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VIRTUAL REALITY BASED UPPER EXTREMITY REHABILITATION FOLLOWING STROKE: A REVIEW

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In the last decade there have been major developments in the creation of interactive virtual scenarios for the rehabilitation of motor deficits following stroke. Virtual reality technology is arising as a promising tool to diagnose, monitor and induce functional recovery after lesions to the nervous system. This evidence has grown in the last few years, as effort has been made to develop virtual scenarios that are built on the knowledge of mechanisms of recovery. In this paper we review the state of the art virtual reality techniques for rehabilitation of functionality of the upper extremities following stroke. We refer to some of the main systems that have been developed within different rehabilitative approaches such as learning by imitation, reinforced feedback, haptic feedback, augmented practice and repetition, video capture virtual reality, exoskeletons, mental practice, action observation and execution, and others. The major findings of these studies show that virtual reality technologies will become a more and more essential ingredient in the treatment of stroke and other disorders of the nervous system.

Introduction

The use of virtual reality (VR) in the field of neurorehabilitation has grown immensely in the last decade. VR is a set of computer technologies that provides an interactive interface to a computer generated environment. In this environment, the individual can see, hear and navigate in a dynamically changing scenario in which he or she participates as an active user by modifying the environment according to his or her actions. VR has also been deployed in different rehabilitation contexts and a number of preliminary studies suggest that this technology has a positive impact on functional recovery (see Rose, Brooks, & Rizzo, 2005 and Holden, 2005 for reviews).

The use of virtual reality technologies in rehabilitation has a number of distinguishing features. First, they can be used as training tools to promote intensive training directed towards specific deficits. Second, training can be defined within scenarios that allow the patients to engage in task-oriented activities. Third, it is a real-time high-resolution monitoring tool, allowing for the quantitative assessment of relevant properties of deficits, performance and recovery.

This latter aspect can be combined with more standard clinical evaluation methods, providing complementary data for measuring diagnostics. Fourth, the versatility of VR technologies can play an important role in engaging motiva-

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tional factors, a key factor in recovery (Maclean, Pound, Wolfe, & Rudd, 2002). Fifth, VR based rehabilitation systems easily transfer from clinic-based training to at-home applications for telerehabilitation, creating a continuum of diagnostic and training possibilities (Holden, Dyar, Schwamm, & Bizzi, 2005; Piron, Tonin, Trivello, Battistin, & Dam, 2004). In this review we will analyze a number of studies with the objective of identifying the underlying principles and routes for future research and applications in this area. In particular, we will describe and analyze different virtual reality systems and methods that have been developed for motor rehabilitation, focusing on rehabilitation of the upper extremities following stroke. We start by briefly summarizing the problematic elements of stroke and its rehabilitation strategies. Subsequently, we review studies of virtual reality systems for the rehabilitation of upper extremity deficits after stroke and describe their major results. Although in the concrete application we have limited ourselves to this specific range of deficits and patients, the core principles and observations will generalize to a wide range of other pathologies.

Stroke and its Rehabilitation

Stroke represents one of the main causes of adult disability and it is estimated that it will still be one of the main contributors to the burden of disease in 2030 (Mathers & Loncar, 2006). Following stroke, up to 85% of patients initially show a motor deficit of the arm contralateral to the lesion, and 55 to 75% display persistent functional limitations three to six months after stroke (Lai, Studenski, Duncan, & Perera, 2002). Several cognitive and motor deficits may be present depending on the lesion site, such as paralysis or weakness, abnormal posture, neglect, abnormal movement or loss of coordination. Moreover, about 60% of people who survive a stroke experience impairments that last throughout life (Parker, Wade, & Langton Hewer, 1986).

After a stroke, the recovery of the motor capacity of the hand is of particular interest since it is very relevant in overall functionality and the ability to perform instrumental activities of daily living (IADL). However, the optimal type of physiotherapy is still under discussion (Dombovy, 2004).

There is a considerable variety of treatment concepts and therapies, but their effectiveness is difficult to measure and compare since there are many variables to take into account. In stroke, as in many other neuropathologies, one of the main problems in assessing the impact of new methods is the difficulty of performing studies with homogenous groups of patients in terms of stroke type and functional deficit. Although traditional physiotherapy-oriented approaches emphasize the manipulation of the peripheral skeletal motor system and the training of IADL, currently the emphasis is shifting to methods that directly address the central nervous system and take into account our understanding of the neural mechanisms underlying recovery (Kalra & Ratan, 2007). An important basic research question, however, is what the best way is to exploit plasticity and functional reorganization.

Irrespective of the technology involved, the effectiveness of stroke therapy has been shown to depend on a number of parameters. First, treatment frequency and intensity has been shown to correlate with recovery (Kwakkel et al., 2004; Sonoda, Saitoh, Nagai, Kawakita, & Kanada, 2004). Increasing therapy time in the first months post-stroke has been shown to promote increased independence in IADL and a reduction of the hospitalization period. In addition, movement practice and repetition seems to play a fundamental role in recovery (Karni, Meyer, Jezzard, Adams, Turner, & Ungerleider, 1995).

Second, the specificity of rehabilitation training with respect to the deficits and required functional outcomes has an impact on recovery (Krakauer 2006). Specificity is also seen as a central concern in occupational therapy (Steultjens, Dekker, Bouter, van de Nes, Cup, & van den Ende , 2003). VR based rehabilitation systems can capture these two core parameters of effective neuro-rehabilitation, while combining them with a number of additional features that are specific to this technology.

VR Rehabilitation

Several virtual reality systems and methods have been developed for motor rehabilitation of the upper extremities following stroke based on different paradigms and hypotheses. Here we delineate a number of specific studies that elucidate the different dimensions that guide the development of deployment of VR-based rehabilitation methods.

Learning by Imitation

Holden and collaborators have developed a VR system based on the so called, “learning by imitation” paradigm (Holden & Dyar, 2002; Holden, Todorov, Callahan, & Bizzi, 1999). This system makes use of a virtual teacher, whose movements are to be followed by the user. The hypothesis is that the repeated observation of this virtual tutor may lead to recovery as a result of direct input to the primary motor area (M1) provided by the bi-modal mirror neuron or action recognition system. Mirror neurons have the property of being active during the execution of goal-directed movements performed with the hand, foot and mouth, and also during the observation of the same actions performed by another individual (Rizzolatti & Craighero, 2004). In a specific experiment, two chronic stroke patients used the system to train reaching movements in a task that consisted of placing an envelope in a virtual mailbox positioned in different locations (Holden et al., 1999). The subjects were asked to follow the instructions of the virtual teacher in this task and both virtual and real movements were used to provide augmented feedback about the patient’s performance. Results showed that both patients improved in the virtual tasks and also in the real world reaching tasks, showing the ability to transfer VR task abilities to the real world. However, there were no significant changes in the standard clinical measures, with only one of the subjects presenting a slight increase of 17% in the total Fugl-Meyer Test for the upper extremities (Fugl-Meyer, Jaasko, Leyman, Olsson, & Steglind, 1975).

Moreover, as with other studies in this domain, the statistical power from an impact study with such a small sample size cannot be considered adequate. In a later study, nine patients practiced reaching tasks in a new version of this system; besides the “virtual mailbox” it also included new virtual scenes and a scoring system to provide feedback (Holden & Dyar, 2002). This system captures the patient’s movements by means of electromagnetic motion tracking sensors and these movements are mapped onto the movement of a virtual representation of the upper extremity. Moreover, when the subjects hold a real object, e.g. a ball, is also represented in the virtual scenes. The purpose of this is to increase the sense of immersion during the task and also to elicit the execution of natural movements. Patients showed improvements in the virtual task and also significant improvements in standard clinical tests such as the Fugl-Meyer Test and Wolf Motor scale (Wolf, Catlin, Ellis, Archer, Morgan, & Piacentino, 2001). The authors emphasize that although the results are quite promising, they do not warrant definite statements on what exact characteristics of their system triggered the improvements in function. Moreover, there is the added problem of not having controls for a comparison standard in any empirical validation. In a follow-up study, further tasks were added to this virtual environment to train different movements (reaching, hand-to-body, and hand grasp/release) and it was used within a telerehabilitation system (Holden, Dyar, Schwamm, & Bizzi, 2005). Preliminary tests with two chronic stroke patients showed the advantages of these kinds of systems in remote training. For clinical evaluation, the authors used the Fugl-Meyer Test, the Wolf Motor Test, and strength tests for shoulder flexion and hand grip. The patients showed improvements in the performance of the virtual task and also in the associated clinical measures, with sustained gains at follow-up. In a later study, an improved version of this system was used with eleven stroke patients (Holden, Dyar, & Dayan-Cimadoro, 2007). The patients followed a treatment course of 30 one-hour sessions, and the evaluation was performed at admittance, session 15, session 30, and 4-month follow-up. The results revealed significant changes in the group mean on the clinical measures (Fugl-Meyer Test, Wolf Motor Test and strength tests) after 15 and 30 sessions, with gains maintained at follow-up except for grip strength. Unfortunately, no controls were used in this study.

Reinforced Feedback

Piron and colleagues base their work on the hypothesis that convenient feedback may improve motor recovery (Piron, Tonin, Piccione, Iaia, Trivello, & Dam, 2005). This feedback can be delivered regarding the quality of the movement (knowledge of performance) and the goal of the task (knowledge of results). The authors want to investigate whether continuous information provided on the quality of the movement of the patients combined with the observation of correct movement may lead to an enhancement in recovery. The setup used, the virtual environment training (VET) system, has a set of exercises that promote several reaching tasks through imitation of a virtual therapist. Subjects were asked to grasp real objects (envelope, ball, cube and glass) in which a magnetic sensor was placed. Movements were first performed by the virtual tutor and afterwards by the subject. The software is the same used by the group above (Holden & Dyar, 2002). The movement trajectories were displayed during the execution of the task and were also presented to the subjects in the end of the task. Forty-five chronic stroke patients used the system during for one hour, five days a week, during one month. In a general overview all the patients increased in clinical scores, with a 15% increase in the mean Fugl-Meyer score. However, the impact on activities of daily living performance was low, with a 6% increase in the mean FIM (Functional Independence Measure) score (Keith, Granger, Hamilton, & Sherwin, 1987). There were also observed improvements in the kinematic parameters of the reaching movements (mean velocity and mean duration). Moreover, the pattern of the grasping movements of the paretic arm approached the correct pattern of movements of the non-paretic one. In a later study, this same type of virtual reality training was used with patients in the early stage of stroke (first three months; Piron, Tombolini, Turolla, Zucconi, Agostini, Dam, et al., 2007). Thirty-eight patients participated in this study and were separated into two groups: 25 subjects received reinforced feedback in the virtual environment (RFVE) and 13 patients (control group) received the same amount of conventional therapy. After the treatment period, the RFVE group showed significant improvements in the mean scores of the Fugl-Meyer Test and of the FIM. The control group presented no significant improvements. This supports the idea that reinforced feedback provided in the early stages of stroke may lead to an enhanced recovery.

Haptic Feedback

Virtual reality training has also been combined with haptic feedback. Regarding arm reaching training, there is a setup proposed by Broeren and colleagues (Broeren, Rydmark, Bjorkdahl, & Sunnerhagen, 2007; Broeren, Rydmark, & Sunnerhagen, 2004). The system is composed of a haptic force feedback interface (PHANToM) connected to a virtual environment and a stereoscopic view setup, allowing for a sense of touch with virtual solid objects. The task consists of knocking down bricks in a pile with a ball with a variable velocity, where the force feedback is provided by a haptic stylus. In a case study with a three month post-stroke patient, the patient improved finger dexterity, grip force and endurance after a four month VR treatment (Broeren et al., 2004). In addition, the patient reported an increase in the use of the paretic arm during activities of daily living. In a later study, five chronic stroke patients with hemiparesis used the system for five weeks (Broeren, et al., 2007). All patients progressed to the highest difficulty in the game level and some improvements in aspects of motor performance were also observed.

Augmented Practice and Repetition

Intensive training of different manual skills has been one of the focuses of the Rutgers group (Jack, Boian, Merians, Tremaine, Burdea, Adamovich, et al., 2001; Merians, Jack, Boian, Tremaine, Burdea, Adamovich, et al., 2002; Merians, Poizner, Boian, Burdea, & Adamovich, 2006). Their system is based on the notion that intensity of training and systematic feedback are important factors to improve motor function (see above). The proposed system makes use of two complementary data glove systems (CyberGlove, Immersion Co., San Jose, USA) and the Rutgers Master II force feedback glove (Bouzit, Burdea, Popescu, & Boian, 2002) to train range of movement, speed of movement, finger fractionation (the ability to move fingers independently) and strength (Jack et al., 2001). This project is associated with an older system developed by the same group for ankle rehabilitation (Girone, Burdea, Bouzit, Popescu, & Deutsch, 2000). The CyberGlove is comprised of strain-gauge sensors that measure finger joint angles, abduction, and wrist flexion, allowing for an appropriate capture of hand movement. On the other hand, the Rutgers Master II force feedback glove is an exoskeleton that applies force to the fingertips by means of pneumatic actuators, allowing for strength training exercises. Four virtual tasks were implemented to train the different hand parameters. First, the range of movement task, designed to improve finger flexion and extension, consisted of moving a window wiper to clean a fogged window, revealing a pleasant landscape. The range of finger flexion controls the rotation of the wiper. Second, the speed of movement task is a catch-the-ball game where the subject is asked to close either the thumb or the other four fingers as fast as possible when required. Third, the finger fractionation task that is used for all fingers except the thumb uses a piano keyboard on which keys depress and highlight when the correspondent fingers move. Fourth, the strength task, used for grasp training, presents a virtual model of the Rutgers Master II glove that is directly controlled by the user. Reacting to the forces applied on the fingertips, schematic pistons start to fill from top to bottom in proportion to the exerted force. In these tasks feedback is provided with respect to the movement goal (knowledge of results) and also related to the movement that was produced (knowledge of performance). A study with three chronic stroke patients showed improvement in some of the trained parameters and also functional gains after the training period, but with variable improvement patterns (Merians et al., 2002). The authors, however, hesitate in attributing the functional changes to their VR-based approach since it cannot be distinguished with certainty from the contribution of real world training. In a later study, eight chronic stroke patients intensively used this system (with an updated speed of movement task) in a three-week program (Merians, Poizner, Boian, Burdea, & Adamovich, 2006). As a group, the patients showed improvements, with retained gains, in the virtual reality measures and in the clinical evaluation measures (Jebsen Test of Hand Function (Jebsen, Taylor, Trieschmann, Trotter, & Howard, 1969) and reach to grasp test). Moreover the improvements were transferred to real world tasks. However, this study has the limitation that the patient group was not homogeneous, making it difficult to establish comparisons and make statements on the efficacy of the proposed method.

Video Capture Virtual Reality

Weiss and colleagues use video capture virtual reality, a technique that consists of tracking a user's movements and mapping them onto an image that is embedded in a virtual environment (Weiss, Rand, Katz, & Kizony, 2004). The users can see themselves within a virtual scenario in a mirror image view, as opposed to the first person point of view provided by head mounted displays. Therefore, users can have feedback about their body posture and quality of movement. Studies carried out to date suggest a positive impact on the recovery of functionality in stroke patients and several platforms have been used and compared. For instance, Weiss et al. (2004) modified the VividGroup's Gesture Xtreme VR (www.vividgroup.com; a platform formerly used for entertainment and education) in order to use it in neurological rehabilitation. In a preliminary usability study, its impact on the recovery of a stroke patient six months post-stroke was assessed (Kizony, Katz, & Weiss, 2003). In this case the proposed virtual tasks were: 1) touching virtual balls that emerge from different locations and fly towards the user; 2) being a goalkeeper in a soccer game, preventing balls from entering the goal area; and 3) being a snowboarder, skiing downhill and avoiding collisions with objects by leaning the whole body to the side. The system had good acceptance, and the patient was able to interact within the virtual scenarios without feeling side effects. Afterwards, a study was carried out with thirteen stroke patients (Kizony, Katz, & Weiss, 2004). After the tests the patients completed a questionnaire to assess their sense of presence, the perceived difficulty of the task, and their overall impressions during the tasks. Cognitive, motor and sensory measures were also taken. The questionnaires revealed that the patients enjoyed the virtual tasks, suggesting a positive contribution to the patient's motivation. Moreover, this study suggested that a relationship exists between the patients' personal characteristics and preferences and the properties of the virtual environment that influence performance. However, such questionnaires can (at best) be seen as a suggestion and not as an unbiased quantitative measure (Nisbett & Wilson, 1977).

Exoskeletons

More recently, VR systems have been augmented with advanced interface systems such as exoskeletons that allow arm gravity support. These systems have been combined with virtual reality scenarios for functional exercising of the upper limbs (Housman, Le, Rahman, Sanchez, & Reinkensmeyer, 2007; Montagner, Frisoli, Borelli, Procopio, Bergamasco, Carboncini, et al., 2007; Reinkensmeyer & Housman, 2007; Sanchez, Liu, Rao, Shah, Smith, Rahman, et al., 2006). One of these systems is the T-WREX, comprised of an orthosis that assists the movement of the arm in a broad range, a grip sensor for grasp training, and software to train functionality (Sanchez et al., 2006). Patients can train with different games related to activities of daily living with emphasis on the repetitive training of different ranges of movement and grips. For simplicity, two of the five degrees-of-freedom of the T-WREX are used for these tasks including: 'Shopping', 'Washing the Stove', 'Cracking Eggs', 'Washing the Arm', 'Eating', 'Making Lemonade' and 'Ranging the Arm'. The system was tested with five chronic stroke patients during two months in order to assess the effect of gravity balance on static positioning and the effect of gravity assisted movements in recovery (Sanchez et al., 2006).

After training, the movements of the patients were shown to be more effective when gravity balance was present, with an increase in the properties of reaching. The subjects also displayed improvements in their ability to move their arms, with some of them showing increased grip strength and augmented distance of reaching with and without support. In a later randomized controlled study, chronic stroke patients were divided in two groups: 11 patients were assigned to eight weeks of therapy with the T-WREX and 12 patients received only conventional therapy for the upper extremities and formed a control group (Housman et al., 2007). The group that used T-WREX showed significant improvements in their Fugl-Meyer scores when compared to the control group. Moreover, subjective questionnaires revealed a preference for the T-WREX when compared with standard therapy (Reinkensmeyer & Housman, 2007).

Montagner and colleagues are also working with an exoskeleton for rehabilitation of the arm following stroke (Montagner et al., 2007). The L-Exos is a five degree-of-freedom arm exoskeleton, therefore allowing for several joint configurations, and also supination and pronation of the wrist. Moreover, the L-Exos is a force feedback exoskeleton, allowing for the application of a controlled force to the palm of the user's hand. The virtual reality scenarios are composed of tasks that promote different movements: Reaching Task, where objects are to be reached at different positions; Constrained Motion Task, where the subject has to move along a circular trajectory while being constrained by an impedance control; and Manipulation Task, which consists of manipulating and arranging different configurations of cubes. In a pilot, three chronic stroke patients used the L-Exos in one-hour sessions, three times per week, during six weeks. After the study, patients presented improvements in the therapy-dependent measures, with a higher impact in reaching movements (Montagner et al., 2007). As in the case of the T-WREX, with the L-Exos user acceptance and satisfaction was also high. Although results to date are very promising, ongoing studies are needed in order to infer which properties of these systems are crucial for recovery.

Mental Practice

Mental practice techniques based on motor imagery have also been assisted by virtual reality systems to help generate and maintain images (Gaggioli, Meneghini, Morganti, Alcaniz, & Riva, 2006). Gaggioli and colleagues developed the VR Mirror, a system to guide mental practice in the rehabilitation of the upper limbs following hemiplegia due to stroke. The system consists of a table with a backprojected horizontal screen, a projector, a mirror and sensors for movement tracking. Basically, this system displays to the patient the previously recorded mirror movements of their non-paretic arm. The observed movement is used to support mental rehearsals of that movement, and to promote the movement of the impaired limb by following the mirror image. In a pilot, a chronic stroke patient used the VR Mirror during a period of four weeks, administered in three sessions per week.

The treatment focused on training the flexion and extension of the wrist, rotation of the forearm, and flexion and extension of the elbow. Mental practice always followed the observation of the virtual representation of the mirrored movements of the healthy arm. Moreover, after the four weeks of training the subject was provided with a portable device to allow training at home during an additional four weeks. Clinical evaluation measures included the Fugl-Meyer Assessment Test for the upper extremity and the Action Research Arm Test (Lyle, 1981). The patient showed an improvement on all these scores after the four weeks of training, followed by limited further improvement after the training at home. In addition, improvements in range of movement and grip strength were reported. The same system and training protocol was later used with nine chronic stroke patients during eight weeks (Gaggioli Meneghini, Pigatto, Pozzato, Greggio, Morganti, et al., 2007). Unfortunately, no significant improvements were observed in the Fugl- Meyer and Action Research Arm scores. However, some patients reported an improvement in the performance of activities of daily living.

Action Execution/ Observation

Verschure and colleagues develop their work based on the paradigm of action execution coupled with motor imagery and action observation (Cameirao, Bermudez i Badia, Zimmerli, Duarte Oller, & Verschure, 2007). Their underlying hypothesis is that functional recovery can be promoted by capitalizing on the life-long plasticity of the brain and the assumption that neuronal plasticity is governed by a few computational principles or objectives (Wyss, König, & Verschure, 2006). To exploit these principles the authors explore a system that combines movement execution with the observation of correlated action of virtual limbs that are displayed in a first-person perspective. The claim is that within such a scenario, recovery can be accelerated and enhanced by driving the mirror neuron system (Rizzolatti & Craighero, 2004). The mirror neuron system is seen as an interface between the neuronal substrates of visual perception and motor planning and execution. Hence, these neurons would allow for a direct pathway to drive the motor systems affected by stroke and in this way provide a task and context relevant state of the afferent and effer-

Figure 1. The Rehabilitation Gaming System (RGS) setup. The RGS constitutes a standard paradigm comprising all the key elements of any VR based cognitive-neurorehabilitation system. Motion capture is achieved through a video based system. The user wears color patches that are tracked by the motion capture system and that are mapped onto a virtual character through a biomechanical model. Data gloves provide finger flexion data. The screen displays a first person view of the gaming scenario in the virtual environment. The versatility of the used gaming technology (Torque, Garage Games, www.garagegames.com) allows the rapid development of new rehabilitation scenarios.

ent pathways that are disrupted by the lesion. In this way, the authors assume that two important objectives of rehabilitation can be achieved: *rescue* where healthy but functionally pathological tissue can be salvaged and protected combined with *recovery* of function through reacquisition. Following these premises, and as a means to evaluate the general predictions of this approach, the authors have developed the Rehabilitation Gaming System (RGS). In its first applications, the RGS has been used as a tool for the evaluation and rehabilitation of motor deficits of the upper extremities in stroke patients. The RGS consists of a vision-based motion tracking system, data gloves and a conventional LCD display (Figure 1). The tracking system detects color patches located on the wrists and elbows of the subjects; a biomechanical model of the upper body allows the reconstruction of the movements. These movements are mapped in real-time to the movements of a virtual character displayed in a first-person perspective. In addition, data gloves capture finger flexure, allowing for a realistic representation of the movements of the arm. The RGS as applied to upper extremity rehabilitation proceeds according to a structured multi-level rehabilitation process with graded difficulty and specificity: 'Hitting' to train range of movement and speed; 'Catching' to train finger flexure; and 'Grasping' to train grasp and release. In a first study RGS was used to investigate the transfer of performance and performance deficits between real and virtual tasks (Cameirao, Bermudez i Badia, Zimmerli et al., 2007) and the effect of different task conditions on stress and arousal measurements (Cameirao, Bermudez i Badia, Mayank, Guger, & Verschure, 2007). RGS is currently being used with acute stroke patients (within the first three weeks of stroke) in a controlled randomized study. The study includes three different therapy conditions: the RGS group and two control conditions. In the visual stimulus control condition the effect of the visual stimulus and the role of the mirror neuron system are removed. Here subjects perform similar motor tasks (as the ones promoted by the RGS), but in the absence of further visual stimulus. The task is performed on a table and includes object manipulation, placement and object grasping with increasing complexity (object drag, object grasp and drag, object grasp-displace-release). The second control group assesses the impact of computer use. The subjects allocated to this group perform non-specific games with the Nintendo Wii (Nintendo, Tokyo, Japan). Each subject follows a three month program, with three weekly sessions of 20 minutes.

The main inclusion criteria are: the patient (age<80 years) should suffer a first event stroke and is in the acute or subacute phase of stroke (<3 week post-stroke), display a severe deficit of the paretic arm in the absence of cognitive deficits. The evaluation of function of the subjects is performed at admittance (beginning of the program), at session 15 (approximately five weeks after the beginning of the study), month three (end of the program) and month six (follow-up). The evaluation scales include, among others, the FIM (Functional Independence Measure), the Motricity Index (Collin & Wade, 1990), the Fugl-Meyer Assessment Test for the upper extremity, and the CAHAI (Chedoke Arm and Hand Activity Inventory; Barreca, Gowland, Stratford, Huijbregts, Griffiths, Torresin, et al., 2004). To date, only one patient completed five weeks of training (15 sessions). This patient is using the RGS, and so far has displayed improvements in the evaluation measures, including an improvement of 35% in the FIM, 41% in the Motricity Index, 27% in the Fugl-Meyer Test, and 21% in the CAHAI. Moreover, this patient largely increased independence in the performance of activities of daily living. However, more data needs to be collected in order to fully assess the impact of the RGS training approach.

Other systems

Other systems explore the combination of different features within virtual environments. Rizzo and colleagues developed different scenarios that aim to assess and rehabilitate relevant perceptual-motor activities such as eye-hand coordination and range of motion (Rizzo, Cohen, Weiss, Kim, Yeh, Zali, et al., 2004). Some of these scenarios are applicable for persons with dysfunctions of the nervous system, such as stroke and brain injury. The systems are based on stereoscopic graphic scenarios where the user interacts with virtual stimuli within a full 360-degree space using a head mounted display. The environments promote reaching and targeting tasks, and allow analysis of body posture and body movement, as well as quantification of motor performance. The work of Stewart and collaborators takes a similar approach (Stewart, Yeh, Jung, Yoon, Whitford, Chen, et al., 2007). Their system encompasses four different virtual tasks for motor skill learning, namely: 'Reaching', to reach for objects; 'Ball Shooting', to reach and intercept a ball launched from a wall; 'Rotation', to train forearm pronation and supination; and 'Pinch' for precision grasp. In this case, the subject experiences a three dimensional view that is provided by shutter glasses. Magnetic trackers attached to the hand and objects are used for movement detection in the first three tasks; while for the 'Pinch' task, two coupled PHANToM devices (SensAble Technologies, Woburn, MA, United States) are used. As a feasibility test, two acute stroke patients with different impairment severity used the system during 12 sessions of 1-2 hours. Results showed that this system facilitates the control of practice intensity and difficulty based on the capabilities of movement of each subject and in this way provides for personalized training. Studies with larger populations are needed, however, to investigate the overall effect on recovery following stroke.

Subramanian et al. combine practice and feedback elements to achieve rehabilitation of the upper extremities (Subramanian, Knaut, Beaudoin, & Levin, 2007; Subramanian, Knaut, Beaudoin, McFadyen et al., 2007). A virtual elevator was created to train pointing movements. Repetitive reaching in different directions is promoted and feedback about motor performance is provided, supporting knowledge of performance and knowledge of results. The system is comprised of a head mounted display, a motion capture system and a data glove, and allows real-time integration of hand, arm and body movements. Comparisons were made between hemiplegic subjects performing real and virtual pointing tasks within this study. Preliminary results suggest that the training in the virtual environment leads to more consistent improvements in movement execution.

Conclusions

In the last decade, extraordinary improvements have been made regarding the development of virtual reality systems for motor neurorehabilitation. Several target populations have been considered, but within these stroke sufferers have received special attention, especially in the rehabilitation of the upper extremities. In the context of virtual reality applied to the rehabilitation of the arm, we reviewed some of the main systems that have been developed and describe their major findings. Different paradigms and therapy concepts have been used, which we grouped in different categories: learning by imitation, reinforced feedback, haptic feedback, augmented practice and repetition, video capture virtual reality, exoskeletons, mental practice, and action execution/observation. However, most of these virtual reality systems are built taking into account the knowledge of the mechanisms of recovery and the therapeutic context. We consider that this is a major step in motor rehabilitation that is also witnessed by the rapid development of this specific technology-based approach towards neuro-rehabilitation in the last few years. In particular, VR-based approaches allow us to shape the technology on the basis of a well-defined hypothesis on the mechanisms underlying recovery. Another improvement is the existence of a larger number of studies that include a relevant number of patients. In general, the patients that used virtual reality environments showed significant improvements in various aspects of performance, with an impact on the activities of daily living. Nevertheless, only a few studies used control groups and this is still an important methodological limitation if we want to assess the efficacy of virtual reality, or any other therapy, in rehabilitation.

In summary, the advantages of the use of virtual reality technologies are vast, and we believe that important developments will take place in the next few years that will establish this as a major breakthrough in the treatment of pathologies of the nervous system.

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