Virtual Reality for Stroke Rehabilitation: assessment, training and the effect of virtual therapy

Rzeczywistość wirtualna w rehabilitacji poudarowej – badania, trening i efekty terapii wirtualnej

Paweł Kiper [A,B,D,E,F], Andrea Turolla [A,B,D,E,F], Lamberto Piron [A,D,F], Michela Agostini [B,F], Alfonc Baba [B,E,F], Simonetta Rossi [B,E,F], Paolo Tonin [D,F]

Department of Neurorehabilitation I.R.C.C.S San Camillo Hospital; Alberoni 70, 30126 Venice, Italy

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Abstract
The motor function impairment deriving from stroke injury has a negative impact on autonomy and on the activities of daily living. Several studies have demonstrated that learning new motor skills is important to induce neuroplasticity and functional recovery. To facilitate the activation of brain areas and consequently neuroplasticity, it may be advantageous to combine traditional motor rehabilitation with innovative technology, in order to promote motor re-learning and skill re-acquisition by means of an enhanced training. Following these principles, exercises should involve multiple sensory modalities exploiting the adaptive nature of the nervous system, in order to promote active patient participation. Movement re-learning could be improved by means of training in an enriched environment focused on optimizing the affordances between the motor system and the physical environment: virtual reality technologies allow for the possibility to create specific settings where the affordances are optimized. Several autors report that patients treated in virtual representation could, in both acute and chronic stroke, improve their arm motor function. Reinforced Feedback in a Virtual Environment (RFVE), can incorporate the elements necessary to maximize motor learning, such as repetitive and differentiated task practice, feedback of performance and results, and reinforcement of the motivation. The RFVE approach may lead to better rehabilitation outcomes in the treatment of the upper limb in stroke patients.

Słowa kluczowe
udar mózgu, rehabilitacja, rzeczywistość wirtualna, kontrola ruchu

Streszczenie
Upośledzenie funkcji ruchowych związanych z udarem mózgu ma w przypadku wielu chorych negatywny wpływ na samodzielność i na czynności życia codziennego i osoby te muszą być poddawane długotrwałej rehabilitacji. Liczne badania wykazały, że uczenie się nowych umiejętności motorycznych pobudza neuroplastyczność mózgu i w efekcie umożliwia poprawę funkcjonalną. W celu ułatwienia aktywacji obszarów mózgu, a w konsekwencji neuroplastyczności, korzystne może być łączenie tradycyjnej rehabilitacji ruchowej z innowacyjną technologią tak, aby poprzez wzmocniony trening promować ponowne uczenie się ruchu i ponowne nabywania umiejętności funkcjonalnych. W myśl tej zasady, wykorzystując adaptacyjne zdolności układu nerwowego, ćwiczenia powinny angażować wiele zmysłów i wymuszać aktywny udziału pacjenta. Trening ponownego uczenia się ruchu może być skuteczniejszy we wzbogaconym przez sprzężenie zwrotne środowisku koncentrując się na optymalizacji intrakcji osoby z komputerem między układem ruchu a fizycznym środowiskiem: technologia rzeczywistości wirtualnej dopuszcza możliwość utworzenia specjalnych ustawień, gdzie interakcja człowieka z komputerem jest zoptymalizowana. Wzmocnione sprzężenie zwrotne w środowisku wirtualnym (RFVE) może zawierać elementy potrzebne do maksymalizacji efektu uczenia się ruchu, np. praktyka powtarzających się i zróżnicowanych zadań, zastosowanie sprzężenia zwrotnego w odniesieniu do działania i efektu działania, oraz zwiększona motywacja. Zastosowanie RFVE może prowadzić do lepszych wyników w usprawnianiu niedowładnej kończyny górnej u pacjentów z udarem mózgu.

INTRODUCTION

Astroke is one of the main causes of death and disability in adults, in different populations, and in different ethnic origins worldwide. There are about 730 000 new or recurrent strokes each year in the USA, with a peak in people older than 75 years[1]. In the first 2 weeks after a stroke, hemiplegia is present in 70-85% of patients while a percentage of between 40 to 75% is

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completely dependent in their activities of daily living.[2] Their functional recovery is greatest during the first 3 months.[3] Disability affects mainly the upper limb, sometimes permanently. Neuro-rehabilitation treatment is often not efficient enough , due to its insufficient frequency and duration, both in the acute and stabilized phases following the cerebral lesion. To maximize the recovery, intensive rehabilitation should be a major priority. The main costs of stroke survivors are related to their motor impairments that interfere with personal, social and/or vocational activities. There are a few therapeutic approaches to restore the lost functions. The available rehabilitative therapies are currently working to develop treatments that are closely related to motor learning principles. Rehabilitation, for patients, is fundamentally a process of re-learning how to move in order to carry out their needs successfully.[4]

A cortical reorganization of motor systems has been found in recovered stroke patients. Passive movements in hemiplegic stroke patients before clinical recovery elicit some of the brain activation patterns that have been described during active movements after substantial motor recovery. Changes of cerebral activation in the sensory and motor systems occur early after a stroke and may be a first step toward the restoration of motor function after a stroke. Thefunctional re-organization of the motor system after a focal stroke in adult primates depends on substantial contributions from the undamaged motor cortex, as well as on early and intensive motor training, consistent with the subject's potentialities.[5] Recently research in motor control and learning provide emerging neurophysiological evidences that could be translated into rehabilitation practice.

Research studies have demonstrated that repeated and intensive massed practice may be necessary to modify the neuronal structure. Innovative technologies, such as robotics and Virtual Reality (VR), are being tested for their applicability in neurorehabilitation and their use in the treatment of the paretic upper limb.

VR defines a simulation of the real environment that is generated by dedicated computer software. When exercising in a VR environment, subjects can monitor their movements and try to emulate the optimal motion patterns that are shown in real time in the virtual scenario.[1] The approach altogether favours "learning by imitation", and the complexity of the requested motor tasks can be progressively increased to facilitate transfer to the real world of those motor patterns learned in the virtual one.[6]

RATIONALE

Motor control and learning

Considering that patient rehabilitation could be considered as a process of motor re-learning to undertake their own needs successfully, it is necessary to dwell on how the Central Nervous System (CNS) determines the movements to achieve specific objectives in the environment that surrounds us.[7] The mechanisms of action of physical assistance in promoting motor learning or relearning are poorly understood.

The computational approaches to the motor system deal with the interaction between the sensory input signals from the body and the motor output commands. The physics of the environment, the musculoskeletal system and sensory receptors are the fundamental elements of the computational analysis directed to describe which rules describe their relationship.[8] One of the main goals of computational neuroscience is to theorize, through experimental evidence, which internal processes within the CNS allow the continuous transformation of this information, during motor behaviour.

The capability to create complex actions cannot be controlled through a simple process of feedback sensory storage and subsequent information retrieving when needed.[9] The biological feedback control is too slow to provide the flow information necessary to sustain the rapid and coordinated actions.[10] This process of the body dynamics and its environmental movement is possible through the construction of internal models.[8]

The internal models can be divided into the following groups: the Forward Internal Model for the internal representation of sensory information coming from motor activity (regarding the prediction of the behavior of the body in the environment), and the Inverse Internal Model for the internal representation of the action related to the modification of the desired background (regarding the transformation of programmed motor behavior to motor command to achieve the desired trajectory).[8,10] The learning process in the finalized motor behavior requires both of the internal models (forward and inverse) to adapt to different tasks and environments.[11] The adaptation to external perturbations during reaching movements with the upper limb relies on the possiblity to create forward internal models that compensate for the perturbing force. [9] This new model, if stored, can be intended as new learning. [12,13,14]

In our context the internal model refers to neural mechanisms, which mimic the characteristics of the afferent and efferent motor system.[10] The concept of the internal model applied to rehabilitation is that it can be updated as the state ("state" - any representation that reduces the number of dimensions) of the limb changes. Namely, the rehabilitation based on a repetition of movements needs to emphasize techniques that promote the formation of appropriate internal models.[4]

Creating a composition of models, CNS describes the movement dividing the information on the sensory data in kinematic and dynamic type. The internal model generalizes the parameters of dynamic motor learning depending on the coordinates of the kinematic type.[15]

Motor control scientists make an important distinction between the geometry and speed of a movement (kinematics) and the forces needed to generate the movement (dynamics).

In the execution phase, motor commands take the complex viscoelastic and inertial properties of multijoined limbs into account, so that the appropriate force is applied to generate the desired movement. The presence of after-effects is strong evidence that the CNS can adapt motor commands of the arm to predict the effects of a perturbing force-field creating a new map of the limb state and muscle forces.[4]

Recently, a few studies have addressed the way assistive forces affect motor performance and/or motor learning[16]. When moving under the effect of assistive forces (for example those provided by a robot) humans tend to quickly incorporate these forces into their motor plan. Assistive forces help subjects to complete the motor task, which in turn may increase subject motivation, even in the early phase of the learning (recovery) process. In addition, assistive forces may affect learning by inducing a sensation of greater stability within the external environment.[17] The learning process may be facilitated if augmented feedback is provided on selected aspects of performance and/ or the outcome of the movement.[18]

However, learning capacity is the ability to predict or generalize the knowledge of a new situation. Theoretically the generalization of capacity learning depends on structural changes in brain tissue, by the rules of synaptic plasticity, or is an emergent property depending on system structure[19]. Poggio and Bizzi suggest that the movement depends more on the CNS architecture and on internal organization, than on the anatomical conformation.[19] Thus, it is necessary to attempt to comprehend the structure of this organization to explain the learning of the motor system.

Some authors have hypotesized that the internal models at the central level can operate like primitives modules at the spinal cord level.[11] The modularity of primitives modules, allowed the CNS to create complex motor behavior by a linear combination of this low dimensional unit.[9]

Brooke et al. indicate that subjects in a predictable environment submitted to motor learning training prefer to be based on forward control, even if a reliance on the somatosensory feedback is suggested.[20] The sensorial afferents and feedback systems continuously correct the effectiveness of the final movement.[20] In stroke survivors, motor impairment is frequently associated with degraded proprioceptive and/or somatosensory functions.[21]

Computational approaches to the motor system

Movement re-learning implies a process of selection of motor actions to perform the requested task. Theoretically, the best movement should be repeated exactly to obtain the relearning. In fact, the subject performs and saves a set of movements more or less similar to the ideal movement, improving their performance based on exercised motor experience.

Doya suggests that different brain areas (cerebellum, basal ganglia, cortex) are involved in the motor learning process by means of their cellular architecture that could hold three different computational learning paradigms: supervised learning, reinforcement learning and unsupervised learning.[22]

In supervised learning the subject receives from the teacher a prompt to adjust the movement. The target may be static (achieve the target) and dynamic (throughout external teacher). The cerebellum is supposed to be involved in the real-time fine-tuning of movements by means of its feedforward structure based on massive synaptic convergence of granule cell axons (parallel fibers) onto Purkinje cells, which send inhibitory connections to deep cerebellar nuclei and to inferior olive. The circuit of the cerebellum is capable of implementing the supervised learning paradigm, which consists of error driven learning behaviors.[22]

In reinforced learning the subject directly estimates information from the performed movement. Reinforced learning is based on the multiple inhibitory pathways of the basal ganglia that permit the reward predicting activity of dopamine neurons and change of behavior in the course of goal directed task learning.[22] This learning through a trial and error paradigm based on knowledge of the results (KR - feedback related to the nature of results produced in terms of the movement goal) and knowledge of the performance (KP - feedback related to the nature of the movement pattern that was produced) is provided.[23,24] In unsupervised learning the environment provides motor system input, but gives neither the desired targets nor any measure of reward or punishment.[22,25]

The authors suggested that after a stroke, if no therapy is given, plasticity due to unsupervised learning may become maladaptive, thereby augmenting the stroke's negative effect[26]. In our experience, motor function improvements may therefore have been enhanced by the synergistic activity of supervised and reinforcement learning. In the absence of supervised and reinforcement learning, the subsequent motor performance worsens with every number of rehabilitation trials. On the contrary, if unsupervised learning is not present, motor performance improves with every number of rehabilitation trials in the late period.

The computational principles of movement neuroscience

The cycle of sensorimotor control begins with the motor command generation (task-state-context → motor command), transforms subsequently into its original state (state-motor command-context → sensory feedback), and finally generalizes the sensory feedback (previous state-motor command-context → state).[8] The complexity of sensorimotor control from the computational viewpoint can be divided into these three stages. The first stage specifies which motor command must be generated by the CNS, giving a particular state and a particular task to be performed by the motor system (Inverse Model). The second determines how the state changes depending on the specified motor command (Forward Sensory Model). The third stage closes the complex sensorimotor control, specifying the sensory feedback that comes from achieving the new state (Forward Dynamic Model).[8]

The complexity of sensorimotor control, as well as the wide range of recovery, makes both the measurement and rehabilitation most challenging.[27,28,29]

Neuro-rehabilitation based on motor learning

Several studies report that in the early phase of recovery, motor control should be favored in order to reduce the formation of wrong synergies. Other studies argue that early stimulation of these movement attempts (i.e. flexion synergy or extension synergy) helps to develop normal movements.[30]

Difficulties in interpreting exhaustively the pathological phenomenon have led to the development of various methods based on a different proposal for the patient, for the motor recovery following neurological injury of the CNS.

The rehabilitation techniques based on motor learning principles include:

- Arm Ability Training – Platz et al show in a randomized clinical trial the benefit of arm ability training compared with classical rehabilitation as assessed by a measure of the efficiency of arm function in ADL[31];
- Constraint-Induced Movement Therapy (CIMT) – several studies have shown a significant improvement and meaningful gains even in patients following a chronic stroke[32,33];
- Electromyogram-triggered Neuromuscular Stimulation – indicates that non-damaged motor areas can be recruited and trained, including the two motor learning principles: repetition and sensorimotor integration[34];
- Robot-aided Therapy – is congruent with the sensorimotor integration theory combined with multisensory feedback (visual, tactile, auditory)[35,36];
- Virtual Reality for Motor Rehabilitation - refers to a range of computing technologies with artificially enhanced feedback generated sensory information in a form which subjects perceive as similar to real-world objects and events.[37-43]

The motor learning that these techniques are aimed to promote is characterized by general principles. The most fundamental principle in motor learning is that the degree of performance improvement is dependent on the amount of practice.[44] The acquisition of new motor skills is possible only through feedback from the environment and depends on the quantity of practice.[18]

The first finding is that the learning is more effective if frequent exercises have rest periods between repetitions (distributed practice) than if blocked repetition is performed (massed practice).[45]

The second finding is that introducing task variability (variable practice) improves the task retention in relation to the same repetition tasks exercised (constant practice).[4]

Another finding is 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.[46]

The aim is how these practices interact on the motor recovery of the patients after stroke lesions. For example, the study of comparison of random and massive practice has demonstrated that patients who learned with random practice displayed a superior retention of the trained functional movement sequence.[47]

Winstein et al. Have observed no systematic differences in the data between groups (stroke vs control) in performance patterns across trials for acquisition, retention or reacquisition phase. Thus, the stroke group (independent of the feedback condition) made more errors while performing tasks than the control group during the whole acquisition, retention and reacquisition phase[48].

Several different sensorimotor exercise strategies may be added to the rehabilitation of the post-stroke hemiparesis patients. Moreover, some forms of augmented feedback have been shown to enhance the learning of simple movements.

Carey et al have reported significantly greater activation of the primary motor cortex area (M1) during precision-demanding tracking movements than during simple repetitive movements.[49] The effect is most probably due to the increased use of the affected hand during the training. On the other hand the results of Jang et al suggest that a cortical reorganization in patients with an M1 infarct occurred, executing simple hand grasp-release movements.[50]

Some studies on primates have reported cortical reorganization arising from exposure to rehabilitation training after the M1 damage. These cortical changes occur only with the learning of the new motor skills and not through movement repetition.[51]

However, the capacity for motor recovery after a stroke is strongly influenced by the integrity of the fast direct motor output pathway from M1 to spinal cord neurons.[52] It is noted that the plasticity of the CNS, and therefore its adaptability to natural developmental changes, is maintained throughout the whole of a subject's life regardless of age.[52,53,54] Several experiments have shown, both animal and human studies, that the cortex has the capacity to change structure in response to environmental change.[54] The important values in relearning motor skills and consequently neural reorganization are the quantity, duration and intensity of the training program.[38]

Nuclear Magnetic Resonance (NMR) imaging and transcranial magnetic stimulation tests in humans provide evidence for the functional adaptation of the motor cortex following injury.[50,52,56,57] Neuroimaging has shown evidence of cortical plasticity after task-oriented motor exercises.[50] Furthermore, many studies have demonstrated that neuroplasticity can occur even in the case of a chronic stroke.[56,57] Such findings indicate the potential for functional plasticity in the adult subjects' cerebral cortex and suggest that the rehabilitation program may influence that process.

Stroke rehabilitation for the hemiparetic upper limb

The traditional method of rehabilitation (passive, active-assisted, active exercises) after a stroke is certainly the most widespread and the most usual for the upper extremity. Nevertheless the influence of multiple variables in the process of the recovery and the variability between subjects requires one to personalize the treatments in order to achieve the best functional goals in every patients.[58] The therapeutic exercise should respect the physiological mechanisms that determine the proximal and distal upper limb function.[58] In addition to the joint mobilization (passive, active-assisted or active) of all districts (shoulder, elbow, wrist and fingers), and muscle strengthening exercises, different exercises are usually performed.

All the exercises described below are in daily use for rehabilitation in post-stroke patients and these include:

- Coordination cephalic-eyes exercises: Related to the two visual fields, which change the subject's glance depending on the distance and location of the object.
- Achieve and indicative exercise: This requires the patient to bring his hand to the object without touching it.
- Exercises for hand pre-configuration: The patient should bring the hand on the object, but not grasp it.
- Exercises to "reach, touch and manipulate": Should be performed by placing objects at different points. In some cases the „compensatory movements" to compensate the motor deficit of the shoulder or elbow must be corrected by the physiotherapist.
- Proximal-distal exercises coordination: The patient, from a static position with the hand placed on his thigh, should try to grasp objects placed by the physiotherapist in different points in space.
- Manipulative and functional skills exercises: The patient is asked to manipulate an object, to recognize the function and then try to make a functional use.
- Adjustment exercise for the hand to the object without visual feedback: The patient re-learns through the use of the healthy hand to prepare the paretic hand to finalize the grasp of an object, with closed eyes.

In addition, several techniques to improve the motor function are also used in stroke rehabilitation. A developed treatment for producing large scale changes in the daily rehabilitation practice in the real world can be constraint-induced movement therapy (CIMT). The focus of CIMT lies on forcing the patient to use the affected limb by restraining the unaffected one. The affected limb is then used intensively for six hours a day for at least two weeks.[59,60] As a result of the patient engaging in repetitive exercises with the affected limb in a positive cortical reorganization of the motor cortex[61].

In cases of non-spontaneous recovery electrical muscle stimulation can be used. When the muscle activity is low (not enough to perform a movement) it is recommend to combine techniques of biofeedback and electrostimulation. The patient is asked to initiate the movement, which is complemented by electrical stimulation of the muscles. This is important and has a very positive effect, because not only does it induce a neuromuscular facilitation through an afferent-efferent circuit, but is also beneficial from a psychological standpoint, because the patient sees the fulfillment of his intentional movement.

Some studies reported that repetitive practice had a greater improvement in motor performance than Bobath-based training, transcutaneous electric nerve stimulation and suprathreshold electric stimulation of hand and wrist muscles.[62]

Based on this assertion in injured arm training some innovative techniques could be used which allow for performance, like robot-aided therapy or repetitive exercise in a virtual environment.

VIRTUAL REALITY AS AN INNOVATIVE TECHNIQUE FOR STROKE REHABILITATION

Virtual reality

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.[1,24,37]

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.[63]

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).[63]

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.[63,65] Several systems have shown the advantage of hand and arm motor skills training for stroke patients, and also showed benefits in cognitive enhancements.[35,39,43,64,66]

There are several ways to realize the visual interaction, with varying degrees of immersion. What determines the sense of presence is the level of immersion provided, which in turn depends on the system used. The literature indicates various systems of virtual environments like: Head Mounted Display, Fish Tank or systems based on projections.[67] 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).[68]

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 this virtual world, the patient learns to manage problematic situations related to his disorder.[69] 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 Rehabilitation System

The virtual environment is a simulation of the real world through PC software. The subjects perform in the physical environment different kinds of motor tasks using a rehabilitation system called "Virtual Reality Rehabilitation System" (VRRS) developed at the Massachusetts Institute of Technology, Cambridge USA. The movement of the entire biomechanical arm system end-effector is simultaneously represented in a virtual scenario by means of motion-tracking equipment.

The patients undergo virtual training by means of a PC workstation connected to a 3D motion-tracking system (Pohlemus 3Space FasTrack, Vermont, U.S.A. – position signal 0.76 mm RMS; orientation signal 0:15° RMS; range resolution of 0.0005cm/cm and 0025°/°; latency of 4 msec unfiltered; sampling frequency of 120Hz) and a high-resolution LCD projector which displayed the virtual scenarios on a wall screen.

Virtual training procedure

In our laboratory, we experimented with a VR based setting for the assessment and treatment of the upper limb motor impairments in patients after a stroke.

During the virtual therapy the subject was seated in front of the wall screen grasping a sensorized real object (ball, disc or cube) with the injured hand. If the grasp was not possible the sensor was fixed on a glove worn by the patient. The virtual environment target objects were displayed on the wall screen. The real object held by the subject, equipped with electromagnetic sensors, was matched to the virtual handling object. The sensor contained in the real object recorded the arm's end effector movements by the means of a magnetic receiver. The virtual scenarios were created by the physiotherapist recording the movements carried out grasping the same sensorized object (for example an envelope, a glass, etc.) used by the patients. Afterwards, the system software displayed a virtual representation (virtual object) of the real object that changed position and orientation on the screen in coherently with the movement of the sensor. Hence, the physiotherapist created a sequence of virtual tasks that the patient had to perform on his workstation. Virtual tasks consisted mainly of simple movements, e.g. pouring water from a glass, using a hammer, turning around the centre of a doughnut, etc.

The physiotherapist determined the complexity of the task, tailored on the patient's motor deficit. In the virtual scenario, the physiotherapist determined the starting position and the characteristics of the target, such as its orientation, for each task or the addition of other virtual objects to increase the task's complexity. In addition, in the first days of virtual training, the physiotherapist could also show the correct trajectory prerecorded in a virtual scene (virtual teacher). Thereafter, the patient moved the real object (envelope, carafe, hammer) following the trajectory of the corresponding virtual object displayed on the computer screen in accordance with the requested virtual task. After each virtual motor task had been completed, the physiotherapist could show on the screen the resulting trajectories to the patient.

Reinforced Feedback in Virtual Environment

During the last few years, considerable effort has been devoted to using innovative technology for delivering therapy to persons with motor disabilities.[70,71] The VR-based therapy in the form of Reinforced Feedback in Virtual Environment (RFVE) for arm motor training, as demonstrated in previous studies, represents a possibility in the field of motor learning based techniques for the upper limb[23,39,40,42,72,73]. Several studies have demonstrated that the treatment in a virtual environment could be advantageous for use in both the subacute and chronic phase of a stroke.[23,39]

In our laboratory we experimented using RFVE training for patients within a 3 month period of an ischemic stroke. We have evaluated the safety and effectiveness of the RFVE treatment in patients suffering from mild to intermediate motor impairment. However, the process of motor recovery after a recent stroke seems to progress from the RFVE rehabilitation treatment.[39]

Aisen et al. have supplemented the rehabilitation program by another robot-aided therapy, to assess whether this robotic treatment of the impaired limb impacted motor recovery in hemiplegic patients.[35] They tested subacute patients after a single stroke with hemiplegia. Patients were treated daily and the experimental group received additionally 4 to 5 hours per week of robot-aided therapy. The authors report that the experimental group showed a greater degree of improvement. They suggest "that more therapy is better" in the sense that this pattern of therapy is effective and the robot-device may have a positive effect on results. Moreover, many studies have pointed out that neuroplasticity and motor improvement can occur even in the case of a chronic stroke.[56,57]

Jack et al. evaluated three stroke patients using two input devices, namely a Cyber Glove and the Rutgers Master II-ND force feedback glove.[38] The subjects were trained during nine rehabilitation sessions to improve their finger motion. The authors demonstrated amelioration in finger movement, speed and fractionation. They concluded that theVR system could be usefully added to traditional rehabilitation.

In another study, the authors compared robot-assisted training with conventional rehabilitation for upper limb motor function after a stroke.[74] The patients received twenty-four one-hour sessions, the robot group was assisted by the robot-machine and the control group received neuro-developmental treatment. Theauthors noted that repetitive movements are effective if facilitated by a robot system and they suggest that for chronic stroke patients the current content of conventional training is not optimal.[74]

Also Kahn et al, using a robot device called Assisted Rehabilitation and Measurement (ARM) Guide, has suggested that the repetitive movement attempts by the patient are the primary stimuli to recovery[75].

In fact, several studies report the benefits from some forms of augmented feedback in hemiparetic limb treatment. Some studies indicate that neural processing is not the same when observing actions in the real world and when observing actions in a virtual-environment[76]. However, the RFVE treatment, composed of repetitive movements may indeed have favoured the acquisition of new motor abilities.

An important factor contributing to the subject's learning of the movements may be the specificity and frequency of feedback provided by the system regarding both the knowledge of their performance (KP) and the knowledge of the results of their actions (KR).

During the RFVE treatment patients perform motor tasks according to constraints specified beforehand by the physiotherapist. Feedback provides information about the success of the action during the performance of motor skills tasks (KP). By the movement of the end-effector in the virtual representation, it informs the subjects' perception as to the need to correct the motion errors. Moreover, the motor task correctness is supplied to patients in the form of simple scores and by displaying the arm trajectory morphology on the screen.

The advantages of VR training as an innovative rehabilitation technique are many. The VR-based therapy allows one to create rehabilitation scenarios very similar to the real-world. The reinforced feedback returns to the patient in real-time, amplifying the reward and specific information on the movement performance. Moreover, the VR technique provides suggestions stimuli and visual feedback that facilitate the execution of the requested task, enabling learning without errors. By modifying scenarios on the monitor to modulate the patient's interaction, the physiotherapist can focuse the training on specific deficits of the motor function and improve the number of trial repetitions.[1,37,77] The VR allows one to record and to review a database and later to analyze the real performance. During the treatment in a virtual environment, the patient can see his motor performance and through the feedbacks derived from the action can adjust the movements according to the task requirements. As far as post-stroke patients are concerned, RFVE training should ideally stimulate the motor re-learning of the impaired limb and facilitate subjects in re-learning the motor skills which are useful in ADL. Therefore, improving the correctness of arm trajectories combined with the novelty and the originality of the RFVE therapy, motivates the patients to participate in the rehabilitation session.

SUMMARY

This review paper describes an innovative technology developed also for clinical settings to augment the rehabilitation of patients with impaired limb function. The various systems for arm and hand treatment have the potential for clinical use to document the measurements of multiple movement variables and to be specifically tuned to patients' needs in terms of goal setting and practice schedules. The VR can be a cost-effective, non-invasive tool whereby patients can practice movements to improve motor control and function. Moreover, this technology may be beneficial to motor neuro-rehabilitation not only its potential for improving motor control, but also because it may help to train multisensory and sensorimotor integration. Robots are capable of delivering interactive and repeatable sensorimotor exercises and a continuous monitoring of the actual motor performance. The feeling of being really present, as provided by the realistic representation of the virtual environment and by the involvement of multiple sensory and motor modalities, enables the subject to live out the virtual experience more realistically than he would do by means of his own imagination.[78]

Studies involving the recovery of motor deficits in upper extremity function after a stroke have demonstrated the efficacy of VR in motor skills reacquisition. Several pieces of data indicate that plastic changes in the motor cortex of stroke patients occur even after a training session of only 1.5 h.[53] However, the most important question is whether the potential benefits seen in VR training transfer themselves to the real world. The changes in the activities of daily living could be due to either the nature or intensity of the VR training or the nature or intensity of the real world tasks. From this point of view, future research will need to clarify whether through technical design and/or new treatment exercises, ADL tasks can be enhanced by virtual training.

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Address for correspondance

Paweł Kiper
Fondazione Ospedale San Camillo
Via Alberoni 70, 30126 Lido-Venezia, Italia
tel/fax: 0039-0412207214
e-mail: pawel.kiper@ospedalesancamillo.net

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