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**MINI REVIEW**

# VIRTUAL REALITY AND MOTOR REHABILITATION OF THE UPPER LIMB AFTER STROKE: A GENERATION OF PROGRESS?

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***Aim:*** **To review the rationale, criteria of application, potentialities and limits of the available procedures for upper limb rehabilitation in virtual reality setups.**
***Methods:*** **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.**
***Results and conclusion:*** **The studies completed to date support application of virtual reality methods in the treatment of the paretic upper limb after stroke, but the superiority of virtual reality methods in comparison with conventional procedures currently in use is still unproven. Larger samples, adequate controlled study design and follow-up, greater homogeneity in the selection criteria and parameters measuring severity of stroke, motor impairment and recovery are necessary.**

*Key words:* virtual reality, rehabilitation of upper limb, stroke.

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## INTRODUCTION

Functional re-organization of the motor system after focal stroke in adult primates depends on substantial contributions from the undamaged motor cortex (1), as well as on early (2) and intensive (3, 4) motor training consistent with the subject's potentialities (5, 6). An estimated 30–66% of patients do not achieve satisfactory motor recovery of the upper limb with current rehabilitative procedures (7), as early training usually focuses on the leg and trunk to allow hemiplegic subjects to stand and walk. Rehabilitation of the leg benefits from functional integration between the paretic and unaffected lower limbs. Conversely, the paretic upper limb is inhibited by the now-dominant contralateral arm. Constraint-induced movement therapy (CIMT) can compensate for this functional interference, but is poorly tolerated, and only strongly motivated patients accept its intensive training schedule (8). To date, rehabilitation of the paretic arm and hand remains, to a significant extent, challenging, and there is little agreement on the procedures to be followed.

Innovative technologies, such as advanced robotics and virtual reality (VR), are being tested for applicability in neuro-rehabilitation, and their use in the treatment of the paretic upper limb appears promising (9–11). Recently emerging experiences use a VR environment in combination with robotic devices to assist recovery of hand-arm function (12, 13).

VR defines a simulation of the real environment that is generated by dedicated computer software and can be experienced via a human-machine user-friendly interface (see Fig. 1 for a schematic outline). The rationale for its application in rehabilitation rests mainly on the hypothesis that some functional re-arrangement of the damaged motor cortex can be activated with the mediation of mirror neurones (10, 14) or through the subject's motor imagery (15). When exercising in a VR environment, subjects can monitor their movements and try to mimic the optimal motion patterns that are shown in real time in the virtual scenario. VR environments are interactive and can be manipulated to tailor individual treatments for movement (re)training. Motor impairment and recovery can also be measured and appropriate (visual, auditory or haptic) feedback of the movement efficiency with respect to the movement purpose can be provided (16–18). VR can also counterbalance adaptation and prevent boredom and therefore sustain attention by enhancing environmental diversity and

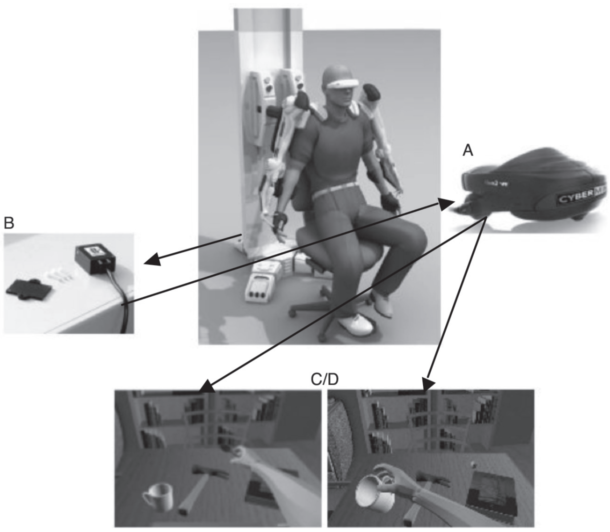


*Fig. 1.* Robotic and virtual reality setup designed for the rehabilitation of the upper limb after stroke. (A) Head-mounted display Visette 45 SXGA (Cybermind B.V., Maastricht, the Netherlands). (B) 3DOF visual tracking system. (C and D) Examples of interacting virtual environment as seen by the patient undergoing treatment.

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promoting the subject's interest (19). The approach altogether favours "learning by imitation" (10), and the complexity of the requested motor tasks can be progressively increased to facilitate transfer to the real world those motor patterns learned in the virtual one.

The potentialities and actual advantages of this "learn-and-transfer" approach are a matter of debate (10). There are indications of greater efficiency of VR training compared with conventional rehabilitation in patients with a neglect syndrome (20) or with walking disabilities (21), but generalized evidence is still lacking. The purpose of this review was to outline the rationale, criteria of application, and limits of the available procedures for upper limb rehabilitation in VR setups.

## REVIEW OF PATIENTS' SAMPLES AND METHODS

Comparison among studies is, to an extent, biased by heterogeneities among studies and the small size of most patients' samples (Table I). 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). 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 (22–25). Others have provided a non-immersive desktop display focusing on hand function and haptic feedback using a glove (26–29). Others have favoured semi-immersive VR with a haptic feedback device (30, 31) or immersive VR with video-projection onto a large screen and cyber-gloves (32).

The VR rehabilitative training began at least 6 months after stroke in most studies (22, 23, 25, 27–29, 31, 32); studies in the acute stage (within 3 months after stroke) are exceptional (24, 30). There was no consensus or agreement in the selection criteria for pathophysiology and localization of the brain lesion: ischaemic stroke was a requisite in some studies (24, 25), while patient with either ischaemic or haemorrhagic stroke were admitted in others (29, 31, 32). Damage had to be restricted to the cortex (i.e. the area supplied by the main cerebral artery) (24, 25), could include the thalamus and radiations (32), or could vary across subjects without pre-selected criteria of admission (23, 29). Motor impairment was assessed in most cases by means of the Fugl-Meyer (FM) scale, with required moderate to severe (22) or mild to moderate impairment (FM 30–60) (23–25). Scores lower than 45 on the Box and Block Test functional scale (normality between 56 and 86) were required for admission to one study (31). The inclusion criteria were derived from CIMT in some trials, with threshold active extension of the wrist above 20°, metacarpophalanx extension of fingers above 10° (27–29), or elbow extension against gravity (32). 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 (23–32), apraxia (24, 25), tremor (32), spasticity (modified Ashworth Scale score $>2$) (32), other

Table I. *Summary of studies analysed*

| Development VR groups | Author, year | Sample size/stage | Study design | Type of VR | Intervention | Outcome | Conclusions |
|---|---|---|---|---|---|---|---|
| MIT group | Holden et al., 1999 (22) | 2/chronic | Pre-post | Non-immersive | 16 sessions over 11–13 weeks | FM, SAILS | Little or no change in both patients |
| | Holden et al., 2002 (23) | 9/chronic | Pre-post | Non-immersive | 1 h/day, 3 days a weeks, 20–30 sessions | FM, WMFT | Significant difference in FM and WMFT |
| Rutgers group | Boian et al., 2002 (27) | 4/chronic | Pre-post | Non-immersive | 2 h/day, 5 days a week, 3 weeks | JTHF computerized measure | Significant difference in computerized measure of thumb range, finger speed, fractionation and JTHF |
| | Merians et al., 2006 (29) | 8/chronic | Pre-post | Non-immersive | 2–2.5 h/day, 13 days, 3 weeks | JTHF computerized measure | Significant difference in computerized measure of thumb range, finger speed, fractionation and JTHF |
| Swedish group | Broeren et al., 2004 (30) | 1/acute | Single case | Immersive | 1.5 h/day, 12 sessions, 4 weeks | PPT, dynamometer test | Significant difference in change scores in manual dexterity and grip strength |
| | Broeren et al., 2007 (31) | 5/chronic | Pre-post and follow-up | Immersive | 45 min/day, 3 days a week, 5 weeks | Outcomes kinematics, BBT, AMPS | Significant difference in motor performance. No difference in BBT and AMPS |
| Italian group | Piron et al., 2003 (24) | 24/acute | RCT | Non-immersive | 1 h/day, 5 days a week, 5–7 weeks | FM, FIM™ | Little difference between VR and conventional therapy groups in FM and FIM™ |
| | Piron et al., 2005 (25) | 50/chronic | Pre-post | Non-immersive | 1 h/day, 5 days a week, 4 weeks | FM, FIM™ | Significant difference in FM and FIM™ |
| Other group | Jang et al., 2005 (32) | 10/chronic | RCT | Immersive | 1 h/day, 5 days a week, 4 weeks | FM, BBT, MFT | Significant difference between VR and no therapy groups in FM, BBT and MFT |

AMPS: Assessment of Motor and Process Skills; BBT: Box and Blocks Test; FIM: Functional Independence Measure; FM: Fugl-Meyer Arm Scale; JTHF: Jebsen Test of Hand Function; MFT: Manual Function Test; MIT: Massachusetts Institute of Technology; PPT: Purdue Pegboard Test; RCT: randomized controlled trial; SAILS: Structured Assessment of Independent Living Skills; VR: virtual reality; WMFT: Wolf Motor Function Test.

concomitant neurological disorders, and depression (32). The individual training sessions in the VR setup varied in duration from 45 min (30, 31) to 1 h (23–25, 32), to a maximum of 2–2.5 h (27–29), and were run 2 (22), 3 (23, 31), or 5 times per week (24, 25, 27, 28, 32), with a full training programme lasting 3 (27–29), 4 (25, 32), or 5 weeks (24) or with the rehabilitation sessions distributed over a longer period of approximately 11–13 weeks (22). The efficiency of training in VR has been assessed as reaching (22, 23), speed, time needed to reach (24, 25, 30, 31), hand-path ratio reflecting superfluous movements or adjustment to movement (31), finger speed, fractionation (ability to move each finger independently), thumb and fingers range of motion (27–29). 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.

## EFFICACY

The Fugl-Meyer scale detected improvement in most patients whose VR training had begun at least 6 months after stroke, compared with those treated with conventional rehabilitation procedures (22–25, 32), whereas strength recovery was minimal in patients with recent stroke (24). The effect of VR training on motor disability was nevertheless less clear when the clinical outcome was assessed by functional scales, as these often differed among studies. Besides, some of the scales used in VR studies (e.g. the Structured Assessment of Independent Living Skills (SAILS), the Functional Independence Measure (FIM™), the Assessment of Motor and Process Skills (AMPS)) (22, 24, 25, 32) had been designed to assess the subject's autonomy in activities of daily living (ADL), while others measure hand skills (e.g. the Jebsen Test of Hand Function, the Wolf Motor Test (WMT), the Purdue Pegboard Test, the Box and Block test, the Manual Function Test (MFT)) (22, 23, 27–29, 31, 32). A significant improvement was observed in all studies measuring hand skills, while the effect of rehabilitation in VR was reportedly small (24, 25), negligible (22) or questionable when scales assessing functional autonomies were applied. Worsening was occasionally reported probably because the patient starts to manage their needs using the affected upper limb in ADL (31). The strength tests with a dynamometer (e.g. shoulder flexion or finger strength) (23, 27–29, 31) gave controversial indications of efficacy, that was unambiguously positive in some studies (23, 32) or inconsistent with other quantitative tests estimates (29). Patients trained by VR were compared with untreated patients in only one randomized controlled trial (32), in which the Fugl-Meyer Scale and Box and Block Test scores correlated to functional magnetic resonance imaging evidence of cortical re-organization. In these subjects, cortical activation increased ipsilaterally to the lesion and decreased contralaterally following intensive VR training; the observation is indicative of a proper compensation for the inhibition of the impaired arm by the dominant unaffected upper limb. Follow-up was reported in only a few studies, with observation varying from 20 (30) to 12 weeks (31), to few weeks after completing of the VR training (27, 29), to a 6 month follow-up of a patients' small subgroup (2 patients out of 8) (29). In all cases, the early improvement appeared transient, with a progressive trend over time toward the previous conditions. Cybersickness or other, related side-effects have never been reported. Instead, the VR training experience was described by most patients as being positive (25, 27, 30, 31). Informal reports have been supplemented and confirmed by formal tests assessing the subjects' satisfaction and psychological/physical stress during the VR training (29) or questionnaires about the perceived movement improvement after training (32).

## DISCUSSION

Although unsystematic, 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 favoured 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 collectively defined as "cybersickness" (headache, nausea, vomiting, dizziness and unsteadiness) (10). Two studies only were designed to include a control group. In one study (24), VR rehabilitation begun 3 months after stroke proved more efficient than conventional rehabilitation in a relatively large ($n=24$) patients' group, while untreated patients served as the control group in another study (32). There was greater homogeneity in the criteria of impairment evaluation, and the Fugl-Meyer Motor scale was widely used to derive inference on the efficacy of rehabilitation as well as to classify patients by severity. The negligible improvement, or even worsening, eventually identified by means of scales such as the FIM™, SAILS or AMPS (31) may reflect the subject's better perception of disability with the increased use of the rehabilitated arm in everyday activities after growing accustomed to relying on the unaffected one.

A scrutiny of studies applying VR procedures in upper limb rehabilitation emphasizes the lack of agreed criteria to assess kinematics and kinetic impairment in neurology (33). Systematic neuroimaging 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, which also remain unsystematic to date (29–31). This discrepancy contrasts with the increased availability of advanced technologies and the need for reliable criteria to help define cost/benefit ratios and priorities in private and public health facilities. In general, the scenario would motivate research to achieve widespread application with reduced costs, possibly by making home rehabilitation under remote control a realistic option and by extending the use of VR to people who are computer- or technologically- illiterate (35–37). In this respect, basing on the potentialities of this approach, the lack of the long-term efficacy of VR rehabilitation procedures could challenge physicians, physiotherapists and bio-engineers.

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