Virtual Reality Use in Motor Rehabilitation of Neurological Disorders: A Systematic Review

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Abstract: Recent experimental evidence suggests that rapid advancement of virtual reality (VR) technologies has great potential for the development of novel strategies for motor rehabilitation. Virtual reality is a computer based, interactive, multi-sensory simulation environment that occurs in real time. The aim of this review was to discuss the rationale, criteria of application, limits of the available procedures and the effects of VR in the rehabilitation of patients with stroke and those with cerebral palsy (CP). Seventeen published articles from 1/1/2002 to 1/05/2010 were reviewed. Classification of the available virtual reality setups and comparison among published studies, with focus on the criteria of motor impairment and recovery assessment, rehabilitation procedures, and efficacy were reviewed. The studies completed to date support the application of VR in the treatment of patients after stroke and CP patients. The duration of the rehabilitation effects after discontinuing VR training is crucial and should be determined in controlled follow-up studies.

Key words: Virtual reality • Wii • Nentindo • Video games • Motor rehabilitation • Neurological disorders

INTRODUCTION

Two major goals of rehabilitation are the enhancement of functional ability and the realization of greater participation in community life. These goals are achieved by intensive intervention to improve sensory, motor, cognitive and higher level-cognitive functions as well as to practice in everyday activities and occupations to increase participation [1,2]. Intervention is based primarily on the performance of rote exercises and/or different types of purposeful activities and occupations [3,4]. For many injuries and disabilities, the rehabilitation process is long and arduous and clinicians face the challenge of identifying a variety of appealing, meaningful and motivating intervention tasks that may be adapted and graded to facilitate this process. Virtual reality-based therapy, one of the most innovative and promising recent developments in rehabilitation technology, appears to provide an answer to this challenge [5].

Virtual reality is a computer based, interactive, multi-sensory simulation environment that occurs in real time. It presents users with opportunities to engage in activities within environments that appear, to various extents, similar to real-world objects and events [6-8]. These environments are usually three-dimensional and are regarded as being immersive in that the user has a strong “sense of presence.”[9]. The concept of presence is the illusion of going into the computer generated world and depends on the convergence of multi-sensory input (sight, sound and sometimes touch) in the virtual environment. In general, there are two types of virtual environments, immersive and non-immersive. Fully immersive VR uses large screen projection (LSP), headmounted display (HMD), or cave (BNAVE) systems, where the environment is projected on a concave surface to create the sense of immersion. Immersive systems may also use environments such as video capture systems (e.g. IREX, PHANToM; SensAble Technologies Inc.), where the users view themselves or an avatar (representation of the limb) in the scene on a computer screen as if watching TV. In a non-immersive VR system, users interact to different degrees with the environment displayed on a computer screen, with or without interface devices such as a computer mouse or haptic devices such...
Virtual reality systems have been developed specifically for rehabilitation of the upper extremity, lower-extremity training and gait retraining [11-14]. Most of these systems are not commercially available and, when available, are very expensive. Therefore, low-cost, commercially available technologies, such as gaming systems, are being trial tested for rehabilitation applications [15].

The potentialities and actual advantages of this "learn and-transfer" approach are a matter of debate [16]. There are indications of greater efficiency of VR training compared with conventional rehabilitation in patients with a neglect syndrome [17] or with walking disabilities [18], but generalized evidence is still lacking. In this article a brief overview of the rationale, criteria of application, limits of the available procedures and the effects of VR in the rehabilitation of patients with stroke and patients with CP.

RESULTS

SUBJECTS AND METHODS

In order to gather the articles we carried out a search on five databases: Medline (through Pubmed), ISI (ISI Web of Knowledge), Scopus, IEEE Xplore and ACM (Association for Computing Machinery). The query used on Pubmed was schematically “Virtual Reality, Nintendo Wii and Video Games” and “Motor Rehabilitation related terms (such as motor function, Injury, Rehabilitation, Neurological disorders, Disability, Brain Damage). On the other databases we used solely “Virtual Reality” as to broaden our search and we applied time scale restrictions (1/1/2002 to 1/05/2010) and also excluded non-related subject areas (e.g. Psychology, Chemistry, Sociology,...).

This search yielded 860 articles. Duplicate articles were excluded. After duplicate exclusion, we had a total of 840 articles. These were subjected to a three stage selection process. In the first stage two reviewers read the title of the article and included or excluded it. In case of disagreement the article was excluded. After this stage of the selection process, we were left with 100 articles.

In the second stage, the same two reviewers read the abstract of the article. If the abstract referred the use of VR and/or VR-based therapy such as Nintendo Wii or video games for patients with neurological disorders, the article was included. In doubt or in case of disagreement, the article was excluded. After the second stage, 40 articles were selected. In the third and final stage, the article was subjected to a full text reading. To be included it had to be an article (not a letter) and clearly related to VR and its use for motor rehabilitation of patients with stroke and those with CP.

After the final stage, 17 articles were selected. It is important to refer that 9 articles were excluded because they were letters, 8 were studies with only their abstract published and 6 couldn’t be obtained. Therefore, the population of this study consists of 17 articles published in English on Medline, Scopus, ISI and IEEE, from 1st January 2002 to 1st May 2010. They clearly refer to the impact of the use of VR for motor rehabilitation of patients with stroke and those with CP.

After selecting the articles they were read and the following variables were extracted; date of publication, pathologic condition, sample size, study design, type of VR, intervention procedures, outcome measures and conclusions.

Comparison among studies is, to an extent, biased by heterogeneities among studies and the small size of most patients’ samples (Table 1). Several subject/VR interfacing setups have been used, with substantial differences in the degree of environmental immersion, display, supporting hardware/software (from the commercial desktop to professional video projectors) and interface devices (e.g. haptic devices, electromagnetic sensors).

For stroke rehabilitation, some applied systems have featured and enhanced VR setup with a virtual teacher for upper limb tasks, desktop computer display and electromagnetic motion tracking sensors [19-22] and more recently wii gaming technology [23]. Immersive VR was also used with video-projection onto a large screen and cyber-gloves [24]. Others have provided a non-immersive desktop display focusing on hand function and haptic feedback using a glove [24-26]. While others have favoured semi-immersive tele-rehabilitation VR using rutger arm telerehabilitation system (VRRS.net) [27,28]. Semi-immersive VR was also provided by other researches with a haptic feedback device [29].

The VR rehabilitative training began at least 6 months after stroke in most studies [23,26-28] while other studies began the treatment after 1 year [22,24,26]; studies in the acute stage (within 3 months after stroke) are exceptional [19,20,29]. There was no consensus or agreement in the selection criteria for pathophysiology
## Table 1: Summary of the analyzed studies

<table>
<thead>
<tr>
<th>No.</th>
<th>Author(s), Year of Publication</th>
<th>Pathology and Sample Size</th>
<th>Design of Study</th>
<th>Type of VR</th>
<th>Intervention</th>
<th>Outcome Measures</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Boian et al. (2005) [25]</td>
<td>4 / Stroke</td>
<td>Pre-post</td>
<td>Non-immersive</td>
<td>VR exercises to reduce impairments in finger range of motion, speed, fractionation and strength.</td>
<td>computerized measures, JTHF</td>
<td>A precondition task was performed 9-40% faster for three of the patients after the intervention</td>
</tr>
<tr>
<td>2</td>
<td>Merians et al. (2007) [20]</td>
<td>2 / Chronic Stroke</td>
<td>Pilot study</td>
<td>Immersive</td>
<td>4 VR games (Reaching, Ball Shooting, Rotation ad Pinch)</td>
<td>FM, FTHUE, BBT, SIS</td>
<td>Successful improvement of movement and rate of performance</td>
</tr>
<tr>
<td>3</td>
<td>Heidi et al. (2007) [26]</td>
<td>15 / Stroke</td>
<td>Pilot Study</td>
<td>Non-immersive</td>
<td>Training in reach-to-grasp of virtual and actual objects</td>
<td>FM, McMaster Hand Scale, WMFT, RLA</td>
<td>Slight decrease in time to perform some of functional tasks</td>
</tr>
<tr>
<td>4</td>
<td>Cameiro et al. (2008) [19]</td>
<td>14 / Acute Stroke</td>
<td>Pre-post</td>
<td>Immersive</td>
<td>RGS including Hitting, Grasping and Placing</td>
<td>FIM, BI, MI, FM, CAHAII</td>
<td>Improvement with observed benefits in performance of ADL</td>
</tr>
<tr>
<td>5</td>
<td>Kuttuva et al. (2006) [27]</td>
<td>1 / Chronic Stroke</td>
<td>Case study</td>
<td>Semi-immersive</td>
<td>Tele-rehabilitation for 16 sessions</td>
<td>Shoulder flexion/ Extension, exercise time, wrist displacement, Velocity, FM</td>
<td>Improvement in arm motor control</td>
</tr>
<tr>
<td>7</td>
<td>Saposnik et al. (2010) [2]</td>
<td>20 / Stroke</td>
<td>Pilot randomized clinical trial</td>
<td>Immersive</td>
<td>VR Wii versus recreational therapy</td>
<td>WMFT, BBT, SIS</td>
<td>VR Wii gaming is feasible, safe and efficient in stroke rehabilitation</td>
</tr>
<tr>
<td>9</td>
<td>Brutsch et al. (2010) [35]</td>
<td>10 / Different neurological gait disorders and 8 / Healthy controls</td>
<td>Comparative study (VR versus non-VR conditions)</td>
<td>Semi-immersive</td>
<td>Patients walked on the Lokomat in four different, randomly-presented conditions</td>
<td>Man-machine interaction forces, acceptance of the RAGT with VR was assessed using a questionnaire</td>
<td>No difference between VR and non-VR conditions</td>
</tr>
<tr>
<td>10</td>
<td>Bryant et al. (2006) [33]</td>
<td>10 / Spastic CP</td>
<td>Pre-post</td>
<td>Immersive</td>
<td>Ankle selective motor control exercises (VR) exercise system and conventional exercises</td>
<td>ROM, VAS</td>
<td>VR improved exercise compliance and enhance exercise effectiveness</td>
</tr>
<tr>
<td>11</td>
<td>Chen et al. (2007) [31]</td>
<td>4 / Spastic CP</td>
<td>Single-subject design</td>
<td>Semi-immersive</td>
<td>Individualized VR training program with 2 VR systems</td>
<td>4 kinematic parameters, PDMS-2</td>
<td>Improvement in the quality of reaching, especially in children with normal cognition and good cooperation</td>
</tr>
<tr>
<td>12</td>
<td>Deutsch et al. (2008) [34]</td>
<td>1 / Spastic diplegic CP</td>
<td>Case study</td>
<td>Semi-immersive</td>
<td>Wii sports games (Boxing, Tennis, Bowling and Golf)</td>
<td>Visual-perceptual processing, postural control and functional mobility tests</td>
<td>Positive outcomes at the impairment and functional levels</td>
</tr>
<tr>
<td>13</td>
<td>Qiu et al. (2009) [32]</td>
<td>2 / Spastic hemiplegic CP</td>
<td>Pre-post</td>
<td>Semi-immersive</td>
<td>Haptic Master, 6-degree of freedom, admittance controlled robot and a suite of rehabilitation simulations</td>
<td>AROM and strength, Melbourne Assessment of forward and lateral reaches, time of hand to mouth reach, Kinematic measurements</td>
<td>The feasibility of integrating robotics and rich virtual environments to address functional limitations and decreased motor performance</td>
</tr>
</tbody>
</table>

**JTHF**: Jebsen Test of Hand Function, **FM**: Fugl-Meyer, **FTHUE**: Functional Test of Hemiparetic UE, **IBT**: Box and Block Test, **SIS**: Stroke Impact Scale, **WMFT**: Wolf Motor Function Test, **RLA**: Rancho Los Amigos functional test of the hemiparetic UE, **SFQ**: Scenario Feedback Questionnaire, **FRT**: Functional Reach Test, **FAC**: Functional Ambulation Category, **RGS**: Rehabilitation Gaming System, **FIM**: Functional Independence Measure, **MMAS**: Modified Motor Assessment Scale, **VAS**: Visual Analog Scale, **B1**: Barthel Index, **MCI**: Motricity Index, **CAHAL**: Chedoke Arm and Hand Activity Inventory, **ADL**: Activity of Daily Living, **HPR**: Hand-Path Ratio (the quotient between actual hand trajectory and the straight-line distance between two targets), **RAGT**: Robotic Assisted Gait Training, **PDMS-2**: Fine Motor Domain of the Peabody Developmental Motor Scales-Second Edition, **ROM**: Active ROM.
and localization of the brain lesion: ischaemic stroke was a requisite in some studies [28], while patients with either ischaemic or haemorrhagic stroke were admitted in others [23,24]. On other researches, the main cause of stroke was an infarct of posterior capsule, left corona radiata of the posterior limb of the internal capsule and middle cerebral artery. Other studies did not describe the criteria of pathology [20,26,29].

Motor impairment was assessed in most cases by means of the Fugl-Meyer (FM) scale, with required moderate to severe or mild to moderate impairment [19-21,27,28]. Scores lower than 45 on the Box and Block Test functional scale (normality between 56 and 86) were required for admission to two studies [20,23].

In most of the studies, the inclusion criteria were active extension of the wrist above 20°, metacarpophalangeal extension of fingers above 10° [24,26], or elbow extension against gravity and Mini Mental Exam Score = 24.4) [20]. Fore rehabilitation of lower extremity (LE), the patient must have the ability to extend the knee more than 60°. The exclusion criteria common to most studies were severe cognitive or visuo-spatial impairment, neglect, language impairment incompatible with communication at the levels needed for VR rehabilitation [22,26,28], apraxia [23], tremor, spasticity (modified Ashworth Scale score more than 2) [22], other concomitant neurological disorders and depression [20].

The individual training sessions in the VR setup varied in duration from 20 minutes [19] to 1 hour [23], or 2-2.5 hours [20,25] to a maximum 3.6 hours [24] and were run 3 times [19], 4 times [20] or 5 times per week [25], with a full training programme lasting 2 weeks [23,24], 3 weeks [20,25], 4 weeks [28] or 6 weeks [26,27] or with the rehabilitation sessions distributed over a longer period of approximately 11-13 weeks [19]. On the other hand, other researches did not mention the details of treatment protocol [22,29]. The efficiency of training in VR has been assessed as reaching [20], speed, time needed to reach, grasping, placing [19,24,26], hand-path ratio reflecting superfluous movements or adjustment to movement [29], finger speed, fractionation (ability to move each finger independently), thumb and fingers range of motion [19,24,25]. No other treatment was reportedly associated. All study protocols had been approved by the appropriate ethics committee and all subjects had signed informed consent upon admission to the trial.

Mirelman et al [30] evaluated gait biomechanics after training with a VR system (semi-immersive VR six degree of freedom force feedback robot interfaced with VR intervention) in 18 hemiparetic patients after stroke by using kinematic and kinetic gait parameters. The training was performed three times a week for 4 weeks for approximately one hour each visit. Subjects in the VR group demonstrated a significantly larger increase in ankle power generation at push-off as a result of training. The VR group had greater change in ankle ROM post-training as compared to the non-VR group. Significant differences were found in knee ROM on the affected side during stance and swing, with greater change in the VR group. No significant changes were observed in kinematics or kinetics of the hip post-training.

Regarding the children with CP, Chen et al [31] used VR system with sensor glove to provide auditory and visual feedback for rehabilitation of upper extremity (UE). Qiu et al [32] used New Jersey Institute of Technology Robot-Assisted Virtual Rehabilitation (NJIT-RAVR) system (haptic master) which consisted of adaptive robotics with complex VR stimulation for rehabilitation of UE. On the other hand, children with spastic CP completed ankle selective motor control exercises using VR exercise system and conventional exercises [33]. Other studies used VR (wii gaming system with haptic feedback) for enhancement of visual perception, postural control and functional mobility [34].

The age at which the VR rehabilitation program could be applied with CP children varied in different studies. It was 6.3 years [31], 7 to 10 years [32], 7 to 17 years [33] and 13 years [34]. Most of children were spastic hemiplegia and spastic diplegia. Motor impairment was evaluated in most of studies by 4 kinematic parameters (movement time, path length, peak velocity and number of movement units) for mail-delivery activities in 3 directions (neutral, outward and inward) and Fine Motor Domain of the Peabody Developmental Motor Scales-Second Edition (PDMS-2) [31]. Upper extremity active range of motion and strength, (MAUULF), Melbourne Assessment including forward and lateral reaches, time of hand to mouth reach [32], range of motion (ROM) of ankle joint and Test of Visual Perceptual Skills, weight distribution, sway measures and gait distance [33,34].

For UE rehabilitation the children were included if they were able to follow verbal instructions in the reaching task, reach forward for more than half of their arm length and grasp a tennis ball with flexed fingers and if they had normal or corrected-to normal vision and hearing [31,32]. While for LE rehabilitation CP Children must have Gross Motor Functional Classification System (GMFCS) scores 7 of 1 or 2, indicating independent ambulation with or without an assistive device [33,34]. The exclusion criteria common to most studies were children received or
scheduled to receive surgery or botulinum toxin type A injections in the training arm or leg within the preceding 4 to 6 months or during the planned study period or if they had a severe attention deficit, as confirmed from their medical records.

The individual training sessions in the VR setup varied in duration from 60 minutes to 1.5 hours [32-34], to a maximum of 2 hours and were run 1 time [31], 3 times [32] or 5 times per week [20], with a full training programme lasting 3 [32] and 4 [31] weeks. Other researches did not mention the details of treatment demonstrating clearly that VR promotes greater motor recovery than the traditional physical therapy program protocol [33].

Brutsch et al. [35] compared the immediate effect of different supportive conditions (VR versus non-VR conditions) on motor output in patients and healthy control children during training with the driven gait orthosis Lokomat (semi-immersive VR system consisted of robotic assisted treadmill training (RAGT) with feedback devices). A total of 18 children (ten patients with different neurological gait disorders and eight healthy controls) took part in this study. They were instructed to walk on the Lokomot in four different, randomly-presented conditions: (1) walk normally without supporting assistance, (2) with therapists’ instructions to promote active participation, (3) with VR as a motivating tool to walk actively and (4) with the VR tool combined with therapists’ instructions. The authors concluded that active participation in patients and control children increased significantly when supported and motivated either by therapists’ instructions or by a VR scenario compared with the baseline measurement "normal walking". They stated that the VR scenario used induces an immediate effect on motor output to a similar degree as the effect resulting from verbal instructions by the therapists.

**DISCUSSION**

From the initial 860 articles retrieved by our search only 17 were kept after selection (1.98%). This probably means that our queries, especially in ACM were too broad. However, they seemed to gather all the articles available about the theme in the 5 databases. The efficiency of our queries was different. The most efficient one was the one we used on Pubmed (10 out of 410) and the least efficient was ACM (0 out of 860). Searching in ACM proved to be useless as no article was included in the study from that database. Searching IEEE proved to be unnecessary as the only final article found there was also found in Scopus and ISI.

This study demonstrates that from 1/1/2002 to 1/05/2010, the first 2 complete studies about the uses of VR in rehabilitation (article 1) was published only 2002. Since then, many studies have been published, 1 study in 2004, 1 study in 2005, 2 studies in 2006, 3 studies in 2007, 3 studies in 2008, 2 studies in 2009 and 3 studies in 2010. This probably reflects a growing interest in the potential of VR in terms of its health effects.

Studies concerning the use of VR in stroke rehabilitation are more organized, gathering groups and demonstrating clearly that VR promotes greater motor recovery than the traditional physical therapy program (articles 1 to 12 in Table 1). However, only 1 study out of 13 studies (7.69%) reported that there is no significant difference between VR and non-VR conditions (article 13 in Table 1). From all these 13 studies, 3 studies (23.08%) used non-immersive VR, 5 studies (38.46%) used semi-immersive VR and 5 studies (38.46%) used immersive VR program.

Regarding the use of VR in the rehabilitation of CP children, few studies were published. All the 4 reviewed articles (articles 14 to 17 in Table 1) reported the therapeutic effects of VR with such children in that VR could be used effectively in their motor rehabilitation. Three studies out of 4 studies (75%) used semi-immersive VR and 1 study (25%) used immersive VR program.

The available evidence supports the applicability of VR in the rehabilitation of the paretic arm and hand. A comprehensive scientific rationale and a pathophysiological understanding of the underlying mechanisms nevertheless remain to be investigated. The differences among studies in the criteria of evaluation of the kinetic or clinical outcome limit direct comparison among different VR setups and the training conditions to be favored in clinical practice or in research therefore remain unidentified.

The variety of available VR settings and subject-machine interfaces allow different degrees of the subject’s immersion in the virtual environment. However, the benefit-to-cost ratio of full immersive VR procedures has never been estimated in detail, with proper evaluation of the advantage of an artificial environment perceived as real and the incidence of collateral disadvantages, such as those defined as “cybersickness” (headache, nausea, vomiting, dizziness and unsteadiness) [16].

The main rehabilitation benefits derived from the reviewed articles included better hand performance, improvements of UE, LE and cognitive functions, recovery of the neuro-plasticity and locomotion, improvement of ADL and improved exercise compliance.
Systematic neuro-imaging research is today mandatory for the cortical functional re-arrangement to be correlated in full detail with the clinical effects of neuro-rehabilitation, irrespective of the applied rehabilitative procedures; it would allow documentation of cortical functional damage and efficacy of training. Rehabilitation needs to be carried out intensively over long periods of time and requires dedicated staff, resources and logistics. The duration of the rehabilitation effects after discontinuing VR training is crucial and should be determined in controlled follow-up studies [12,36]. The lack of the long-term efficacy of VR rehabilitation procedures could challenge physicians and physiotherapists.

Importantly, the loss of selective motor control may interfere with overall level of functioning even when other impairments are treated [37] since the underlying strength and coordination may be limited. There are no specific modalities to treat selective motor control but physical and occupational therapy in conjunction with a home program may improve selective motor control enough to affect functioning. Thus repetitive activities guided by a therapist or as in this case, a virtual environment and a continuation of repetitive activities in daily functioning may improve gross motor skills.

The degree of functional movement outcome achieved by therapy is often suboptimal since intensive therapy is limited by resource allocation and access. For many individuals, such as traumatic brain injury survivors, access to therapy is terminated once a level of function is achieved even if residual deficits remain. For other individuals, even when therapy is available such as during in-patient neurological rehabilitation, low levels of interaction between the patient and environment have been reported [38,39]. For example, Tinson [39] reported that individuals post stroke typically spent only 20-60 minutes per day in formal therapy. Common problems influencing the degree of interaction include boredom, fatigue, lack of motivation and lack of cooperation in attending therapy [40]. Clinicians agree that such problems are undesirable and restrict progress in rehabilitation. Increasing interaction is seen as vital to effective rehabilitation, a fact borne out by experimental studies of recovery after brain damage [41]. Development and incorporation of VR applications in rehabilitation may increase the possibility of stimulation and interaction with the world with potentially little or no increase on the demands of staff time. Virtual reality may provide interesting and engaging tasks that are more motivating than formal repetitive therapy.

**CONCLUSIONS**

Functional re-organization of the motor system after focal damage depends on substantial contributions from the undamaged motor cortex [42], as well as on early and intensive [43] motor training consistent with the subject’s potentialities [44]. Innovative technologies, such as VR are being tested for applicability in neuro-rehabilitation and their use in the treatment of the paretic UE, LE and gait abnormalities appears promising [16]. It is feasible to incorporate VR into rehabilitative hand training, even for individuals with severe hand impairment following stroke.

Virtual reality may have contributed to positive changes in neural organization and associated functional ambulation. Clinically, VR may be used as augmented chronic stroke rehabilitation.

The general experience of the VR application approach suggests that this intervention seems to be a promising tool in motor and cognitive rehabilitation, with a wide range of applicability. It can provide a real-time quantitative 3D task analysis and provides preliminary evidence that interactive computer use with the right training conditions may increase subjects’ motor and cognitive skills for both stroke patients as well as CP children.

Evidence from the literature has demonstrated the feasibility, usability and flexibility of video-capture VR and there is little doubt that this technology provides a useful tool for rehabilitation intervention.

Much work remains to be done to identify which type of patients will benefit from VR treatment, which system features are critical and what types of training routines will work best. However, a few findings appear to be solidly emerging from the VR work to date, as they have appeared repeatedly in multiple studies by different research groups. These findings are that: (1) patients with different disabilities appear capable of motor learning within the virtual environments; (2) movements learned in VR by patients with disabilities transfer to real world equivalent motor tasks in most cases and in some cases even generalize to other untrained tasks; and (3) when motor learning in real versus virtual environments was compared, some advantage for VR training has been found.

**REFERENCES**


