A Strategy for Computer-Assisted Mental Practice in Stroke Rehabilitation

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Objective. To investigate the technical and clinical viability of using computer-facilitated mental practice in the rehabilitation of upper-limb hemiparesis following stroke. *Design.* A single-case study. *Setting.* Academic-affiliated rehabilitation center. *Participant.* A 46-year-old man with stable motor deficit of the upper right limb following subcortical ischemic stroke. *Intervention.* Three computer-enhanced mental practice sessions per week at the rehabilitation center, in addition to usual physical therapy. A custom-made virtual reality system equipped with arm-tracking sensors was used to guide mental practice. The system was designed to superimpose over the (unseen) paretic arm a virtual reconstruction of the movement registered from the nonparetic arm. The laboratory intervention was followed by a 1-month home-rehabilitation program, making use of a portable display device. *Main outcome measures.* Pretreatment and posttreatment clinical assessment measures were the upper-extremity scale of the Fugl-Meyer Assessment of Sensorimotor Impairment and the Action Research Arm Test. Performance of the affected arm was evaluated using the healthy arm as the control condition. *Results.* The patient's paretic limb improved after the first phase of intervention, with modest increases after home rehabilitation, as indicated by functional assessment scores and sensors data. *Conclusion.* Results suggest that technology-supported mental training is a feasible and potentially effective approach for improving motor skills after stroke.

Key Words: *Motor skill—Rehabilitation—Psychomotor performance—Virtual reality—Stroke—Upper limb.*

Mental practice (MP) with motor imagery (MI) is a training method that consists of mentally rehearsing a movement with the goal of improving performance.[1] In sport psychology, it has long been known that mental training can optimize the execution of movements in athletes and help novices in learning motor skills.[2] Recently, MP with MI has been applied in poststroke hemiparesis, with encouraging results.[3] This approach is supported by neuroimagery studies, which have shown similar neural networks associated with imagination and execution of a movement.[4] However, the use of mental training in rehabilitation poses practical issues. Although there is evidence that brain-injured, hemiplegic patients can retain the ability to mentally simulate movements they can no longer perform,[5] this task is cognitively demanding. To help patients in generating accurate motor images, Stevens and Stoykov used a mirror-box apparatus.[6] In this approach, patients move the healthy arm in front of a mirror, resulting in a reflection of the affected left limb moving successfully in space. Then, participants are asked to imagine the reflected limb is actually their limb moving. A second method suggested by these authors is to provide patients with movies depicting the motor exercises and instructing them to imagine the movement observed on the screen.[6]

The aim of the present case study was to evaluate the feasibility and the effectiveness of using computerized technology to guide MP in the rehabilitation of upper-limb hemiparesis following stroke. A custom-designed system was developed to superimpose over the (unseen) affected limb a virtual reconstruction of the movement, previously registered from the nonparetic arm. The objective of this strategy was to present the patient with a first-person perspective of the movement to be mentally simulated. After being trained with the visualization prototype, the patient used a commercially available portable display device to practice at home. The proposed approach is based on the hypotheses that 1) MP with MI can be facilitated using technology; 2) the inclusion of a home-rehabilitation phase can increase effectiveness of training; and 3) the use of visualization technology can reduce the need for skilled support, therefore improving the cost-effectiveness of training.[7]

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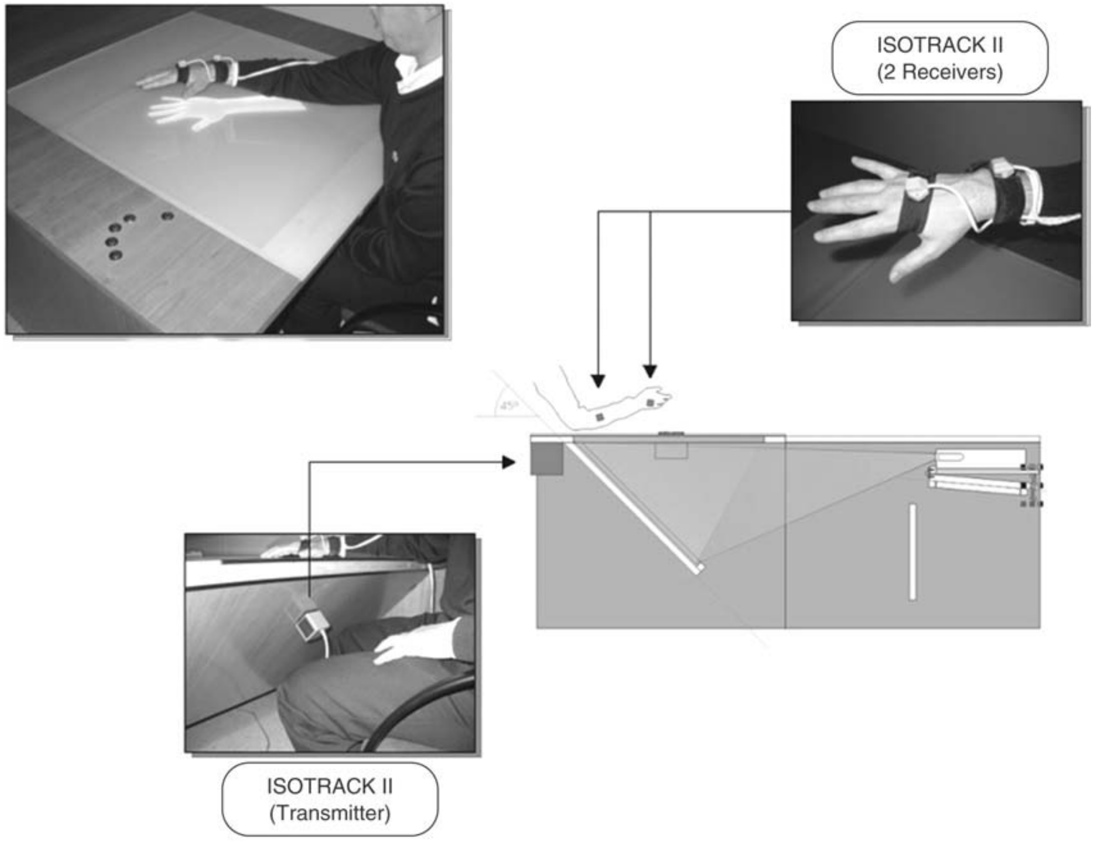

Figure 1. The custom-made visualization prototype. Top left: the simulated movement is displayed on the retro-projected screen. Bottom right: the internal architecture of the prototype. Also shown are the 2 movement-tracking sensors that are connected to the system.

METHODS

Subject

The institutional ethical board reviewed and approved the experimental treatment program. The participant was a 46-year-old who had suffered a right motor hemisyndrome for the upper limb owing to cerebral ischemia 13 months earlier. Incoming computerized axial tomography examination revealed a bilateral ischemic lesion in semioval centers. This neurological state was confirmed by 2 successive RMN examinations performed after 3 months and at treatment start. The patient was shown to have normal communication and cognitive skills, as measured by the Mini-Mental State Examination.[8] Memory, attentional, visuospatial, and executive functions were at average levels. The patient's mental imagery ability was measured through the Vividness of Visual Imagery Questionnaire,[9] the Shepard-Metzler Mental Rotation Test,[10] and the Comparison of Mental Clocks Test.[11] The Vividness of Movement Imagery Questionnaire[12] was used to test the patient's ability to imagine prior to his engagement in the motor imagery intervention. The patient showed preserved visual and movement imagery skills.

Materials

The custom-made visualization prototype is depicted in Figure 1. The system consists of the following components: a retroprojected horizontal screen incorporated in a wooden table; an 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); and a personal computer equipped with a graphics accelerator. For the home rehabilitation, the patient was provided with a portable display device. The portable display stored a sequence of prerecorded movies, picturing the movements to be trained, and audio instructions for the correct execution of the exercises.

Intervention

The 1st phase of treatment consisted of 1 daily session, 3 days a week, for 4 consecutive weeks. Each therapeutic session included 1/2 h of standard physiotherapy, plus 1/2 h of computer-facilitated training. The treatment focused on the following motor exercises:

Table 1. Functional Improvements after Training

Test	Baseline	Laboratory Training 1 Week	Laboratory Training Midterm	Laboratory Training 4 Weeks	Home Rehabilitation 8 Weeks
Fugl-Meyer (upper limb motricity) scores	20/66	20/66	27/66	34/66	36/66
Percentage of improvement	—	0	11	21	24
Action Research Arm scores	12/60	12/60	20/60	26/60	29/60
Percentage of improvement	—	0	13	23	28

1) flexion-extension of the wrist; 2) intra-extra rotation of the forearm; and 3) flexion-extension of the elbow, with assisted stabilization of the shoulder.

The training procedure with the visualization prototype consists 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 3-dimensional simulation. Then, the virtual arm is superimposed over the (unseen) paretic limb, so that the patient can observe and see as if the impaired arm is actually performing the movement. Next, the patient is asked to mentally rehearse the movement he has just observed, taking a first-person perspective (mental imagery response times are collected). 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 nonparetic 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 procedure was repeated 5 times within each practice session, for each target exercise. At the end of the laboratory training phase, the patient used the portable display device to practice at home. 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 for 4 consecutive weeks.

Testing

The patient was evaluated 5 times: 1) 2 weeks before treatment start (baseline assessment); 2) at the beginning of the hospital practice; 3) 1.5 weeks after starting hospital practice (midterm evaluation); 4) at hospital practice termination; and 5) at the end of home training. Pretreatment and posttreatment measures were the upper-extremity motor component of the Fugl-Meyer Assessment of Sensorimotor Impairment[13] and the Action Research Arm Test (ARA).[14] Performance was also evaluated through response times and sensors data. At the end of the treatment program, the patient was administered the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST)[15] to measure satisfaction with technology.

RESULTS

Fugl-Meyer and ARA scores consistently increased during the 4 weeks of intervention (respectively, 21% and 23% compared with baseline assessment, see Table 1), with modest additional increases during the 1-month home rehabilitation training. Measurements of wrist function revealed increases in range of motion during the 1st phase of intervention, with no losses in movement range occurring after the intervention was completed. Moreover, the patient showed appreciable increases in grip strength for the affected right limb.

Sensors data were analyzed to quantify performance changes during laboratory training. The motor exercise selected for this analysis was flexion-extension of the wrist. Performance on this task has been previously used as an index of upper-limb motricity improvement.[16]

In particular, we considered precision as an indication of exercise performance, comparing the movement performed with the paretic arm with the "correct" movement, previously registered from the nonparetic arm (Figure 2). This difference (position error) was calculated as follows:

$$Ed_t = \sqrt{(x_t - X_t)^2 + (y_t - Y_t)^2 + (z_t - Z_t)^2},$$

Where x_t, y_t, z_t are the spatial coordinates at time t of the sensor positioned on the patient's affected hand, and X_t, Y_t, Z_t are the spatial coordinates at time t of the sensor positioned on the patient's healthy hand.

The percentage of precision improvement for flexion-extension of the wrist was then calculated as the mean of the last 2 sessions of treatment minus the mean of the first 2 sessions, divided by the mean of the first 2 sessions; the resulting quotient was multiplied by 100. The result of this calculation indicated an 11% increase in precision after 4 weeks of intervention. MP response times were also collected during laboratory training.

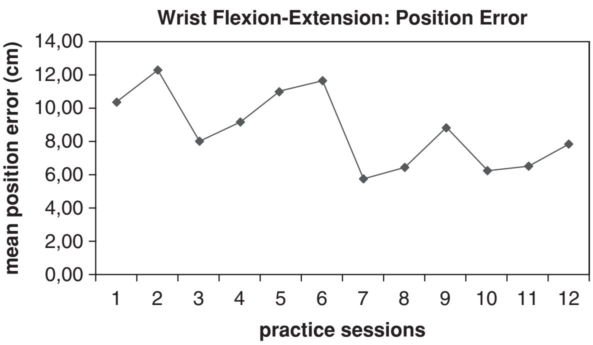

Figure 2. Position error profile for the wrist flexion-extension movement. Performance precision of this exercise improved over the course of training.

Regression analysis performed on these data failed to reveal significant trends, and no correlation was found between mental and physical execution with the affected arm. QUEST overall score was 4, suggesting that the patient found it easy to interact with the prototype.

DISCUSSION

The goal of this case study was to evaluate the technical feasibility and clinical effectiveness of using visualization technology to guide MP in stroke rehabilitation. We found that during 8 weeks of intervention, a patient 13 months poststroke with stable motor deficits at the upper dominant limb showed progressive reduction in impairment (as measured by the Fugl-Meyer Scale) and improvement in arm function (as measured by the ARA). This result is consistent with functional improvements observed in other mental training studies.[6,17] However, inasmuch as the design used in this study did not include a control condition, we were not able to assess the benefit of mental training and the contribution of computerized technology. For example, it is plausible that observation of simulated movement had direct beneficial effects at a neurophysiological level: A recent transcranial magnetic stimulation study on healthy subjects has shown that the excitability of the primary motor cortex (a process involved in the induction of neuroplasticity) is facilitated by viewing a mirror reflection of the moving hand.[18] Another feature that may have contributed to the functional improvement observed is that the patient executed bilateral movements: Practicing the exercise with the healthy arm during the registration phase may have resulted in a facilitation effect from the nonparetic arm to the paretic arm.[19] Finally, physical exercise performed with the affected arm may have played a role. Repetitive training of specific movements in isolation has been shown to promote motor recovery.[20]

A further criticism may concern the use of sophisticated technologies instead of a simple mirror. We argue that the added value of this approach is provided by 3 key features: 1) the use of a mirror requires the patient to perform and observe the movement simultaneously, whereas our approach allows the patient to focus only on the simulated movement, potentially reducing attentional load; 2) the use of arm-tracking sensors makes it possible to compare movements of the healthy and the affected arm, providing performance feedback to the patient—a key requirement for effective motor learning; 3) motor exercises can be made more engaging by displaying background images on the screen.

A future goal is to assess whether MP with an apparatus is better that MP without the system, as well as to identify the best way to introduce technology-supported mental training into current practice.

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