Functional improvement of hemiparetic upper limb after a virtual reality-based intervention with a tabletop system and tangible objects

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ABSTRACT

Rehabilitation of the hemiparetic upper limb after stroke is a common challenge for neurorehabilitation units. Recent advances in behavioural neuroscience and neuroimaging techniques have provided current insights of brain plasticity mechanisms that support the functional improvement after an injury to the brain. Different interventions have provided evidence of improvement associated to cortical reorganization. Initial studies report the benefits of virtual reality interventions to recreate enriched and controlled environments that promote brain plasticity mechanisms. This paper presents a novel virtual reality-based tabletop system that focuses on the motor learning principles to promote functional improvement of the hemiparetic upper limb in chronic individuals with stroke. The system allows users to perform a set of exercises that train different movements and skills interacting with or without tangible objects. A preliminary study to determine the clinical effectiveness and acceptance of a virtual reality-based intervention is provided.

1. INTRODUCTION

Upper extremity hemiparesis is the most common disability after stroke (Gresham et al, 1995). An injury to the brain involving the primary motor cortex and/or the corticospinal tract usually affect the voluntary control of the contralateral skeletal musculature. The result, depending on the extent and location of the lesion, is mainly paresis of the contralateral limbs. The mechanism of motor recovery after stroke may involve reorganization of the surviving networks (Takenobu et al, 2013), which take over functions that previously involved the affected tissues. Neuroplasticity, evidenced as the underlying neural mechanism of this reorganization, occurs as an endogenous process during the first weeks after the event due to different neural mechanisms (resolution of the diaschisis, rewiring, etc.) (Dancause et al, 2011). After this period of time, plasticity, though possible, must be driven externally. Even though this period is continuously being extended, it is commonly assumed that spontaneous recovery takes place within the first six months (Dobkin, 2004). However, thirty to sixty-six percent of subjects with stroke present functional disabilities related with the upper extremities after six months since the onset (Kwakkel et al, 2003; Stoykov et al, 2009). Thus, rehabilitation interventions are needed to maximize the functionality of stroke survivors in order to improve their self-dependence and wellbeing. There is no standardized protocol for upper limb rehabilitation after stroke. Throughout the years, different interventions have been presented, such as constraint-induced movement therapy (Corbetta et al, 2010; Wolf et al, 2010), mirror therapy (Invernizzi et al, 2013; Radajewska et al, 2013), or robotic therapy (Takahashi et al, 2008). Nowadays, there is evidence that physiological and anatomical changes are driven, among other factors, by sensory stimulation and skill acquisition (Nudo, 2006). Significant functional and structural changes have been observed in all sensory and motor areas as a result of the experience (Butefisch et al, 2000; Kleim et al, 2002). Nevertheless, reorganization is not driven by mere repetition but it only occurs when the experience implies learning (Dancause et al, 2011). Motor cortical plasticity is therefore learning or skill-dependent, and not simply use-dependent (Nudo, 2006; Grefkes et al, 2014). Consequently, motor rehabilitation should focus on driving plasticity by experiences that mean a challenge for the motor skills of the patients. In connection with this, Virtual Reality (VR) is a specially interesting research field since it allows to recreate computer-generated environments and provide customized experiences involving different sensory channels, commonly sight, hearing, and/or touch. The motivation of using VR in motor rehabilitation after a brain lesion is the administration of specific experiences to drive cortical reorganization that supports the reacquisition of motor skills. There is an increasing number of studies using VR for rehabilitation with promising results (Gil-Gomez et al, 2011; Laver et al, 2012; Llorens et al, 2012), most of them focusing on upper limb rehabilitation (Cameirao et al, 2012; Subramanian et al, 2013; Turolla et al, 2013). Even though the neural basis that supports VR interventions has been vaguely studied, initial studies report promising results (Jang et al, 2003; Saleh et al, 2011; Orihuela-Espina et al, 2013).

The objective of this study is twofold: to present a novel VR-based tabletop system for the rehabilitation of the hemiparetic arm that allows hemiparetic individuals to interact with a set of exercises designed to promote the motor learning mechanisms with their own movements or using tangible objects; and to determine the clinical effectiveness and acceptance of an experimental intervention using the system in a sample of chronic hemiparetic individuals post-stroke.

2. METHODS

2.1 Participants

All the stroke survivors who were attending a rehabilitation program and presented a residual hemiparesis from the lesion were candidates to participate in the study. Inclusion criteria were 1) age ≥ 35 and < 65 years old; 2) chronicity > 6 months; 3) absence of severe cognitive impairment as defined by Mini-mental state examination (Folstein et al, 1975) cut-off > 23; 4) able to follow instructions as defined by Mississippi Aphasia Screening Test (Romero et al, 2012) ≥ 45; 5) able to move the joints (proximal and distal) as defined by Medical Research Council Scale for Muscle (Paternostro-Sluga et al, 2008) ≥ 2; and 6) no increase or slightly increase in muscle tone as defined by Modified Ashworth Scale < 3. The exclusion criteria were 1) individuals with ataxia or any other cerebellar symptom; 2) orthopedic alterations or pain syndrome of the upper limb; 3) peripheral nerve damage affecting the upper extremities; and 4) individuals whose visual or hearing impairment does not allow possibility of interaction with the system.

2.2 Instrumentation

The VR-based rehabilitation system (UMBRELLA: upper limb rehabilitation lamp) consisted of a projective tabletop system that allowed multitouch interaction with the hands or via manipulation of tangible objects. Essentially, the system consisted of a depth sensor and a projector attached to the upper plane of a rigid frame (Figure 1.a). The sensor and the projector pointed down so that when the frame was placed on a table their field of view overlap on the surface of the table, thus defining an area of interaction (AOI) (Figure 1.b). The system projects a virtual environment (VE) on that area, which reacts according to the users' movements, mimicking the interaction with the real world. A standard computer generated the VE, tracked the movements of the user on the AOI, and modified the VE according to it (Figure 1.c). The hardware used in this experiment consisted of a Kinect™ (Microsoft®, Redmond, WA, USA), a computer Vostro 420 (Dell Inc., Round Rock, TX, USA) equipped with a QuadCore @ 2.83 GHz and 4 GB of RAM, and a LCD projector EB-1720 (EPSON, Suwa, NGN, Japan).

The interaction of the users within the AOI was detected from the depth information of the scene. In each exercise, the required movements of the upper limb segments, fingers, and tangible objects were tracked, and the interaction with the virtual objects was calculated to update the VE (Lloréns et al, 2012).

The exercises developed covered a wide range of hand and arm movements, mostly focusing on the flexion and extension of the elbow and the wrist (Table 1). The interaction with some exercises required tangible objects with different thickness to be grasped and moved by the participants. Exercises covered tasks that were likely to belong to the motor repertory of the participants (previous to the onset) and aimed to maximize the correlation with activities of daily living. Exercises provided audio-visual feedback while performing the task and showed information about the remaining time, the repetitions successfully completed, and the record previously achieved by the participant in the exercise. The difficulty of the exercises was determined by different parameters, which mainly adjusted the required speed, intensity, and accuracy of the movements. Before the intervention, the therapists defined different levels of difficulty of each exercise. When the success rate after a session was higher than 80%, the system automatically increased the level of difficulty. When the success rate was lower than 20%, the system decreased the level of difficulty.

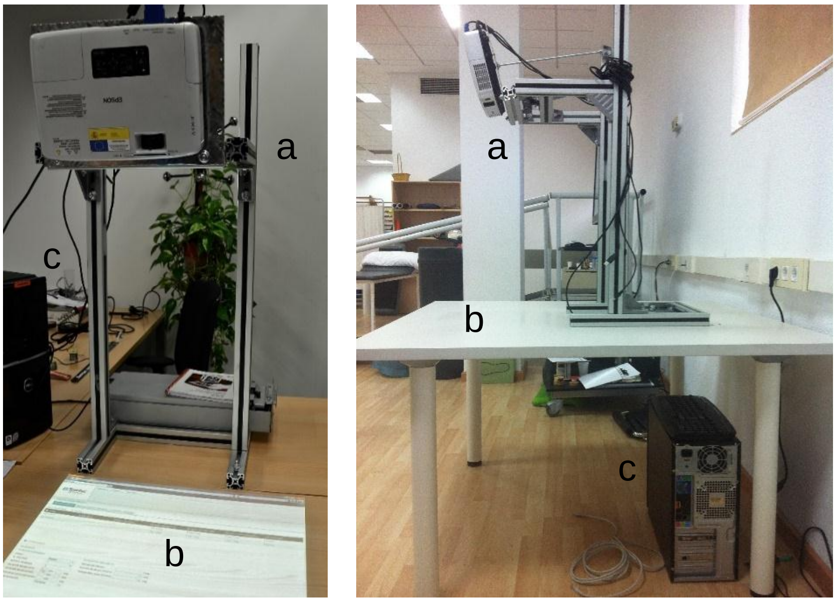
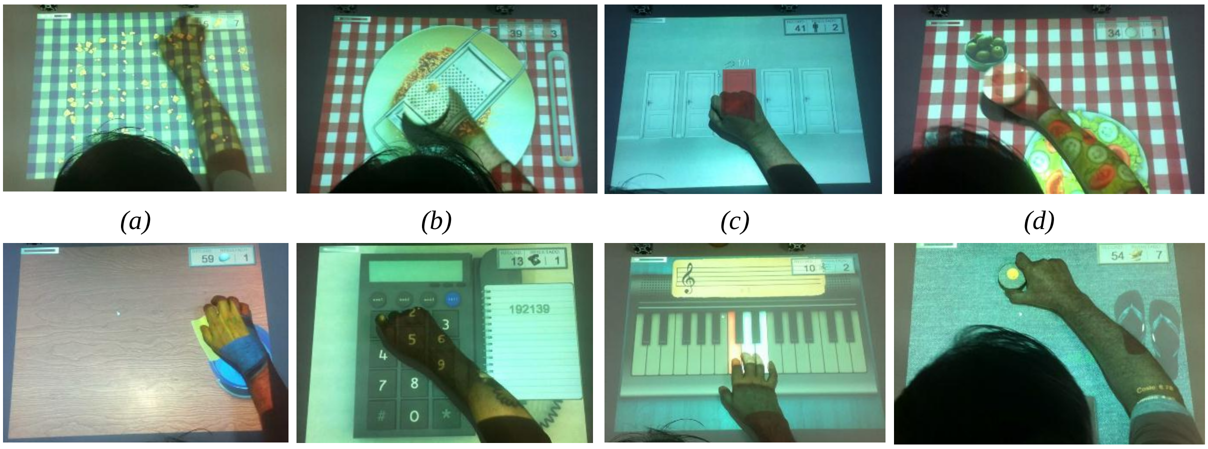


Figure 1. *Prototype of the UMBRELLA system.*

Table 1. *Equivalence of movements and exercises.*

Movement	Exercise
Flexion-extension of the wrist without involving the fingers	To sweep the crumbs from the table (Figure 2.a)
Grasping and flexion-extension of the wrist	To grate (Figure 2.b)
Flexion-extension of the wrist against gravity	To knock on doors (Figure 2.c)
Grasping involving flexion-extension of the elbow and rotation of the shoulders	To cook (Figure 2.d)
Flexion-extension of the metacarpophalangeal-interphalangeal joint	To squeeze a sponge (Figure 2.e)
Tapping	To dial a number (Figure 2.f)
Flexion-extension of the thumb, index, and middle finger	To play piano (Figure 2.g)
Pincer grasping with the thumb and index involving flexion-extension of the elbow and rotation of the shoulders	To buy ítems (Figure 2.h)


(a) *(b)* *(c)* *(d)*

(e) *(f)* *(g)* *(h)*

Figure 2. *Participant interacting with the UMBRELLA system.*

2.3 *Intervention*

The clinical trial was conducted through the specialized neurorehabilitation service of a large metropolitan hospital. All the participants who agreed to take part in the study and provided an informed consent were included in the clinical trial. Ethical approval for the study was granted by the Institutional Review Board at Hospitales NISA, Spain. An ABA design was chosen to determine the behaviour of the participants while undergoing the conventional therapy, the effect of changing the intervention, and the maintenance of gains after the experimental intervention. Phase A consisted of 30 training sessions of conventional physical therapy intervention, and phase B consisted of 30 sessions of an experimental intervention with the VR-based system. In both phases, the sessions were 45-minute long and were administered with a frequency of three to five days a week. A physical therapist supervised all the training sessions in all the phases. The intensity of both interventions was paired. No robotic therapy, electrotherapy, mirror therapy, motor imagery therapy, or constraint-induced movement therapy were administered during the clinical study.

The conventional physical therapy intervention included passive, active-assisted, and active-resistive joint mobilization, muscle toning (active or active-assisted movement in weightless conditions), strengthening, sensory retraining (Perfetti’s method), and manual dexterity exercises. Two two-minute breaks were allowed after 15 and 30 minutes of the beginning of the session. The difficulty of the training was determined by a physical therapist in a previous exploratory session. During the intervention, exercises gradually increased in resistance (weights) and in repetitions. The experimental intervention included the eight exercises described in Table 1 in randomized order. Duration of the exercises was set to five minutes each. Two-minute breaks were allowed after the third and sixth exercise. The difficulty of the experimental intervention was also initially determined in a previous exploratory session, and was automatically adjusted by the VR-based system during the intervention depending on the success rate of each participant within the exercises or by the physical therapist who supervised the sessions.

All the participants were assessed four times along the intervention: 1) at the beginning of the initial phase A (A_i); 2) at the end of the initial phase A, which was the beginning of phase B (B_i); at the end of phase B, which was the beginning of the second phase A (B_f), and at the end of the second phase A (A_f). The assessment protocol evaluated 1) the body structures, with the Modified Ashworth Scale (MAS) (Sloan et al, 1992); 2) the body functions, with a strength test with a dynamometer (ST) (van der Ploeg et al, 1991), the Motricity Index (MI) (Kopp et al, 1997), and the Fugl-Meyer Assessment Scale (FMAS) (Duncan et al, 1983); 3) the body activities, with the Manual Function Test (MFT) (Miyamoto et al, 2009), the Wolf Motor Function (WMF) (Woodbury et al, 2010), the Box and Blocks Test (BBT) (Mathiowetz et al, 1985), and the Nine Hole Peg Test (NHPT) (Oxford Grice et al, 2003); 4) the participation, with the subscales of Quality of Movement and Amount of Use of the Motor Activity Log (MAL-QOM and MAL-AOU, respectively) (Hammer et al, 2010), and 5) the usability of the experimental system, only assessed in B_f, with the System Usability Scale (SUS) (Bullinger et al, 1991), and with four subscales of the Intrinsic Motivation Inventory (IMI) (McAuley et al, 1989).

2.4 *Statistical analysis*

For each scale and test, scores in all the assessments were compared using repeated measures analyses of variance (ANOVAs). Post-hoc simple contrasts (Bonferroni) were conducted for each significant time main effect to determine the source of the significant difference. The α level was set at 0.05 for all analyses. All analyses were computed with SPSS for Mac, version 15 (SPSS Inc., Chicago, USA).

3. RESULTS

After inclusion/exclusion the final sample consisted of 11 participants. One participant was discharged of the neurorehabilitation program by the Public Healthcare System and dropped out. Consequently, his data are not included in the study. The characteristics of the participants are shown in Table 2.

Repeated measures analyses of variance (ANOVAs) at every assessment of the clinical trial revealed a significant time effect in most of the scales that assessed the body activities (WMF, BBT, and NHPT), and in the participation scale (MAL-QOM and MAL-AOU) (Table 3). With respect to these scales throughout the therapy, post-hoc analysis showed significant improvement after the experimental intervention (from B_i to B_f). However, this improvement was not detected after the previous (from A_i to B_i) or following conventional intervention (from B_f to A_f). No significant differences were detected in either the body structures or functions.

With regards the usability, scores of the SUS (79.58±8.99 from a total score of 100) and the subscales of the IMI (5.46±0.40 from a total score of 7) showed good acceptance of the experimental system.

Table 2. *Characteristics of the participants. Data are expressed in mean ± standard deviation when possible.*

Characteristic	**Value**
Sex (n,%)	
Male	8 (80 %)
Female	2 (20 %)
Age (years)	53.65±17.32
Chronicity (days)	273.90±97.13
Aetiology (n,%)	
Haemorrhagic	3 (30%)
Ischemic	7 (70%)
Hemiparesis (n,%)	
Right	6 (60%)
Left	4 (40%)

Table 3. *Characteristics of the participants. Data are expressed in mean ± standard deviation when possible. NS: no significance.*:p<0.05. **:p<0.01.*

Measure	**Start of phase A** (A_i)	**Start of phase B** (B_i)	**End of phase B** (B_f)	**End of phase A** (A_f)	**Significance**
Modified Ashworth Scale	0.60±0.65	0.60±0.65	0.60±0.65	0.60±0.65	NS
Dynamometer (kg)	31.80±14.64	31.20±14.17	32.80±14.66	32.80±13.73	NS
Motricity Index	74.60±9.08	75.60±8.17	77.80±13.17	77.80±13.17	NS
Fugl-Meyer Assessment Scale	51.00±6.65	51.40±6.06	52.30±6.39	52.40±6.82	NS
Manual Function Test	21.30±4.59	22.10±4.72	22.70±4.64	22.60±4.74	NS
Wolf Motor Function Test (s)	76.22±53.36	77.59±61.75	40.87±20.59	48.22±25.83	Bi>Bf*
Box and Blocks Test (blocks)	19.90±10.39	21.20±11.39	26.60±10.94	25.80±11.74	Ai<Bf** Ai<Af** Bi<Bf** Bi<Af*
Nine Hole Peg Test (s)	53.51±21.95	48.30±20.81	40.74±17.81	42.40±19.10	Ai>Bf** Ai>Af* Bi>Bf* Bi>Af*
Motor Activity Log – Quality of Movement	80.25±30.44	82.90±26.10	100.75±25.65	97.05±19.69	Ai<Bf** Ai<Af* Bi<Bf** Bi<Af**
Motor Activity Log – Amount of use	72.35±38.16	76.35±32.21	98.85±32.06	93.65±33.65	Ai<Bf** Ai<Af** Bi<Bf** Bi<Af**
System Usability Scale	-	-	79.58±8.99	-	-
Intrinsic Motivation Inventory	-	-		-	-
Interest/enjoyment			5.75±0.82		
Perceived competence			5.27±1.02		
Pressure/tension			1.96±0.60		
Value/usefulness			5.77±0.73		

4. DISCUSSION

The high incidence of hemiparesis after a brain injury and its uncertain prognosis make the rehabilitation of the hemiparetic upper limb a challenge for neurorehabilitation units. In the last decade new therapeutic approaches with proved effectiveness, as robotic-based interventions or constraint-induced movement therapy, have been reported and integrated in the motor rehabilitation protocols. However, the high cost of robotic-based devices and their space requirements limit their purchase to large neurorehabilitation units, and the constraint-induced movement therapy presents a low adherence in most patients (Page et al, 2002). Conventional rehabilitation programs include physical and occupational therapy interventions that can be not very motivating, intensive, or easy to replicate outside the clinical environment. This study analyses the effectiveness of a VR-based intervention in the functional improvement of the hemiparetic upper limb following a stroke. The experimental system is a transportable low-cost solution that provides intensive game-oriented exercises that can be configured to tailor interventions according to each patient's needs. These features are specially interesting since changes in motor cortical maps are only associated with an adaptation of the behavioural demands or skill acquisition, rather than with mere repetition (Nudo, 2006).

The experimental intervention provided improvement in the majority of the scales related to the activity of the hemiparetic upper limb, i.e. the WMFT ($p<0.05$), BBT ($p<0.01$), and NHPT ($p<0.05$), and to the participation, i.e. the MAL-QOM ($p<0.01$) and the MAL-AOU ($p<0.01$), with limited improvement in the body structures and functions. This improvement must be highlighted considering the chronicity of the sample. Interestingly, this fact could also explain the absence of changes in those scales that assessed the body structures and functions, as the muscle tone, the motor index, or the strength of the global mobility of the upper limb as measured by the Fugl-Meyer. Results showed improvement in the timed tests, the WMFT, the BBT, and the NHPT. An increase in the speed of task performance has been associated to greater improvements in chronic stages (Levin et al, 2009). The discrete nature of the MFT (scores of each item have discrete values ranging from 1 to 4) can explain that though the clinical improvements after the treatment, this improvement was not significant. The interaction with tangible objects allowed to recreate functional tasks involving not only proximal movements but also grasping and pincer grips. The specificity of these tasks could explain the maintenance of gains observed weeks after the experimental training.

Interestingly, the clinical improvement was also perceived by the participants, who reported the quantity (MAL-AOU, $p<0.01$) and quality (MAL-QOM, $p<0.01$) of the movement of their hemiparetic arm in the activities of daily living. These results are in accordance with the scores to the subjective questionnaires. The interaction of the participants with the system was successful, as reported by the SUS (usability and robustness) and the IMI (usefulness, competence, enjoyment, and low frustration). This could be promoted by some of the features of the system, such as the interface and the exercises. The ecological validity of the tasks (the exercises were designed to address activities commonly present in the motor repertory of the participants) within a natural interaction framework, both in manual tasks and in activities that required manipulation of tangible objects, could have led the participants to increase their confidence in the performance of activities of daily living, thus influencing the scores of the usefulness and the perceived competence subscales.

These results must be interpreted taken into account the limitations of the study. First, the sample was defined according to the requirements of the system. With regards to the motor domain, even though the VR-based system used a conventional table to remove the gravity (and to project the VE), participants were required to have enough mobility to move their hemiparetic arm by the table. In addition, the technological limitations of the system required the participants to be moderate to high functioning as they needed to robustly grasp objects in order them to be tracked. With regards to the cognitive domain, to understand the objective of the exercises all the participants were required to present a good cognitive condition, as defined by Mini-mental state examination > 23. Second, the sample of the study (n=10) can be considered as a small sample, which can limit the extrapolation of the results. Finally, the design of the study did not include a control group. In spite of this, the high chronicity of the sample (far from the initial stages where spontaneous recovery is assumed to occur) and the absence of remarkable improvements after conventional interventions with paired intensity and number of sessions, support the effectiveness of the intervention.

There is a great body of evidence of the motor improvement in chronic individuals post-stroke after specific interventions involving repetitive and intensive task-oriented exercises (Krakauer, 2006). This could support that VR-based interventions satisfying the motor learning principles may enhance the motor improvement in comparison with conventional interventions (Gil-Gomez et al, 2011; Laver et al, 2012). In addition, it is commonly accepted that the ceiling effect of some interventions can be caused by a physiological adaptation to the treatment. New therapeutic approaches, as the one presented here, can be a possible alternative for the motor rehabilitation of stroke individuals with independence of their chronicity.

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