery process after acute stroke is effectively enhanced by the use of RFVE training[55, 61].

Authors in some research projects have combined non-immersive virtual reality with robotic devices which assist with the required movement.

Some studies indicate that neural processes are not the same if the activities are performed within the real world or within a virtual environment[62]. In a study Saposnik et al.[63] suggested that virtual reality is a safe and potentially effective alternative treatment for the treatment of hemiparesis following a stroke.

As mentioned above, virtual reality encompasses a range of innovative technology, which artificially generates sensory information in a form that people perceive as similar to the real ones. The basis for most virtual therapy systems is a three-dimensional visual simulated environment presented on a monitor or wall projection. To experience realistic exploration and interaction computers must upload new images rapidly enough to give the impression of real time reaction. It is important that simulated objects and events can be felt not only in a visual sense, but they can interact with the user, as if they were real. The psychological impact of exploration and interaction with a virtual environment means that you have some sense of 'presence' in a simulated world. This feeling of presence is probably the result of the experience of virtual reality.

Perhaps the sense of presence is caused by actions that occur in the simulated world perceived as real feeling. It is not assumed that the ability acquired in virtual reality will replace real actions but would provide better information to perform real tasks. In relation to stroke patients virtual training should ideally stimulate motor re-learning and motor skills necessary to perform activities of daily living.

Virtual reality technology is also used for the rehabilitation of the patient at home using the internet, called tele-rehabilitation. The patient receives information on how to perform the exercises from a physiotherapist located in the hospital, and on the computer in the patient's home shows the required task. Continuous contact with the patient is ensured through a webcam and voice messaging. Tele-rehabilitation may be the solution to provide continuous rehabilitation and reduce the cost of hospitalization of stroke patients, at the same level as hospital based virtual reality[64,65]. Piron et al.[45,64] studied the use of virtual therapy both in clinical settings and in the patient's home. In these studies, both patient groups achieved better results if they performed virtual therapy when compared to conventional treatment[45,64]. Currently, integrating virtual reality technology into rehabilitation at home is under development.

The main benefit of using virtual therapy in stroke rehabilitation is to engage people in a simulated event and eliminates the limitations associated with disability, in addition to being able to safely perform the task.

Piśmiennictwo / References

1. Hummel F.C. Stymulacja mózgu w neurorehabilitacji. [In:] Hamzei F. (ed.). Neurorehabilitacja oparta na dowodach naukowych. MedPharm Polska. Wroclaw 2010. pp. 118-40 [Polish].
2. Ertelt D., Buccino G., Binkofski F. Od neuronów lustrzanych do neurorehabilitacji. [In:] Hamzei F. (ed.). Neurorehabilitacja oparta na dowodach naukowych, MedPharm Polska: Wrocław 2010; pp. 98-117 [Polish].
3. Dobkin B. Neurologic Rehabilitation. Contemporary Neurology Series. Dobkin B. (ed.), FA Davis Publishers. Philadelphia 1996.
4. Vearrier L.A., Langan J., Shumway-Cook A., Woollacott M. An intensive massed practice approach to retraining balance post-stroke. Gait Posture, 2005; 22(2): 154-63.

5. Platz T., Winter T., Muller N., Pinkowski C., Eickhof C., Mauritz K.H. Arm ability training for stroke and traumatic brain injury patients with mild arm paresis: a single-blind, randomized, controlled trial. Arch Phys Med Rehabil 2001; 82(7): 961-8.
6. Platz T., Prass K., Denzler P., Bock S., Mauritz K.H. Testing a motor performance series and a kinematic motion analysis as measures of performance in high-functioning stroke patients: reliability, validity, and responsiveness to therapeutic intervention. Arch Phys Med Rehabil, 1999; 80(3): 270-7.
7. Mussa-Ivaldi F.A. Modular features of motor control and learning. Curr Opin Neurobiol 1999; 9(6): 713-7.
8. Cauraugh J., Light K., Kim S., Thigpen M., Behrman A. Chronic motor dysfunction after stroke: recovering wrist and finger extension by electromyography-triggered neuromuscular stimulation. Stroke 2000; 31(6): 1360-4.
9. Bolton D.A., Cauraugh J.H., Hausenblas H.A. Electromyogram-triggered neuromuscular stimulation and stroke motor recovery of arm/hand functions: a meta-analysis. J Neurol Sci 2004; 223(2): 121-7.
10. Straudi S., Benedetti M.G., Bonato P. Neuroplasticità e motor learning: nuove strategie nella riabilitazione dell'arto superiore nel paziente con ictus cerebrale. Scienza Riabilitativa 2011; 13 (1): 5-11.
11. Opara J. Aktualne metody usprawniania ruchowego chorych po udarze mózgu. Udar Mózgu Via Medica 2003; 4(1): 33-8 [Polish].
12. Taub E., Crago J.E., Burgio L.D., Groomes T.E., Cook E.W., 3rd, DeLuca S.C., et al. An operant approach to rehabilitation medicine: overcoming learned nonuse by shaping. J Exp Anal Behav 1994; 61(2): 281-93.
13. Liepert J., Graef S., Uhde I., Leidner O., Weiller C. Training-induced changes of motor cortex representations in stroke patients. Acta Neurol Scand 2000; 101(5): 321-6.
14. Liepert J., Bauder H., Wolfgang H.R., Miltner W.H., Taub E., Weiller C. Treatment-induced cortical reorganization after stroke in humans. Stroke 2000; 31(6): 1210-6.
15. Reiss A.P., Wolf S.L., Hammel E.A., McLeod E.L., Williams E.A. Constraint-Induced Movement Therapy (CIMT): Current Perspectives and Future Directions. Stroke Res Treat 2012; 2012: 159391.
16. Liepert J., Miltner W.H., Bauder H., Sommer M., Dettmers C., Taub E., et al. Motor cortex plasticity during constraint-induced movement therapy in stroke patients. Neurosci Lett 1998; 250(1): 5-8.
17. Mark V.W., Taub E. Constraint-induced movement therapy for chronic stroke hemiparesis and other disabilities. Restor Neurol Neurosci 2004; 22(3-5): 317-36.
18. Ramachandran V.S. Plasticity and functional recovery in neurology. Clin Med 2005; 5(4): 368-73.
19. Michielsen M.E., Smits M., Ribbers G.M., Stam H.J., van der Geest J.N., Bussmann J.B., et al. The neuronal correlates of mirror therapy: an fMRI study on mirror induced visual illusions in patients with stroke. J Neurol Neurosurg Psychiatry 2011; 82(4): 393-8.
20. Aisen M.L., Krebs H.I., Hogan N., McDowell F., Volpe B.T. The effect of robot-assisted therapy and rehabilitative training on motor recovery following stroke. Arch Neurol 1997; 54(4): 443-6.
21. Prange G.B., Jannink M.J., Groothuis-Oudshoorn C.G., Hermens H.J., Ijzerman M.J. Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. J Rehabil Res Dev 2006; 43(2): 171-84.
22. Krebs H.I., Ferraro M., Buerger S.P., Newbery M.J., Makiyama A., Sandmann M., et al. Rehabilitation robotics: pilot trial of a spatial extension for MIT-Manus. J Neuroeng Rehabil 2004; 1(1): 5.
23. Boian R., Sharma A., Han C., Merians A., Burdea G., Adamovich S., et al. Virtual reality-based post-stroke hand rehabilitation. Stud Health Technol Inform, 2002. 85: 64-70.
24. Kahn L.E., Lum P.S., Rymer W.Z., Reinkensmeyer D.J. Robot-assisted movement training for the stroke-impaired arm: Does it matter what the robot does? J Rehabil Res Dev 2006; 43(5): 619-30.
25. Burgar C.G., Lum P.S., Scremin A.M., Garber S.L., Van der Loos H.F., Kenney D., et al. Robot-assisted upper-limb therapy in acute rehabilitation setting following stroke: Department of Veterans Affairs multisite clinical trial. J Rehabil Res Dev 2011; 48(4): 445-58.
26. Staubli P., Nef T., Klamroth-Marganska V., Riener R. Effects of intensive arm training with the rehabilitation robot ARMin II in chronic stroke patients: four single-cases. J Neuroeng Rehabil 2009; 6: 46.
27. Silvoni S., Ramos-Murguialday A., Cavinato M., Volpato C., Cisotto G., Turolla A., et al. Brain-computer interface in stroke: a review of progress. Clin EEG Neurosci 2011; 42(4): 245-52.
28. Turolla A., Daud Albasini O.A., Oboe R., Agostini M., Tonin P., Paolucci S., et al. Haptic-Based Neurorehabilitation in Poststroke Patients: A Feasibility Prospective Multicentre Trial for Robotics Hand Rehabilitation. Computational and Mathematical Methods in Medicine 2013: p. 12.
29. McCombe Waller S., Whitall J. Bilateral arm training: why and who benefits? NeuroRehabilitation 2008; 23(1): 29-41.
30. Wu C.Y., Chuang L.L., Lin K.C., Chen H.C., Tsay P.K. Randomized trial of distributed constraint-induced therapy versus bilateral arm training for the rehabilitation of upper-limb motor control and function after stroke. Neurorehabil Neural Repair 2011; 25(2): 130-9.
31. Hesse S., Schmidt H., Werner C., Bardeleben A. Upper and lower extremity robotic devices for rehabilitation and for studying motor control. Curr Opin Neurol 2003; 16(6): 705-10.
32. Whitall J., Waller S.M., Sorkin J.D., Forrester L.W., Macko R.F., Hanley D.F., et al. Bilateral and unilateral arm training improve motor function through differing neuroplastic mechanisms: a single-blinded randomized controlled trial. Neurorehabil Neural Repair; 2011; 25(2): 118-29.
33. Krishnan C., Ranganathan R., Dhaher Y.Y., Rymer W.Z. A pilot study on the feasibility of robot-aided leg motor training to facilitate active participation. PLoS One, 2013. 8(10): e77370.
34. Iosa M., Morone G., Bragoni M., De Angelis D., Venturiero V., Coiro P., et al. Driving electromechanically assisted Gait Trainer for people with stroke. J Rehabil Res Dev, 2011. 48(2): 135-46.
35. Todorov E., Shadmehr R., Bizzi E., Augmented Feedback Presented in a Virtual Environment Accelerates Learning of a Difficult Motor Task. J Mot Behav.1997. 29(2): 147-58.
36. Shea C.H., Kohl R.M., Composition of practice: influence on the retention of motor skills. Res Q Exerc Sport, 1991. 62(2): 187-95.
37. Hauptmann B. Podstawy uczenia się proceduralnego i motorycznego w praktyce postępowania terapeutycznego. [In:] Hamzei F. (ed.). Neurorehabilitacja oparta na dowodach naukowych. MedPharm Polska: Wrocław 2010. pp. 69-89 [Polish].
38. Krakauer J.W. Motor learning: its relevance to stroke recovery and neurorehabilitation. Curr Opin Neurol 2006; 19(1): 84-90.
39. Moryś J. Podstawy anatomiczne procesów zapamiętywania i emocji. [In:] Jodzio K. (ed.). Neuronalny świat umysłu. Oficyna Wydawnicza "Impuls": Kraków 2005 [Polish].
40. Hanlon R.E. Motor learning following unilateral stroke. Arch Phys Med Rehabil 1996; 77(8): 811-5.
41. Winstein C.J., Merians A.S., Sullivan K.J. Motor learning after unilateral brain damage. Neuropsychologia 1999; 37(8): 975-87.
42. Kiper P., Turolla A., Piron L., Agostini M., Baba A., Rossi S., et al. Virtual Reality for Stroke Rehabilitation: assessment, training and the effect of virtual therapy. Med Rehabil 2010; 14(2): 15-23.
43. Burdea G.C., Coiffet P. Virtual Reality Technology 2th., Hoboken, New Jersey: John Wiley & Sons, Inc. 2003.
44. Stanney K.M. Handbook of virtual environments: design, implementation and applications. London: Lawrence Erlbaum. 2002.
45. Piron L., Turolla A., Agostini M., Zucconi C.S., Ventura L., Tonin P., et al. Motor learning principles for rehabilitation: a pilot randomized controlled study in poststroke patients. Neurorehabil Neural Repair 2010; 24(6): 501-8.
46. Mehrholz J., Hadrich A., Platz T., Kugler J., Pohl M. Electromechanical and robot-assisted arm training for improving generic activities of daily living, arm function, and arm muscle strength after stroke. Cochrane Database Syst Rev 2012; 6: CD006876.
47. Christiansen C., Abreu B., Ottenbacher K., Huffman K., Masel B., Culpepper R. Task performance in virtual environments used for cognitive rehabilitation after traumatic brain injury. Arch Phys Med Rehabil 1998; 79(8): 888-92.
48. Deutsch J.E., Myslinski M.J., Kafri M., Ranky R., Sivak M., Mavroidis C., et al. Feasibility of virtual reality augmented cycling for health promotion of people poststroke. J Neurol Phys Ther 2013; 37(3): 118-24.
49. Laver K.E., George S., Thomas S., Deutsch J.E., Crotty M. Virtual reality for stroke rehabilitation. Cochrane Database Syst Rev 2011; (9): CD008349.
50. Sisto S.A., Forrest G.F., Glendinning D. Virtual reality applications for motor rehabilitation after stroke. Top Stroke Rehabil 2002; 8(4): 11-23.
51. Holden M.K. Virtual environments for motor rehabilitation: review. Cyberpsychol Behav 2005; 8(3): 187-211; discussion 212-9.
52. Broeren J., Bjorkdahl A., Claesson L., Goude D., Lundgren-Nilsson A., Samuelsson H., et al. Virtual rehabilitation after stroke. Stud Health Technol Inform 2008; 136: 77-82.
53. Turolla A., Dam M., Ventura L., Tonin P., Agostini M., Zucconi C., et al. Virtual reality for the rehabilitation of the upper limb motor function after stroke: a prospective controlled trial. J Neuroeng Rehabil 2013; 10: 85.
54. Adamovich S.V., Merians A.S., Boian R., Tremaine M., Burdea G.S., Recce M., et al. A virtual reality based exercise system for hand rehabilitation post-stroke: transfer to function. Conf Proc IEEE Eng Med Biol Soc 2004; 7: 4936-9.
55. Kiper P., Piron L., Turolla A., Stozek J., Tonin P. The effectiveness of reinforced feedback in virtual environment in the first 12 months after stroke. Neurol Neurochir Pol 2011; 45(5): 436-44.
56. Merians A.S., Jack D., Boian R., Tremaine M., Burdea G.C., Adamovich S.V., et al. Virtual reality-augmented rehabilitation for patients following stroke. Phys Ther 2002; 82(9): 898-915.
57. Kiper P., Agostini M., Luque-Moreno C., Tonin P., Turolla A. Reinforced Feedback in Virtual Environment for Rehabilitation of Upper Extremity Dysfunction after Stroke: Preliminary Data from a Randomized Controlled Trial. Biomed Research International 2014; 2014(Article ID 752128): 8.
58. Keshner E.A. Virtual reality and physical rehabilitation: a new toy or a new research and rehabilitation tool? J Neuroeng Rehabil 2004; 1(1): 8.
59. Sveistrup H. Motor rehabilitation using virtual reality. J Neuroeng Rehabil 2004; 1(1): 10.
60. Saleh S., Bagce H., Qiu Q., Fluet G., Merians A., Adamovich S., et al. Mechanisms of neural reorganization in chronic stroke subjects after virtual reality training. Conf Proc IEEE Eng Med Biol Soc 2011; 2011: 8118-21.
61. Piron L., Turolla A., Agostini M., Zucconi C., Tonin P., Piccione F., et al. Assessment and treatment of the upper limb by means of virtual reality in post-stroke patients. Stud Health Technol Inform 2009; 145: 55-62.
62. Nudo R.J. Neural bases of recovery after brain injury. Journal of Communication Disorders 2011; 44(5): 515-20.

63. Saposnik G., Teasell R., Mamdani M., Hall J., McIlroy W., Cheung D., et al. Effectiveness of virtual reality using Wii gaming technology in stroke rehabilitation: a pilot randomized clinical trial and proof of principle. Stroke 2010; 41(7): 1477-84.
64. Piron L., Turolla A., Agostini M., Zucconi C., Cortese F., Zampolini M., et al. Exercises for paretic upper limb after stroke: a combined virtual-reality and telemedicine approach. J Rehabil Med 2009; 41(12): 1016-102.
65. Perry J.C., Ruiz-Ruano J.A., Keller T. Telerehabilitation: toward a cost-efficient platform for post-stroke neurorehabilitation. IEEE Int Conf Rehabil Robot 2011; 2011: 5975413.

Address for correspondence

Paweł Kiper, PhD PT
Fondazione Ospedale San Camillo IRCCS
Dipartimento di Neuroriabilitazione
Laboratorio di Cinematica e Robotica
via Alberoni 70
30126 Venezia, Italy
tel.: +39 0412207214
e-mail: pawel.kiper@ospedalesancamillo.net