Annual Review of Cybertherapy and Telemedicine

Volume 3 Year 2005 ISSN: 1554-8716

Interactive Media in Training and Therapeutic Intervention

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The Virtual Reality Mirror: Mental Practice with Augmented Reality for Post-Stroke Rehabilitation

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Abstract *The aim of the project is to apply augmented-reality technology to teach motor skills to patients suffering from stroke. To achieve this goal the project adopts an innovative approach based on the use of so-called "motor imagery." Recent studies in neuroscience have provided converging evidence that "imagining" a motor action involves the same brain areas involved in performing the action. This supports the idea – already exploited by sports trainers – that training with motor imagery (mental practice) could be effective in learning new motor skills or in promoting motor recovery after damage to the central nervous system. Previous clinical studies have shown that the rehabilitation of post-stroke hemiplegic patients can be made more effective by combining physical practice with mental practice. However, for many patients who suffer from damage to the central nervous system, mental simulation of movements can be difficult, even when the relevant neural circuitry has not been injured. Starting from these premises, we have designed and developed an augmented-reality workbench (called "VR Mirror") to help post-stroke hemiplegic patients evoking motor images. First, the movement is acquired by the system from the healthy arm. Second, the movement is being mirrored and displayed so that the patient can observe and see as if the impaired arm is performing the movement. Third, the patient is instructed to rehearse in his/her imagination the movement he/she has just observed. Last, the patient has to perform the movement with the affected arm. In this article, we describe preliminary results of a pilot clinical study, which has evaluated the feasibility of using technology-supported mental simulation as an adjunct in the rehabilitation of the upper limb following stroke. DESIGN: Single-case study. SETTING: Physical Rehabilitation Unit of Padua Teaching Hospital, Padua, Italy. SUBJECTS: A 46-year-old man with stable motor deficit of the upper right limb following stroke. INTERVENTION: The patient underwent a single-case design, with four weeks intervention. The intervention consisted of 3 practice sessions per week at the hospital using the VR-Mirror, in addition to usual therapy (Bobath method). This intervention was followed by 1-month home-rehabilitation program using a portable device. MAIN OUTCOME MEASURES: The patient was evaluated for level of impairment and disability. Pretreatment and posttreatment measures included: the upper-extremity scale of the Fugl-Meyer Assessment of Sensorimotor Impairment and the Action Research Arm Test. RESULTS: The patient showed improvement in upper limb score as measured by the two scales. CONCLUSIONS: The improvement observed in the patient is encouraging and warrants further study.*

INTRODUCTION

Hemiplegia is total paralysis of the arm, leg, and trunk on one side of the body. The paralysis presents as weakness that may be associated with abnormal muscle tone (e.g., rigidity or spasticity). The most common cause is stroke, which occurs when a rupture or blood clot reduces blood flow to a specific area of the brain, killing cells and disrupting the abilities or functions they control. Hemiplegia can be caused by damage to a variety of structures including primary sensorimotor areas, supplementary motor, premotor, and parietal cortices, basal ganglia and/or the thalamus.[1] Traditional rehabilitation after stroke focuses on passive (non-specific) movement or on compensatory training of the non-paretic arm. However, only a small percentage

(5–52%) of patients regain functional recovery of the upper extremity.[2] This observation may be related to the limited effectiveness of current therapy techniques used for improving upper limb function, and the very small percentage of the patient's day actually spent in upper limb intervention.[2] Clinical research has demonstrated that intensive, repetitive practice of active functional tasks shows more positive outcomes for upper limb rehabilitation (Langhorne et al, 1996). It has been suggested that these changes occur by modifying neural reorganization of the cerebral cortex.[3] In particular, there is evidence that the reorganization of the cortex may be stimulated not only by physical practice of the task, but also by mental practice of the task without any accompanying movement.[4]

Mental practice, also called symbolic rehearsal or motor rehearsal, is a training technique in which the subjects repeatedly "rehearse" a motor act in working memory, without producing any overt motor output.[5,6] In recent years, several clinical studies have described the contribution of motor imagery practice for improving upper limb motor function after stroke.[7-11] From a neuropsychological point of view, the benefit of mental practice would be to repetitively activate cerebral and cerebellar sensorimotor structures damaged by a stroke, thereby engaging compensatory networks to promote motor rehabilitation.[4,11] Recent neuroimaging experiments using positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) have shown that imagining a motor act is a cognitive task that engages parts of the executive motor system: in particular the supplementary motor area, premotor area, superior parietal lobule, and cerebellum.[4] Efferent discharges produced during imagery may also activate descending motor pathways. Motor imagery increases spinal reflex excitability at a level only slightly weaker than during movement, and corticospinal excitability is similar during imagery and movement.[12] However, for many patients with damage to the central nervous system, mental simulation of movements can be difficult, even when the relevant neural circuitry has been spared.[13] The goal of this project was thus to develop technology tools to assist patients in creating motor imagery. In the following section, we describe a pilot clinical study, which has evaluated the feasibility of using technology to assist patients in creating motor imagery. The rehabilitation protocol consists of an inpatient and an outpatient phase, combining physical and mental practice. In the inpatient phase, patient was trained in a laboratory setting, using a custom-made augmented-reality workbench (VR-Mirror). At the end of this phase, the patient used a portable display device to guide mental and physical practice at his home.

METHODS

Recruitment

Upon an appeal by the researcher to individuals who had been discharged from the rehabilitation setting, VP was the first volunteer who satisfied inclusion criteria for participation in the pilot experiment. VP was a 46-year-old man hospitalized from early November 2003 until end of February 2004 after an ischemic stroke with right hemiplegia.

Comparison between our observations at initial screening and medical records, discharge summaries, therapist observations, and physiatrist observations suggested that the patient's affected limb function had not improved since the time of discharge from the hospital. Before starting the intervention, VP signed an informed consent statement, in accordance with the guidelines of the institutional ethical review board, outlining his rights as a subject.

Neuropsychological assessment

VP was shown to have normal communication and cognitive skills, as measured by the Folstein *Mini-Mental State Examination*,[14] with his score of 28/30 falling within the normal range. The Mini Mental State Examination is a widely used standardized method by which to grade cognitive mental status. It assesses orientation, attention, immediate and short-term recall, language, and the ability to follow simple verbal and written commands. The patient's ability to image mentally was measured using the *Vividness of Visual Imagery Questionnaire*.[15] In the VVIQ patient is asked to imagine different scenarios and rate the vividness of the images generated. The responses to all the questions can be summed to provide an overall score. VP scored 75/80 on the VVIQ, showing good visual imagery ability. This result was confirmed by the positive performance on the Shepard-Metzler *Mental Rotation Test*, which measures the ability to mentally rotate three-dimensional objects.[16] The *Vividness of Movement Imagery Questionnaire*[17] (VMIQ) which is extensively used in sports, was used to test VP's ability to imagine prior to his engagement in motor imagery intervention. The VMIQ was constructed specifically to test kinaesthetic imagery ability (the ability to "visualize" and "feel" movement) and contains 24-item scale consisting of movements that the subject is requested to imagine. The questionnaire incorporates a variety of relatively simple upper-extremity, lower-extremity, and whole-body movements. The best attainable score is 120, and the worst obtainable score is 24. VP scored 120 on the VMIQ, showing good movement imagery skills. Further neuropsychological examination excluded motor apraxia, ideomotor apraxia, and ideational apraxia.

Testing of motor abilities

VP was tested 5 times: (1) 2 weeks before the first practice session (baseline assessment); (2) at the beginning of the intervention period; (3) 1,5 weeks after starting MI practice (midterm evaluation); (4) at the end of the intervention period; (5) 1 month after hospital practice termination. Further follow-up evaluations are scheduled 12 and 24 weeks after practice termination. VP was evaluated for level of impairment and disability. Pretreatment and posttreatment measures were the *Fugl-Meyer Assessment of Sensorimotor Impairment* (Fugl-Meyer Scale), and the *Action Research Arm Test* (ARA). The *Fugl-Meyer Scale*[18] has been used extensively as a measure of impairment in studies measuring functional recovery in patients with strokes. Its primary value is the 100-point motor domain, which has received the most extensive evaluation.[19] The specific items in the upper-extremity subsections were derived from the Brunnström stages of poststroke motor recovery. The upper-extremity motor component, which consists of 66 points, was used in this study. The *Action Research Arm* Test[20] is an outcome measure designed specifically for use with patients with strokes. The test is divided into 4 categories (grasp, grip, pinch, and gross movement), with each item graded on a 4-point scale (0=can perform no part of the test, 1=performs test partially, 2=completes test but takes abnormally long time or has great difficulty, 3=performs test normally) and a total possible score of 60.

Intervention

Based on VP's responses to the VMIQ, we determined that he was able to use both kinesthetic and visual forms of imagery equally well. Therefore, internal as well as external imagery scenes were applied in his intervention protocol. The intervention focused on the amelioration of specific impairments and on improving speed and precision. All inpatient practice sessions were conducted by the same medical professionals. The coordinator of the practice session is a physiatrist, specialized in Orthopedics and Traumatology, with over 25 years of clinical experience.

Inpatient phase: the Virtual Reality Mirror

The inpatient intervention consists of one daily session, three days a week, for four consecutive weeks. This time frame was chosen because according to available literature the majority of upper extremity rehabilitation programs last 4 to 6 weeks and because substantial improvement has been demonstrated after 4 weeks of imagery practice.[12] Each therapeutic session included ½ hour of traditional physiotherapy (muscle stretching and Bobath neuro-motor rehabilitation) plus ½ hour of VR-Mirror treatment. The treatment focused on the following motor exercises: 1) flexion/extension of the wrist; 2) prono-supination of the forearm; 3) flexion/ extension of the elbow with (assisted) stabilization of the shoulder. The apparatus used by the patients consists of a movement tracking system and a custom-designed visualization workbench that we call the *Virtual Reality Mirror*.[21] The VR mirror displays a 3D electronic image of the movement performed by the patient's healthy limb. This is viewed from an first-person perspective, which is supposed to facilitate the generation of kinesthetic motor imagery.[22] Each practice session with the VR-mirror was composed of four phases.

1. During the *pre-training phase* the patient receives instructions, which explain how the treatment works, encouraging the patient to relax and reducing performance anxiety.

2. In the next, *physical training phase* the therapist shows the patient how to perform the movement with the unaffected arm. When the patient then performs the task, the system tracks his arm and creates a 3D model of the movement.

3. In the next, *imagery training phase*, the patient is asked to create a mental image of the impaired arm performing the movement, as viewed from an internal perspective. When the patient starts to imagine the movement, he presses a button (using her healthy hand), pressing it again when he has finished. This allows the therapist to measure the time he takes to imagine each movement (RT). Basic research has shown that response times for physical and imagined movements are subject to common laws and principles[5]: comparing a patient's RTs, while imagining and physically performing the same movements, allows the therapist to statistically assess the quality of the patient's motor imagery.

4. After the patient has completed the mental rehearsal exercise, he is instructed to watch the display on the VR mirror (*virtual training phase*). The 3D model created earlier is used to generate a mirror image of the movement originally performed by the healthy arm. After watching the reflected limb on the screen, the patient is invited to physically perform the exercise, moving her arm in time with the mirror image (see fig. 1). During execution of the task, the system tracks the movement of the impaired arm, measuring the deviation between the movement the patient performs with the impaired arm and the "ideal" movement, as performed by the healthy arm. Using this measurement, which is performed in real time, the system provides the patient with visual feedback describing his performance on the task.

Home-based rehabilitation exercises

Home-based rehabilitation has the advantage that stroke patients can practice skills and develop compensatory strategies in the environment where they normally live.[23] In this protocol, the equipment provided is a Home Portable Device (a portable display) with multimedia capabilities (see fig, 2). The Home Portable Device displays a sequence of pre-recorded movies, picturing the movement to be trained. After viewing the movies, the patient is instructed to take a first person perspective and to imagine performing the task with the impaired arm. The patient performs this sequence three times a week.

RESULTS

The clinical assessment scores are listed in Table 1. Fugl-Meyer scores notable increased during the 4 weeks of intervention with modest increases during the 1 month follow-up. Action Research Arm Test scores consistently increased during the 4 weeks of intervention. There were 3-point increases during the 1 month follow-up. Moreover, the patient had appreciable increases in grip strength for the affected right limb. Measurements of wrist function revealed increases in range of motion during the first phase of intervention, with no losses in move-

Figure 1. Pictures of the Virtual Reality Mirror in action

Figure 2. The portable display used for the home rehabilitation mental imagery exercises

ment range occurring after the intervention was completed. VP was highly motivated throughout the intervention period and was present at all sessions. From the third week on, he reported on increase in self-confidence using the affected limb.

DISCUSSION

The purpose of this case report was to describe the implementation of technology-supported mental practice for improving motor performance in one individual with hemiplegia of the upper extremity following stroke. We found that mental training combined with physical training improved key measures of sensorimotor impairments and functional ability. Furthermore, these results were maintained (and even improved) at 1 month after home rehabilitation training, suggesting that home practice was useful. A rationale regarding the reason why mental practice with technology combined with physical practice seems to be effective can be found in the motor behaviour and neuropsychology literature. Jackson et al.[4] have recently created a model, comparing the potential therapeutic effects of mental practice with other forms of training. The model assumes that practice involves declarative knowledge, non-conscious processes and physical execution. In their model, declarative knowledge is the explicit knowledge that subjects need before practicing a motor task (i.e., a knowledge of the sequence of movements to be performed); skills that are not directly accessible to verbal description, such as the timing of motor responses to cues or the co-articulation of small segments of movement and the rapid, sequential activation or inhibition of different muscle groups are regulated by non-conscious processes; physical execution is the musculoskeletal activity necessary to carry out the intended action. According to Jackson and his collaborators, these different levels of processing interact in different ways in different forms of training. Physical practice involves all three levels of processing; in mental practice, on the other hand, learning depends crucially on the interaction between declarative knowledge and non-conscious processes: in physical practice it is possible to learn a motor task implicitly; in mental practice subjects have a good declarative knowledge of the different components of the task before they start practicing. The similarity between the circuitry involved in imagining and executing movements suggests, however, that the neuronal network implicated in the non-conscious aspects of a task can be primed as effectively through mental as through physical practice (p. 1138). In addition, the model predicts that internally driven images, promoting kinesthetic "sensations" of movement, could be highly effective in activating the non-conscious processes involved in motor training.

Test	**Baseline**	**Inpatient phase**			**Home rehabilitation phase**
		1 week	Midterm	4 weeks	1 month
Fugl-Meyer (upper limb motricity)	20/66	20/66	27/66	34/66	36/66
Action Research Arm Test	12/60	12/60	20/60	26/60	29/60

Table 1. Functional Improvements After Training

According to Jackson and his colleagues, this would explain why kinesthetic imagery is more effective than purely visual imagery. Their model proposes to conceptualize mental practice with motor imagery as a means to access the otherwise non-conscious learning processes involved in a task. They recognize, however, that the absence of direct feedback from physical execution makes mental practice on its own a less effective training method than physical practice.

In conclusion, results of this pilot study indicate that the stimulation of mental practice through the use of advanced visualization technology, combined with physical practice, leaded to functional gains in the paretic upper extremity of a patient with stable motor deficit of the upper right limb following stroke. Although a single-case study does not allow us to determine precisely the contribute of mental practice and which parameters of the training are most useful, a future goal is to systematically define the most efficacious protocol for each patient. Finally, randomized clinical studies are needed to assess whether this experimental protocol durably improves upper extremity motor function in hemiplegic patients and how these functional motor adaptations are mediated by central neural mechanisms.

ACKNOWLEDGEMENT

The present work was supported by the Commission of the European Communities (CEC), in particular by the IST programme (Project I-Learning, IST 2001-38861) and by the Italian Ministry of University and Research (MIUR) within the project FIRB-NEUROTIV.

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