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Computer-Guided Mental Practice in Neurorehabilitation

Andrea GAGGIOLI[a,b], Francesca MORGANTI[b], Andrea MENEGHINI[c], Ilaria POZZATO[d], Giovanni GREGGIO[d], Maurizia PIGATTO[c,d], Giuseppe RIVA[a,b]
[a]*Psychology Faculty, Catholic University of Milan, Italy*
[b]*Applied Technology for Neuro-Psychology Lab, Istituto Auxologico Italiano, Italy*
[c]*Advanced Technology in Rehabilitation Unit, Padua Teaching Hospital, Italy*
[d]*Padua University, Italy*

Abstract. Motor imagery is the mental simulation of a movement without motor output. In recent years, there has been growing interest towards the application of motor imagery-based training, or "mental practice", in stroke rehabilitation. We have developed a virtual reality prototype (the VR Mirror) to support patients in performing mental practice. The VR Mirror displays a three-dimensional simulation of the movement to be imagined, using data acquired from the healthy arm. We tested the system with nine post-stroke patients with chronic motor impairment of the upper limb. After eight weeks of training with the VR Mirror, remarkable improvement was noted in three cases, slight improvement in two cases, and no improvement in four cases. All patients showed a good acceptance of the procedure, suggesting that virtual reality technology can be successfully integrated in mental practice interventions.

Keywords. Motor imagery, mental practice, stroke, rehabilitation, virtual reality

1. Introduction

Motor imagery refers to the mental simulation of a motor act in the absence of any gross muscular activation [1]. The mental process of motor imagery has been investigated within different areas of research, such as cognitive psychology, neuroscience and sport psychology, sometimes with different terminology. In the context of athletic performance studies, a frequently used concept is *mental practice*. This term refers to a training technique by which a motor act is cognitively rehearsed with the goal of improving performance. It is important to distinguish this specific definition from the broader term *mental preparation*, which includes a variety of disparate sport psychology techniques that share a goal of enhancing performance, such as positive mental imagery, performance cues/concentration, relaxation/activation, self-efficacy statements, and other forms of mental training. A distinction also needs to be made between the "external" and "internal" perspectives in motor imagery. The external perspective, considered to be mainly visual in nature, involves a third-person view of the movement, as if watching oneself on a screen. The internal (or kinaesthetic) perspective, on the other hand, requires a subject to take a first-person view and to imagine the somesthetic feedback associated with action [2].

Recent studies in neuroscience have provided robust evidence that mental practice with motor imagery may induce plastic changes in the motor system similar to actual physical training [3, 4]. This supports the idea that mental training could be effective in promoting motor recovery after damage to the central nervous system. In this chapter, we first provide the rationale for using mental training in neurorehabilitation. Next, we describe results of a pilot clinical trial, in which we examined the technical and clinical feasibility of using virtual reality technology to support mental practice in stroke recovery.

2. Motor imagery

Scientific investigation of motor imagery dates back to 1885, when the Viennese psychologist, Stricker, collected the first empirical evidence that overt and covert motor behaviours involve the same processing resources [5]. Over the past thirty-five years, a number of studies have investigated this hypothesis further, by means of behavioural, psycho-physiological and neuroimaging methodologies. Overall, these studies have provided robust evidence about the existence of a striking functional similarity between real and mentally imagined actions.

2.1. Chronometric studies

Chronometric studies are based on the Mental Chronometry paradigm, which involves comparing real and imagined movement durations. In general, results of these studies indicate a close temporal coupling between mentally imagined and executed movement.

Decety and Michel [6] compared actual and imagined movement times in a graphic task. They found that the time taken by right-handed subjects to write a sentence was the same whether the task was executed mentally or physically. Also, subjects took approximately the same time, both physically and mentally, whether they wrote the text in large letters or in small letters. This observation suggests that the "isochronic principle", which holds for physically performed drawing and writing tasks, applies also to mentally-simulated motor tasks.

In another experiment, Decety and Jeannerod [7] investigated whether Fitt's law (which implies an inverse relationship between the accuracy of a movement and the speed with which it can be performed), applies also to imagined movements. These authors investigated mentally simulated motor behaviours within a virtual environment.

Participants were instructed to imagine themselves walking in a computer-generated three-dimensional space toward gates of different apparent widths placed at three different apparent distances. Results showed that response time increased for decreasing gate widths when the gate was placed at different distances, as predicted by Fitt's law. According to authors, these findings support the hypothesis that mentally simulated actions are governed by central motor rules.

The temporal correspondence between real and imagined motion is affected by moderating variables such as the type of motor task and the time of the day. Rodriguez and colleagues [8] asked a group of healthy subjects to perform or imagine a fast sequence of finger movements of progressive complexity. Findings showed real-mental congruency in relatively complex motor sequences (4 to 5 fingers), while in the simplest sequences (performed with 1 to 2 fingers) real-mental congruency remarkably decreased. The influence of the time of the day on real-mental congruency was investigated by Gueugneau and colleagues [9]. They found that the real-virtual isochrony was only observable between 2 pm and 8 pm, whereas in the morning and later in the evening, the durations of mental movements were significantly longer than the durations of real movements.

2.2. Psycho-physiological studies

Further evidence of the functional similarity between physical and imagined movements is provided by studies that have measured patterns of autonomic response during mental simulation of effortful motor actions. Decety and colleagues [10] measured cardiac and ventilatory activity during actual and mental locomotion at different speeds. Data analysis showed a strict correlation between heart and respiratory rates and the degree of imagined effort. For example, the authors found that the amount of vegetative arousal of a participant mentally running at 12 km/h was similar to that of a subject physically walking at a speed of 5 km/h. In another study, Decety and colleagues [11] analysed heart rate, respiration rate and muscular metabolism during both actual and mental leg exercise. During motor imagery, vegetative activation was found to be greater than expected from metabolic demands. The authors explained the additional autonomic activation as the involvement of central mechanisms dedicated to motor control, which anticipate the need for energetic mobilization required by the planned movement.

Bonnet et al. [12] investigated changes in the excitability of spinal reflex pathways during mental simulation and actual motor performance. In their experiment, subjects were instructed either to exert or to mentally simulate a strong or a weak pressure on a pedal with the left or the right foot. Modifications in the H- and T reflexes were measured on both legs by electromyography (EMG). Findings showed that spinal reflex excitability during motor imagery was only slightly weaker than in the reflex facilitation associated with the actual performance. A further interesting result of this study was that the lateralization and intensity of the imagined movement significantly modulated the EMG activity during motor imagery.

2.3. Brain imaging studies

A large body of recent research has investigated neural substrates underlying motor imagery by comparing the brain activation that occurs during mental and physical execution of movements. Taken together, results derived from these studies suggest that imagining a motor act is a cognitive task that engages a complex distributed neural circuit, which includes the activation of primary motor cortex (M1), supplementary motor area, dorsal and ventral lateral pre-motor cortices, superior and inferior parietal lobule, pre-frontal areas, inferior frontal gyrus, superior temporal gyrus, primary sensory cortex, secondary sensory area, insular cortex, anterior cingulate cortex, basal ganglia and cerebellum [13, 15].

The pattern of cerebral activation associated with motor imagery can be influenced by the level of motor expertise. Ross and colleagues [16] used fMRI to evaluate motor imagery of the golf swing of golf players with different handicap. Results showed activation of cerebellum, vermis, supplementary motor area, as well as motor and parietal cortices. Moreover, the authors found a correlation between increased handicap of participants and an increased number of activated brain areas. According to the authors of this study, increased brain activity may reflect a failure to learn and become highly automatic, or be related to a loss of automaticity with the need for compensatory processing.

A controversial point is whether different types of movement imagery (e.g., visual and kinesthetic) involve distinct neural networks. By using EEG, Davidson and Schwartz [17] observed different patterns of occipital and sensory motor alpha activity during kinesthetic versus visual imaging. In particular, visual imaging was associated with greater relative occipital activation. In a fMRI experiment, Guillot and colleagues [18] found that visual imagery was correlated with activation of the occipital regions and the superior parietal lobules, whereas kinaesthetic imagery yielded more activity in motor-associated structures and the inferior parietal lobule. These results suggest that, like physical motion, these two imagery modalities are mediated by separate brain systems.

2.4. Clinical neuro-psychology studies

Further evidence in support of the functional equivalence hypothesis comes from clinical neuropsychological studies, showing that motor imagery is not dependent on the ability to execute a movement but rather on central processing mechanisms. Impaired motor imagery was observed in patients with lesions in the parietal cortex [19] and in patients suffering from Parkinson's disease, which affects supplementary motor area, prefrontal cortex and basal ganglia [20, 22]. In those patients, movement velocity during both motor execution and motor imagery is slower compared to healthy controls; in contrast, patients with spinal lesions only show longer of motor execution times but the same duration of MI motor imagery [23].Reduced functional motor imagery was also identified in stroke patients with contralateral and premotor lesions, with particular reference to upper limb pointing and rotation tasks [24, 25].

Furthermore, it appears that both imagery accuracy and temporal coupling can be disrupted after a stroke, a phenomenon that has been defined by Sharma and colleagues [26] as "chaotic motor imagery".

3. Mental practice

In the previous section, we have reviewed evidence suggesting that the execution of mental and physical actions obey the same biomechanical constraints and share similar neuromuscular mechanisms. Another stream of research has investigated the effects of mental rehearsal on motor skill learning. Laboratory experiments involving healthy individuals have shown that motor learning can occur through mental practice alone, and that the combination of physical and mental rehearsal can lead to superior performance compared to physical practice only [27]. Positive effects of mental practice have been reported in a variety of motor tasks and for different outcome variables, including performance accuracy, movement speed and muscular force [28, 31].

Neuro-physiological studies have consistently shown that prolonged mental practice induce plastic changes in the brain which are similar to those resulting from physical training. Pascual-Leone and colleagues [3] used transcranial magnetic stimulation to examine patterns of functional reorganization of the brain after mental or physical training of a motor skill. Participants practiced a one-handed piano exercise over a period of five days. Results showed that the size of the contra-lateral cortical output map for the long finger flexor and extensor muscles increased progressively each day, and that the increase was equivalent in both physical and mental training.

Furthermore, both conditions produced performance improvements, although subjects in the physical practice group displayed greater learning. However, the addition of one physical training session allowed participants who practiced the task mentally to reach the same level of performance as those who practiced physically.

Jackson and colleagues [4] used positron emission tomography to examine functional changes associated with the learning of a sequence of foot movements through intensive mental practice. The improvement of performance determined by mental training was found to be associated with an increase in activity in the medial aspect of the orbitofrontal cortex (OFC), and a decrease of activity in the cerebellum. Data analysis also highlighted a positive correlation between the blood flow increase in the OFC and the percentage of improvement on the foot sequence task.

Sacco and colleagues [32] used fMRI to measure the activity of brain areas involved in locomotor imagery tasks (basic tango steps) at baseline and after one week of training consisting of combined physical and mental practice. Findings showed an expansion of active bilateral motor imagery areas during locomotor imagery after training. Moreover, these authors found a decrease in visuospatial activation in the posterior right brain, suggesting a decreased role of visual imagery processes in the post-training period in favor of motor-kinesthetic ones.

3.1. Factors affecting mental practice

Other mental practice studies have examined the conditions under which this approach is more effective. Driskell and colleagues [33] conducted a meta-analysis to determine the effect of mental rehearsal and different moderators on performance. The key factors highlighted by the review are summarized below:

- *Type of task*: mental practice seems to be more effective when the task to be learnt require cognitive or symbolic components/operations (i.e. make decisions, solve problems, generate hypotheses, p. 485);
- *Retention interval*: the effects of mental practice on performance become weaker over time. To gain the maximum benefits of mental practice, one should refresh training on at least a one- or two-week schedule (p. 489);
- *Experience level*: while experienced subjects benefit equally well from mental practice, regardless of task type (cognitive or physical), novice subjects benefit more from mental practice on cognitive tasks than on physical tasks (p. 488). Mental practice may be more effective if novice subjects are given schematic knowledge before mental practice of a physical task (p. 489);
- *Duration of mental practice*: the benefit of mental practice decreases with the training duration. To maximize learning outcome, an overall training period of approximately twenty minutes is recommended (p. 488).

The type of imagery modality (internal or external) used by the participant is another important variable to consider when defining mental practice protocols. Fery [34] found that in learning a new task, visual imagery is better for tasks that emphasize form, while kinesthetic imagery is more suited for those tasks that emphasize timing or fine coordination of the two hands. In another study, Hall and colleagues [35] highlighted that kinesthetic imagery is better for learning closed motor skills, whereas visual-based imagery is more effective for learning open motor skills.

4. Mental practice in neurological rehabilitation

In recent years, there has been growing interest towards the application of mental practice in rehabilitation. Studies have been reported on patients with different neuromuscular conditions, including Parkinson disease [36], spinal cord injury [37], and intractable pain [38]. However, the largest body of mental practice research has been conducted on stroke patients. Within these studies, the effects of combining mental and physical practice are usually compared with conventional treatment based on physical practice alone. In a recent meta-analysis, Zimmermann-Schlatter and colleagues [39] reported a positive (albeit modest) effect of combined mental and physical practice on stroke recovery, though the low number of randomized trials (four) prevented the authors from drawing firm conclusions about the effectiveness of this integrated approach.

Jackson et al. [40] proposed a model that describes the potential benefit of mental practice for rehabilitation. These authors suggest that on one hand, mental practice with motor imagery can be an effective means to access the otherwise non-conscious learning processes involved in a task. On the other hand, the absence of direct feedback from physical execution makes mental practice on its own a less effective training method than physical practice. Sharma and colleagues [41] conceptualized motor imagery as a "backdoor" to accessing the motor system after a stroke because "it is not dependent on residual functions yet still incorporates voluntary drive." (p. 1942). However, the use of this approach with brain-injured patients poses several practical issues. Patients can find the mental simulation task too overwhelming and difficult to understand. Also, neuropsychological evidence suggests that after stroke, motor imagery is not symmetrical, and motor imagery vividness is better when imagining movements on the unaffected than on the affected side [42]. Finally, it is not a simple task to instruct the patient to imagine movements using a first-person perspective (kinesthetic imagery), an approach that is believed to be effective for training fine motor skills [34].

Different strategies have been proposed to support brain-injured patients in executing mental practice on the affected limb [40, 43]. One such strategy involves the use of a mirror box apparatus [44]. In this approach, the patient is required to perform the movement to be re-trained with the non-affected arm in front of a mirror placed on the frontal-coronal plane and observe the resulting mirrored image. Then the patient is instructed to mentally simulate the movement he has just observed. One shortcoming of this approach, however, is that the use of a mirror requires the patient to split his attention between the movement executed with the healthy arm and its mirrored image, which enhances the cognitive burden of the task. Moreover, this approach does not permit recording of patient’s movements.

In an attempt to overcome these issues, we developed a non-immersive virtual reality prototype equipped with arm-tracking sensors, the “VR-Mirror” [45]. The VR-Mirror was designed to superimpose a virtual reconstruction of the movement registered from the non-paretic arm over the (unseen) paretic arm. This allows the patient to observe a model of the movement that has to be imagined. The objective of this strategy is to guide the patient in mentally simulating the movement to be re-trained by taking a first-person perspective (kinesthetic imagery).

5. Pilot clinical study

5.1. Subjects

Before starting the intervention, all patients signed an informed consent statement, in accordance with the guidelines of the institutional ethical review board, outlining their rights as experimental subjects. The following inclusion criteria were adopted:

- stroke onset between 1 and 6 years;
- no cognitive deficits (Mini Mental Status Examination > 24);
- age 18-80;
- no excessive spasticity or pain in the affected limb;
- completely discharged from all forms of physical rehabilitation;
- ability to perform mental imagery.

Nine patients who received an inpatient rehabilitation program matched eligibility criteria and were enrolled in the study. All patients had suffered an ischemic stroke resulting in a chronic hemiplegia. Clinical observations suggested that the patients' affected limb function had not improved since the time of discharge from the hospital. The mean time from stroke onset to enrollment in the study was 25.3 months (S.D. 14.6, range 13-96). A summary of demographics and clinical characteristics of the sample is presented in Table 1.

5.2. Neuropsychological assessment

Patients underwent neuropsychological assessment, which included the evaluation of communication and cognitive skills, memory, attention, visuo-spatial, and executive functions. Mental imagery ability was measured through the Vividness of Visual Imagery Questionnaire (VVIQ) [46], and the Mental Rotation Test [47]. In the VVIQ, the patient is asked to imagine different scenarios and rate the vividness of the images

Table 1. Demographics and clinical characteristics of sample

Patient ID	Gender	Age	Stroke onset (Mo)	Side of impairment	Hand dominance
VP	M	46	13	Right	Right
GT	M	68	24	Right	Right
MLR	F	61	27	Right	Right
LS	M	39	24	Left	Right
SS	M	57	20	Right	Right
RG	M	68	25	Left	Right
LL	F	63	96	Left	Right
TP	F	40	36	Right	Bilateral
PZ	M	27	14	Left	Left
Mean		52.1	31		
SD		14.6	25.3		
Range		27-68	13-96		

that are generated. The responses to all the questions can be summed to provide an overall score. The Mental Rotation Test is used to assess the ability to mentally rotate three-dimensional objects. The Vividness of Movement Imagery Questionnaire (VMIQ) [48] was used to test patient's ability to perform motor imagery. The VMIQ is constructed specifically to assess kinesthetic imagery ability, and contains 24-item scale consisting of movements that the subject is requested to imagine. The questionnaire includes a variety of relatively simple upper-extremity, lower extremity, and whole-body movements. The best score is 120, and the worst score is 24.

5.3. System

The VR Mirror consists of the following components (Figure 1):

- a retro-projected horizontal screen incorporated in a wooden table;
- a LCD projector with parallax correction;
- a mirror that reflects the projector beam onto the horizontal screen;
- 2 movement tracker sensors (Polhemus Isotrack II, Polhemus, Colchester,VT) positioned on patient’s hand and forearm;
- two sets of five buttons placed at the side of the screen;
- a personal computer equipped with a graphics accelerator.

The laboratory intervention using the VR-Mirror was integrated with a home-rehabilitation program making use of a DVD. The DVD stored prerecorded movies that showed the patient how to perform the motor exercises.

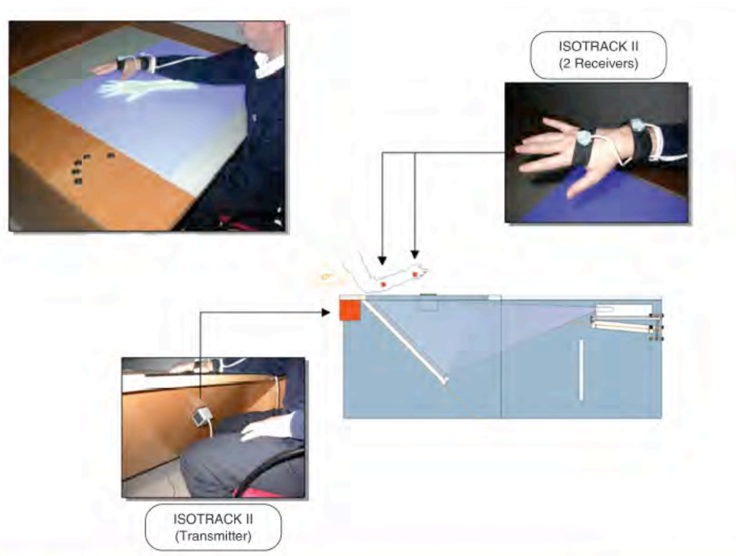

Figure 1. The Virtual Reality Mirror. Top left: the patient is performing the movement with the healthy arm during the registration phase. Top-right and bottom: positioning of sensors and structure of the prototype.

5.4. Intervention

The day-hospital rehabilitation protocol includes a minimum of two weekly sessions, for eight consecutive weeks. Each therapeutic session at the hospital included 1/2 h of standard physiotherapy plus 1/2 h of VR Mirror training. The treatment focused on the following motor exercises:

1) flexion-extension of the wrist;
2) supination/pronation;
3) flexion-extension of the elbow with assisted stabilization of the shoulder.

The training procedure with the VR Mirror consisted of the following steps. First, the therapist shows the patient how to perform the movement with the unaffected arm. When the patient performs the task, the system registers the movement and generates its mirrored three-dimensional simulation. Then, the virtual arm is superimposed over the (unseen) paretic limb, so that the patient can observe a model of the movement to be imagined. Next, the patient is asked to mentally rehearse the movement he has just observed, taking a first-person perspective. When the patient starts to imagine the movement, he presses a button (using his healthy hand), pressing it again when he has finished. This allows the therapist to measure the time the patient takes to imagine each movement exercise. Last, the patient has to perform the movement with the affected arm. During the execution of the physical exercise with the paretic arm, the system tracks the movement and measures its deviation from the movement performed with the non-paretic arm. Using this measurement, which is done in real time, the system provides the patient with audiovisual feedback describing his performance on the task. The feedback consists of a red bar chart, which changes its shape according to the precision of the movement. This procedure was repeated at least 5 times within each practice session for each target exercise.

In parallel to hospital-based treatment, patients were asked to practice home-based exercises using the DVD three times a week for one hour. The DVD stored pre-recorded movies showing the correct exercise to be performed. After viewing the movies, the patient was asked to take a first-person perspective and to imagine executing the movement with the impaired arm. The patient performed this sequence at home 3 times a week.

5.5. Evaluation

Patients were evaluated 4 times:

1) at the beginning of the hospital practice (baseline assessment);
2) four weeks after starting hospital practice (midterm evaluation);
3) eight weeks after starting hospital practice;
4) 12 weeks after the end of hospital practice (follow-up).

Primary pretreatment and post-treatment measures included the Action Research Arm Test (ARAT) [49] and Fugl-Meyer Upper Extremity Assessment Scale (FMA-UE) [50]. ARAT includes four domains (grasp, grip, pinch and gross motor) and contains 19 items. Each item is graded on a four-point scale with total score ranging from 0 to 60. Higher scores indicate better upper extremity function. The Fugl-Meyer Upper Extremity Assessment Scale is composed of 33 items, with total scores ranging between 0 and 66. Higher FMA-UE scores mean better motor function.

Functional outcome measures were integrated with health-related quality of life assessments to evaluate the impact of the treatment on patients' perceived well-being. The EuroQol (EQ-5D) [51] generic health measure was used for this purpose. This index consists of a five-part questionnaire and a visual analogue scale (VAS) that asks for an overall rating of the respondent's self-perceived health. The questionnaire describes states of health in five dimensions: mobility, self care, usual activities, pain or discomfort, and anxiety or depression. Each dimension comprises three levels (1=no problems, 2=some problems, 3=severe problems), and the respondent is asked to indicate his/her health state by choosing the most appropriate statement. The EuroQol VAS is similar to a thermometer and has endpoints of 100 ('best imaginable health state') at the top and 0 ('worst imaginable health state') at the bottom. Finally, patients were asked to keep a rehabilitation diary, in which they recorded their compliance with the home-based exercise program.

5.6. Results

Results of the pilot clinical trial are summarized in Table 2. A paired t-test was used to compare functional evaluation scores at baseline with follow-up assessments. Results showed no significant improvement of function as measured with the ARAT, and a quasi-significant difference in pre-post Fugl-Meyer scores (t=2,18; *p*<.06). However, a case-by-case analysis revealed a notable improvement in patients VP, TP and GT. In those patients, the score on both functional outcome measures increased throughout the eight weeks of treatment with no loss of improvement at follow-up evaluation. Measurements of wrist function revealed increases in range of motion during the first phase of intervention with no losses in movement range occurring after the laboratory intervention was completed. Moreover, these patients showed appreciable increases in grip strength for the affected right limb. Patients MLR and PZ, who were less severely affected, showed complete recovery of the functions assessed by the Fugl-Meyer scale but no further improvement in the ARAT scores. Furthermore, the analysis of the rehabilitation diary revealed that patient MLR regained the ability to paint, and that patient PZ reported feelings of enhanced dexterity and control on the affected limb.

Table 2. Functional assessment after treatment

ARAT	Baseline	4 weeks	8 weeks	follow-up
VP	12	26	29	29
GT	25	26	29	30
MLR	57	57	57	57
LS	0	0	0	0
SS	5	5	5	5
RG	0	0	0	0
LL	0	0	0	0
TP	20	24	28	28
PZ	60	60	60	60
Mean	19,9	22,0	23,1	23,2
SD	23,7	23,6	23,8	23,8
FUGL-MEYER	Baseline	4 weeks	8 weeks	follow-up
VP	20	34	36	36

GT	25	25	32	32
MLR	59	60	66	66
LS	10	10	10	11
SS	14	15	15	15
RG	6	7	7	7
LL	14	15	15	15
TP	0	2	5	5
PZ	54	54	58	62
Mean	19,1	24,7	27,1	27,7
SD	15,9	20,7	22,5	23,1

Patients LL, LS, SS and RG presented a more negative pattern of results. None of them showed improvement on the functional scales, and the effect of treatment on functional recovery was negligible. This result might be partially explained by the low compliance with the home-based exercise program that was reported by these patients in their diaries.

When practicing with the VR Mirror, patients were asked to press a button (with the healthy arm) in order to record imagined movement times (Figure 2). The analysis of these data did not reveal any significant correlation between real and imagined movement durations.

Despite post-treatment measures showing moderate gains in motor function, all patients reported increased well-being and reduced stress. A Wilcoxon signed-rank test revealed a significant pre-post difference for EuroQol VAS scores (W=28, $p < .02$). Furthermore, patients reported improvements of key health status dimensions, with particular reference to daily activities (t = 1.18, $p < .05$). In particular, patients MLR and PZ reported the achievement of remarkable gains in leisure, household and community tasks.

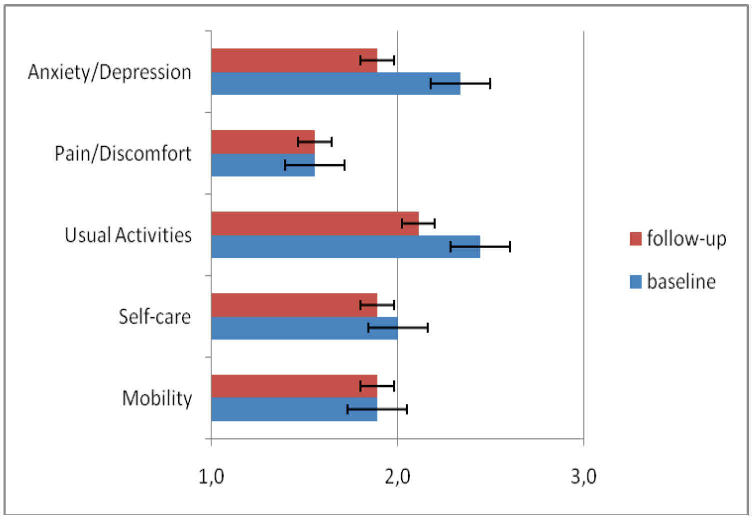

Figure 3. Mean EQ-5D scores for the five health dimensions (1= no problems; 3 = severe problems).

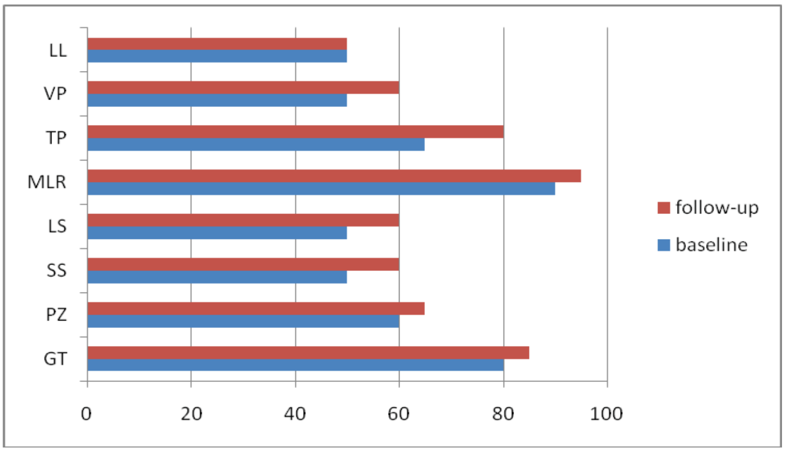

Figure 4. EQ-5D assessment of patients' own health status before and after treatment (0 = worst imaginable health state; 100 = best imaginable health state).

6. Conclusions

The main objective of this pilot study was to evaluate the technical and clinical feasibility of using virtual reality technology to support mental practice in neurorehabilitation. This strategy was tested in nine post-stroke patients with chronic motor impairment of the upper limb. After eight weeks of treatment, remarkable improvement was noted in three cases, slight improvement in two cases, and no improvement in four cases. The limited number of patients and the absence of a control condition did not allow us to draw any conclusion about the efficacy of this intervention. However, results showed a good acceptance of VR Mirror therapy by both patients and therapists, suggesting that virtual reality technology can be successfully integrated into mental practice interventions. A future goal is to define appropriate technology-based strategies for motivating patients to execute mental practice at home without therapist supervision.

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