Virtual Environment Training Therapy for Arm Motor Rehabilitation

Abstract

Enhanced feedback provided by a virtual reality system has been shown to promote motor learning in normal subjects. We evaluated whether this approach could be useful for treating patients with motor deficits following brain lesions. Fifty subjects with mild to intermediate arm impairments due to stroke were selected for the study. The patients received treatment daily for one month, consisting of an hour of virtual-environment therapy with enhanced feedback. Before and after the therapy, we assessed the degree of motor impairment and autonomy in daily living activities using the Fugl-Meyer scale for the upper extremities and Functional Independence Measure, respectively. We also analyzed the velocity, duration, and morphology of a sequence of reaching movements, finally comparing the kinematic measures with the scores obtained on the clinical scales. The rehabilitation therapy yielded significant improvements over baseline values in the mean scores on the Fugl-Meyer and Functional Independence Measure scales. The mean Fugl-Meyer score correlated significantly with the duration and velocity of reaching movements. The collated data indicate that motor recovery in post-stroke patients may be promoted by the enhanced feedback provided in a virtual environment and that kinematic analysis of their movements provides reliable measures of motor function changes in response to treatment.

1 Introduction

The long-term and diffuse structural and functional changes that may take place in the cortical tissue spared by a neurological lesion have been demonstrated to provide the neurophysiological basis for a patient’s recovery (Nudo, 1999). These findings have had a major impact in the field of neurorehabilitation and may lead to the development of science-based therapies. For the time being, the proposed therapeutic strategies encompass very different approaches that include the use of drugs for enhancing natural recovery mechanisms (Goldstein, 1998), constraint-induced movement therapy for correcting the learned non-use of the damaged arm (Taub et al., 1993), treadmill training with partial body-weight support to favor gait recovery (Hassid, Rose, Commisarow, Guttry, & Dobkin, 1997), and sensory stimulation techniques to enhance brain plasticity (Fraser et al., 2002; Johansson, 2000).

Although little is known about the mechanisms by which therapeutic measures influence motor recovery, some neurophysiological studies on healthy subjects have reported that appropriate feedback on the nature of the move-
moment pattern (knowledge of performance) and some variables of outcome (knowledge of results) may help to temporarily or permanently improve motor performance (Gentile, 1972; Khan & Franks, 2000; Newell & Carlton, 1987; Young & Schmidt, 1992; Woldag & Hummelsheim, 2002).

In this regard, computer-based systems can provide subjects with artificially enhanced feedback that may facilitate the acquisition of new motor skills. Todorov and coworkers reported that subjects trained in a virtual environment with enhanced feedback performed a new, complex, multi-joint motor task better than those trained with conventional methods (Todorov, Shadmehr, & Bizzi, 1997). Preliminary reports have indicated that a virtual-reality (VR) based therapy improves upper-limb motor performance in the chronic phase after stroke (Todorov et al.; Holden, Todorov, Callahan, & Bizzi, 1999; Piron, Dam, Trivello, Iaia, & Tonin, 1999; Merians et al., 2002), though these positive results were based on only a small sample of stroke patients. Given these premises, our aim was to assess whether late rehabilitative therapy using a VR system (virtual environment training therapy, or VET therapy) that exploits certain neurophysiological mechanisms for motor learning in normal subjects, could be usefully applied to a larger sample of post-stroke patients with arm impairments.

2 Materials and Methods

2.1 Setup

The VET therapy equipment consisted of a PC workstation, a high-resolution LCD projector (1200 Ansi-Lumen), a wall screen, a 3D motion-tracking system (Polhemus 3Space FasTrak, Vermont, U.S.A), dedicated software and simple manipulable objects, such as an envelope, a ball, a polystyrene cube, or a plastic glass.

The PC workstation was a Pentium IV 1.2 GHz processor, with 256 MB of RAM, a 32 MB video card and a graphic accelerator.

The features of the FasTrak system were: static accuracy of the position signal 0.76 mm RMS and 0.15 degrees RMS for orientation; resolution of 0.0005 cm/cm and 0.025 degree/degree of range; latency of 4 ms un-filtered from the center of the receiver measurement period up to the beginning of the transfer from the output port. The sampling rate was 120 Hz divided by the number of receivers.

The software was developed at MIT; it created the virtual environment and converted the receiver 3D raw data into a virtual representation of the motion displayed in the wall screen.

2.2 Methods

The subject was asked to perform a motor task, that is, grasping an object, which represented the final part of the entire biomechanical arm system (or end-effector).

A 3D magnetic receiver was positioned on the end-effector (a manipulable object) to continuously record its motion. In the case of a severe grasping deficit, the magnetic receiver was attached to a glove worn by the patient. See Figure 1.

Before treatment, the therapist created the virtual motor tasks by moving the object in order to generate arm skills represented in the VE. Examples of VE motor tasks are: putting the envelope in the mailbox, breaking eggs, moving a glass over a table, placing a ball in a basket, and so on. The therapist selected the characteristics and complexity of the motor tasks to suit each patient’s arm deficit. In the virtual scenario, the therapist determined the starting position and the target of the skill, such as target orientation or the addition of other virtual objects to increase the task’s complexity. Some tasks could be accomplished by a simple reaching movement, while others required more complex movements. See Figure 2.

During the VET therapy, patients were asked to perform motor tasks that emulated the therapist’s (pre-recorded) movement, as displayed in the virtual environment. The trajectory of the therapist’s movement could also be displayed in the background of the virtual scene. This setting facilitated the subject’s perception and adjustment of motion errors, according to task constraints specified beforehand by the therapist.

After each virtual motor task had been completed, the therapist could show the resulting trajectories to the patient.
2.3 Patients

Among 310 stroke patients evaluated at our rehabilitation center from January 2001 to December 2002, 50 were selected who had suffered a single ischemic stroke in the region of the middle cerebral artery at least six months before the study. All patients had received conventional physical therapy in the early period after their stroke. These subjects were suffering from mild to intermediate motor impairments of the arm (i.e., on the Fugl-Meyer scale for the upper extremity [Fugl-Meyer UE], subscores ranged from 30 to 60) from 60 (mild) to 30 (intermediate) despite prior rehabilitation therapy (Fugl-Meyer, Jaasko, Leyman, Olsson, & Stegland, 1975). Clinical history or evidence of cognitive impairments, neglect, and apraxia or aphasia interfering with verbal comprehension were all considered exclusion criteria. The demographic characteristics of the 50 patients joining the rehabilitation program are summarized in Table 1.
The study lasted four weeks and consisted in daily one-hour treatment sessions, five days a week. This protocol was approved by the local Ethical Committee and written consent was obtained from all participants.

Before and after VET therapy, the degree of motor impairment and independence in activities of daily living (ADL) were evaluated with the Fugl-Meyer UE score and the Functional Independence Measure scale (FIM) (Fugl-Meyer et al., 1975; Keith, Granger, Hamilton, & Sherwin, 1987). At the same evaluation times, we determined the mean duration (s), mean velocity (cm/s), and morphology of 20 consecutive reaching movements.

The Fugl-Meyer UE score ranges from 0 (arm completely plegic) to 66 (normal); the FIM scale goes from 18 (totally dependent in ADL) to 126 (absolutely independent in ADL).

The examining neurologist was blind to the treatment administered to the patients.

The Wilcoxon test was used to determine the statistical significance of any differences in mean Fugl-Meyer UE score, mean FIM scale score, and mean duration and velocity of reaching movements before and after the therapy.

The Mann-Whitney U test was used to analyze the significance of any differences in measured outcomes among the patient subgroups, divided according to age, stroke-to-rehabilitation interval, level of motor impairment, and side of stroke.

Correlation analysis (Spearman’s ρ) was used to assess the relationship between the duration and velocity of reaching movements and the Fugl-Meyer UE and FIM mean scores.

Statistical significance was set at \( p \leq .05 \).

### 3 Results

Of the 50 patients who entered the study, 5 dropped out for reasons unrelated to the therapy. None reported any side effects due to interaction with the virtual environment, for example, reduced binocular vision, dizziness, disorientation, nausea, or headache.

As shown in Table 2, enhanced-feedback therapy significantly improved the Fugl-Meyer UE mean score by 15% and the FIM mean score by 6%. Moreover, the mean duration and mean velocity of reaching movements improved by 18% and 23%, respectively.

The duration and velocity of the movements correlated significantly with the Fugl-Meyer UE scores before (duration: \( ρ = -0.729, p \leq .01 \); velocity: \( ρ = 0.726, p \leq .01 \)) and after VET therapy (\( ρ = -0.795, p \leq .01 \); \( ρ = 0.798, p \leq .01 \)), but not with the FIM scores before (duration: \( ρ = 0.027, p \leq .05 \); velocity: \( ρ = 0.024, p \leq .05 \)) and after VET therapy (\( ρ = 0.043, p \leq .05 \); \( ρ = -0.056, p \leq .05 \)). Furthermore, the reaching trajectories, which had been irregular and scattered at the beginning of the treatment, came after training to resemble the appropriate and linear movements performed with the unaffected arm. See Figure 3.

Table 3 shows the effects of VET therapy with enhanced feedback on the damaged arm’s motor function in different subgroups of post-stroke patients. Fugl-Meyer UE mean scores improved respectively by 14% and 16%, in older and younger patients, by 12% and 18% in cases whose stroke-to-treatment interval was below and above 12 months, by 14% and 15% in left- and right-stroke patients, and by 21% and 8% in subjects with more and less severe deficits. As shown in Table 4, VET therapy positively affected FIM mean scores, but to a lesser extent than the Fugl-Meyer UE scores. In particular, the FIM mean score improved respectively by 6% and 8% in older and younger patients; by 10% and 3% in those with a stroke-to-treatment interval below
and above 12 months; by 8% and 5% in left or right-stroke patients; and by 4% and 11% in cases with more and less severe deficits.

4 Discussion

In the context of conventional rehabilitation after stroke, it is still impossible to say whether a given treatment yields a greater benefit than others, and no studies have shown to what extent any recovery is due to specific rehabilitation strategies (Johansson, 2000; Ernst, 1990). In this intricate field, it is genuinely difficult to recognize a reference physiotherapeutic technique, making it all the more important to consider the effectiveness of new science-based therapeutic methods.

The goal of this study was consequently not to compare different rehabilitation techniques, but to ascertain whether late therapy based on providing a continuous visual information flow on the appropriateness of a patient’s action vis-à-vis the ideal movement can help post-stroke patients in the process of arm function recovery. This kind of feedback has proved useful for motor learning in normal subjects. Its use as a rehabilitative procedure, simultaneously providing feedback on the kinematics of a patient’s actual arm movement, has only become feasible using VR technology.

We evaluated the effects of VET therapy in patients with mild to intermediate motor impairment of the arm due to a single stroke in the region of the middle cerebral artery.

The fact that none of our patients complained of any discomfort due to interaction with the virtual world indicates that such a non-immersive type of VR is devoid of side effects that may hamper brain function (Rose, Attrice, & Johnson, 1996; Regan, 1995).

The Fugl-Meyer UE scores increased in all the patients in this study. These improvements were scarcely influenced by the patients’ ages, the time elapsing since their stroke, or whether the stroke had occurred on the left or right side, whereas patients with a more severe initial motor impairment improved less than those with a milder deficit. The results that we obtained with enhanced feedback treatment confirm that old age, late therapy, and side and severity of stroke may interfere very little with motor recovery, as suggested in numerous previous studies using different rehabilitation techniques (Jeffery & Good, 1995; Johnston, Kirshblum, Zorowitz, & Shiflett, 1992; Bagg, Paris Pombo, & Hopman, 2002; Tangeman, Banaitis, & Williams, 1990; Dam et al., 1993).

On the whole, our patients had high baseline FIM scores that showed modest changes in response to VET treatment, probably because many of them had already learned to cope without the affected arm in their activities of daily living. In cases treated 6–12 months after their stroke and in those with a Fugl-Meyer UE score below 50, however, the mean FIM score improved remarkably by about 10% over the baseline values. These groups may have included subjects who needed more rehabilitation treatment to restore their ADL abilities.

We found that the Fugl-Meyer UE scores improved along with the mean duration and velocity of the reaching movements, and there was a significant correlation between each kinematic parameter and the clinical score. The reaching trajectories of the affected arm also regained the straight and appropriate features of those performed with the unaffected arm (Morasso, 1981).

### Table 2. Effects of VET Therapy with Enhanced Feedback in Post-Stroke Patients

<table>
<thead>
<tr>
<th>Clinical parameters</th>
<th>Before therapy</th>
<th>After therapy</th>
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<tr>
<td>Fugl-Meyer UE score</td>
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<tr>
<td>44.2 ± 11.3</td>
<td>50.7 ± 10.5*</td>
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<tr>
<td>FIM score</td>
<td></td>
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<td>111.5 ± 16.1</td>
<td>118.6 ± 9.4*</td>
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<tr>
<th>Kinematic parameters</th>
<th>Before therapy</th>
<th>After therapy</th>
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<tr>
<td>Mean velocity of</td>
<td></td>
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<tr>
<td>movement (cm/s)</td>
<td>15.0 ± 2.4</td>
<td>18.5 ± 2.5*</td>
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<tr>
<td>Mean duration of</td>
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<tr>
<td>movement (s)</td>
<td>3.4 ± 0.6</td>
<td>2.8 ± 0.8*</td>
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Note: VET, Virtual Environment Training; Fugl-Meyer UE, Fugl-Meyer Upper Extremity; FIM, Functional Independence Measure. Values are mean ± SD.

*Significantly different from mean score before therapy ($p < .05$).
Figure 3. Representative reaching trajectories performed by a patient posting a virtual envelope, from the starting position to the target consisting of a horizontal slot in a virtual mailbox. Trajectories were scattered and irregular at the baseline (left), but became more regular during the rehabilitation program (center), and straight and appropriate at discharge (right).

Table 3. Effects of VET Therapy on the Fugl-Meyer UE Score in Different Groups of Post-Stroke Patients

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<th>Before therapy</th>
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<td><strong>Age</strong></td>
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<tr>
<td>≥55 years</td>
<td>30</td>
<td>45.3 ± 11.9</td>
<td>51.6 ± 10.5*</td>
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<tr>
<td>&lt;55 years</td>
<td>15</td>
<td>41.9 ± 10.1</td>
<td>48.8 ± 10.5*</td>
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<tr>
<td><strong>Stroke-to-VET interval</strong></td>
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<td>6–12 months</td>
<td>25</td>
<td>45.7 ± 10.8</td>
<td>51.3 ± 10.5*</td>
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<tr>
<td>More than 12 months</td>
<td>20</td>
<td>42.3 ± 11.9</td>
<td>49.9 ± 10.7*</td>
</tr>
<tr>
<td><strong>Side of stroke</strong></td>
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<tr>
<td>Left</td>
<td>20</td>
<td>44.4 ± 14.4</td>
<td>50.7 ± 11.6*</td>
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<tr>
<td>Right</td>
<td>25</td>
<td>44.0 ± 9.9</td>
<td>50.6 ± 9.7*</td>
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<td><strong>Motor function impairment</strong></td>
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<tr>
<td>Fugl-Meyer UE score ≤ 50</td>
<td>28</td>
<td>36.6 ± 6.0</td>
<td>44.2 ± 7.6*</td>
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<tr>
<td>Fugl-Meyer UE score &gt; 50</td>
<td>17</td>
<td>56.6 ± 2.5†</td>
<td>61.4 ± 3.8*†</td>
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</table>

Note: VET, Virtual Environment Training; Fugl-Meyer UE, Fugl-Meyer Upper Extremity; FIM, Functional Independence Measure. Values are mean ± SD.
*Significantly different from mean score before therapy (p ≤ .05).
†Significantly different from the other group of patients.
These modifications in the kinematic characteristics of limb motion are consistent with motor learning and support the useful effects of enhanced feedback on the motor system (Cirstea & Levin, 2000).

The availability of direct information (knowledge of performance) has proved beneficial in learning various motor tasks (Gentile, 1972; Young & Schmidt, 1992; Winstein, 1991; Todorov et al., 1997; Schmidt & Young, 1991). Accordingly, using VR technology in our experimental paradigm, patients were given information about their arm movements during the performance of motor skills. At the end of each task, moreover, patients could see the object’s trajectories displayed on screen and thus evaluate the accuracy of their movement with respect to the target (“knowledge of results”). Correctly presenting this feedback has proved advantageous for performance in some physiological experiments (Todorov et al., 1997; Schmidt & Young, 1991; Winstein et al., 1996).

On the other hand, another mechanism that seems effective for training some biological systems is the so-called supervised learning. This method consists of a set of training inputs that should prompt desired responses; in other words, the standards of correctness are known a priori (Barto, 1994; Rumelhart, Hinton, & Williams, 1986; Doya, 2000). In our study, such supervised learning consisted of the instructions imparted by the therapist during the experimental procedure and by the virtual representation of the correct movement. Indeed, the patients were able to watch the therapist’s movement as they performed their own motor action in the same reference frame.

All the above-described types of feedback, combined with the knowledge of the results, provide the basis for the reinforcement learning mechanism used by modern robotic systems, through the trial and error paradigm (Barto, 1994; Doya, 2000; Fagg & Arbib, 1992).

In our experiment, motor function improvements may therefore have been enhanced by the synergistic activity of supervised and reinforcement learning. Other factors (which can be evaluated by modifying the tasks and/or the complexity of the feedback in the virtual scenarios) may have contributed to the motor improvements, however. For instance, subjects could be shown

**Table 4. Effects of VET Therapy on the FIM Scale in Different Groups of Post-Stroke Patients**

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<td>&lt;55 years</td>
<td>15</td>
<td>112.6 ± 17.7</td>
<td>121.0 ± 5.8</td>
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<tr>
<td>Stroke-to-VET interval</td>
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<tr>
<td>6–12 months</td>
<td>25</td>
<td>107.6 ± 17.5</td>
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<td>More than 12 months</td>
<td>20</td>
<td>116.4 ± 13.0</td>
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<td>Side of stroke</td>
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<td>Left</td>
<td>20</td>
<td>107.1 ± 29.4</td>
<td>115.7 ± 13.0*</td>
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a representation of their end-effector (without the trace), or the whole arm’s motion, with or without any aid from the physical therapist: depending on the influence of such different settings on motor performance, the hierarchic impact of each learning mechanism can be derived.

In conclusion, the present study demonstrated that late rehabilitation therapy, using a VR system that stresses reinforcement learning and supervised learning mechanisms, may be useful in ameliorating arm motor deficits and providing a quantitative evaluation of motor abilities in post-stroke patients.

References


