The Generalization of Motor Recovery After Stroke: 
Assessment Within and Outside the Training Workspace

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Abstract—Stroke patients exhibit a reduced ability or incapacity to selectively activate muscle fibres and consequently motor performance is impaired. The best behavioural outcomes after stroke are associated with the greatest return of brain function toward the normal state of organization. Besides traditional physical therapy, task oriented repetitive movements can help patients recover motor function, improve motor coordination, learn new motor strategies and avoid secondary complications, as many studies using robot-aided therapy attest.

The goal of the present study was to verify the transfer of motor skills from trained to untrained tasks in chronic stroke subjects. We investigated to what extent there is generalization of motor recovery in chronic stroke subjects for point-to-point movements executed within and outside the workspace in which they were previously trained.

Our results suggest that while the generalization of motor recovery is good for new point-to-point movements executed within the training workspace, there is little generalization for point-to-point movements outside. This calls for varied therapy practice to promote improvement in activity of daily living.

I. INTRODUCTION

After cardiovascular disease and cancer, stroke ranks as the third most common cause of death in industrialised countries. Stroke is the most important cause of morbidity and long-term disability in Europe and, as such, imposes an enormous economic burden. After the acute phase all patients require continuous medical care and labour intensive rehabilitation. Arm therapy is used in the neurorehabilitation of patients with upper limb paresis due to lesions of the central nervous system. Besides the traditional physical therapy, task oriented repetitive movements can help patients recover motor function, improve motor coordination, learn new motor strategies and prevent secondary complications. Robot-aided motor training exploits the basic principle that degree of performance improvement is dependent on the amount of practice [1]. It can provide an intensive and highly repeatable administration of therapy, and has proven effective in restoring upper limb function after treatment in both acute and chronic post-stroke populations [2], [3]. These improvements likely result from use-dependent reorganization of the cortical circuitry triggered by the increased use of body parts in behaviorally relevant tasks [4]. In general, robot-aided rehabilitation is based on delivering assistive forces to the limbs which may: a) affect motor learning by reducing effort and fatigue as well as by inducing a sensation of greater stability of the external environment, or some aspects of it [5], [6]; b) increase subjects’ motivation, as they allow trainees to complete the motor task even in the early phases of a learning process [7]; c) promote the ‘correct’ associations in sensory and motor cortical areas, by inducing the generation of ‘correct’ afferent signals (proprioceptive, tactile) [8].

However, much remains to be done to provide an optimal tailoring of treatment to the individual patient’s needs. Therapists cannot possibly train all the challenging tasks a patient will face after rehabilitation discharge. Therefore, facilitating transfer of strategies from trained to non-trained (but related) tasks would be very important for the clinical success of a therapy programme [9].

The goal of the present study was to verify the occurrence of transfer of motor skills from trained to non trained tasks in chronic stroke patients who were trained on point-to-point movements with the assistance of a rehabilitation robot. In particular we investigated if generalization of motor recovery occurs in the case of new point-to-point movements executed both inside and outside the training workspace.

II. METHODS

A. Subjects

Eighteen patients after stroke (6 females, 12 males) were enrolled in this study performed at the Salvatore Maugeri Foundation, IRCCS Rehabilitation Institute of Veruno (NO, Italy). All patients were in chronic stage, their unilateral cerebrovascular accident (CVA) having occurred at least six months prior to enrolment (22±21 months from CVA). Inclusion criteria were the presence of a single unilateral CVA and the presence of at least 10 degrees of motion in the treated joints (shoulder and elbow); this latter criterion ensured that only patients who could really be motivated by use of the robot device were enrolled. Subjects with severe sensory and visual field impairment and aphasia were excluded. Moreover, subjects who showed no significant motor improvement during the rehabilitation treatment were excluded from the study. For these reasons the analyses to investigate generalization of motor recovery were conducted on nine...
of the eighteen subjects initially enrolled. The study was carried out in conformity with the Declaration of Helsinki of the World Medical Association; all patients gave their informed consent to participate in the study, which had been approved by the local scientific and ethics committees.

B. Rehabilitation Device and Training Protocol

The two degrees of freedom (DoF) elbow-shoulder manipulator MEMOS was used in this study [10], [11]. Patients were seated in a chair and had their trunk fastened to the back of the chair to limit compensation phenomena. The patient’s paretic limb was supported at the elbow by a low friction pad that slid over the surface of the robot workspace. Patients had to make a sequence of point-to-point reaching movements in the horizontal plane. The path to follow was initially a square (four reaching subtasks) for all patients. In the case of significant motor improvement, the physiotherapist could decide to use a more complex diamond-shaped path for the training (see Fig. 1). If the patient could not complete the movement by means of voluntary activity, the robot evaluated the current position and guided the patient’s arm to the target along the minimum path trajectory (minimum distance).

Patients were trained twice a day, five days a week for at least three weeks. Each training session consisted of four cycles of exercise lasting 5 minutes each followed by a 3 minutes resting period. On the same days as robot treatment, all patients underwent physical therapy for 45 minutes a day, performed by professionals according to the Italian Stroke Prevention and Educational Awareness Diffusion (SPREAD) guidelines.

![Diagram](image)

Fig. 1 Point-to-point reaching tasks. All the patients had to make a sequence of point-to-point reaching movements in the horizontal plane. The path to follow was initially a square (4 reaching subtasks, panel A). In case of significant motor improvement, the physiotherapist could decide to train a patient on a more complex diamond-shaped path (16 reaching subtasks, panel B). Patients suffering from a left arm paresis were trained to execute series of point-to-point reaching movements which were specular to those executed by patients with right arm paresis.

C. Assessment of Recovery Components

In this study we used kinematic measures of upper limb movements, derived from signals recorded at the robot end-effector. Kinematic measures quantify the spatio-temporal quality of a subject’s movement and are useful for monitoring patient performance during treatment [12]. The following parameters were considered in this study:

1) Active Movement Index (AMI): this quantifies the patient’s ability in executing the assigned motor task without robot assistance. It represents the percentage of trajectory travelled by means of the patient’s voluntary activity (without robot assistance).

2) Mean Velocity (MV): i.e. the average speed of the end-effector.

3) Mean Distance (MD): assessed by measuring the mean absolute deviation of the points of the travelled path from those of the theoretical path. It is a measure of the error of movement accuracy.

4) Normalized Path Length (nPL): obtained by computing the path length of the trajectory travelled by the patient to reach the target and normalized to the theoretical path. It is an index of the error of movement efficiency.

5) Smoothness (SM): the number of peaks per length unit (decimeter) in the speed profile. The number of peaks is expressed as a negative value, i.e. increases in the peak metric equal increases in smoothness. To compare the number of peaks in the speed profile across patients, we normalized this value by the percentage of theoretical path carried out by the patient by his/her voluntary activity (without robot assistance).

D. Data Analysis and statistics

To investigate generalization of motor recovery, the average performance achieved at the end of training on a square path was compared with that on the new (i.e. diamond-shaped) path. To this end, the segments of the diamond-shaped path were subdivided into: those “Within” the trained workspace (Fig 1. Panel B, segments 7, 10, 13, 16) and those “Outside” the trained workspace (Fig 1. Panel B segments 5, 6, 8, 9, 11, 12, 14, 15). In particular we compared:

- **Square vs. Within**: the mean performance achieved in the last session of training on the square path vs. the mean performance reached in the first session on the diamond-shaped path, considering only movements within the trained workspace.

- **Square vs. Outside**: the mean performance achieved in the last session of training on the square path vs. the mean performance reached in the first session on the diamond-shaped path, considering only movements outside the trained workspace.

- **Within vs. Outside**: the mean performance achieved in the first session on the diamond-shaped path, considering only movements within the trained workspace vs. the mean performance reached in the same training session but considering only movements outside the trained workspace.

- **Within<sub>end</sub> vs. Outside<sub>end</sub>**: the same comparison as for the previous point but applied to the last session of treatment.
Patients suffering from right arm paresis were trained to execute series of point-to-point reaching movements that were specular to those executed by patients with left arm paresis. Therefore, segments denoted by the same numerical code (Fig. 1) could be pooled together for data analysis, independently of which arm was trained. The non parametric Kolmogorov-Smirnov test used to compare performances on different clusters of segments to investigate generalization of motor recovery. A significance level of \( p \leq 0.05 \) was used for all tests.

III. RESULTS

Nine (\( n=9 \)) out of eighteen (\( n=18 \)) patients showed significant motor improvement on the selected kinematic parameters during the rehabilitation treatment on square shape. Only this subgroup of subjects switched to the more complex (diamond-shaped path) task, and was used to investigate generalization of motor recovery.

Fig. 2 shows the time course of motor improvement measured by the robotic variables for the square shape (black dashed line, sessions 1 to 30) and the diamond shape (solid line, sessions 10 to 30), averaged over the 9 subjects that performed both exercises. The point-to-point movements performed for the diamond shape are differentiated as "within" (grey solid line) or "outside" (black solid line) the previous training workspace (i.e. square shape). The mean time course of the AMI parameter (Fig. 2, panel A) shows that all the nine patients reached 100% of voluntary activity in about 10 sessions and maintained the acquired skill also when changing to diamond shape, regardless of the type of movement (i.e., "Within" or "Outside" the training workspace). Kolmogorov-Smirnov tests did not reveal significant differences (\( p>0.05 \)) for the AMI parameter for the following comparisons: Square vs. Within, Square vs. Outside, Within vs. Outside and Within\(_{end}\) vs. Outside\(_{end}\). Fig. 2 (panels B, C, D, E) shows that for all other robotic variables, after the change of training path, the “Within” movements maintained approximately the same level of performance as that achieved during the previous training (i.e. square shape) whereas the “Outside” movements showed a worse level of performance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Square vs. Within</th>
<th>Square vs. Outside</th>
<th>Within vs. Within(_{end})</th>
<th>Within vs. Outside(_{end})</th>
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<tr>
<td>AMI</td>
<td>( p &gt; 0.05 )</td>
<td>( p &gt; 0.05 )</td>
<td>( p &gt; 0.05 )</td>
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<tr>
<td>MV</td>
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<td>( p = 0.02^{*} )</td>
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<tr>
<td>MD</td>
<td>( p &gt; 0.05 )</td>
<td>( p = 0.02^{*} )</td>
<td>( p = 0.02^{*} )</td>
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<td>nPL</td>
<td>( p &gt; 0.05 )</td>
<td>( p &lt; 0.01^{*} )</td>
<td>( p &lt; 0.01^{*} )</td>
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<td>SM</td>
<td>( p &gt; 0.05 )</td>
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Fig. 2. Average time course of motor recovery and standard error limits (grey and white area) measured by the robotic variables AMI, MV, MD, nPL, SM. The black dashed line (sessions 1 to 30) is the performance obtained during the course of treatment on the square shape. Solid lines (sessions 10 to 30) show the motor improvement during point-to-point movements obtained for the diamond shape, "within" (black) and "outside" (grey) the training workspace (i.e. the square). Each point represents the average value computed for each training session over the 9 patient that performed both exercises.
Kolmogorov-Smirnov tests confirmed that the comparison Square vs. Within for the four variables did not show significant differences, whereas there was a significant difference for the comparison Square vs. Outside. Furthermore, comparing “Within” movements and “Outside” movements, the performance reached by the two groups was significantly different both at the beginning and at the end of the training on the diamond shape; except for the parameter MD. Table I summarizes the p-values of the Kolmogorov-Smirnov tests on the four groups.

Details about the results obtained in the different directions of movement during the diamond task are been reported elsewhere [13].

IV. DISCUSSION

Generalization of motor recovery has been previously investigated in chronic subjects trained on point-to-point movements with the assistance of a robot, and then evaluated on a circle-drawing task. By the end of the training, subjects were better able to draw circles although they had received no training in this task [14], [15]. This result suggested that motor recovery generalizes to untrained tasks across the same workspace. In particular, generalization appears to occur both at a coarser level, i.e. the shape became more circular, and at a finer level, i.e. the movements became smoother. This fact, could be related to a difficulty that the patient had in splitting a subtask in more than one subtask.

In this paper we investigated to what extent generalization of motor recovery occurs in chronic subjects for point-to-point movements executed outside the workspace in which they were previously trained. Subjects were trained on a planar square-shaped workspace (training workspace), and then evaluated on a different diamond-shaped workspace, which included point-to-point movements both within and outside the training workspace.

Our results suggest that while there is a good generalization of motor recovery for new point-to-point movements executed inside the training workspace (in line with [14], [15]), generalization is limited for point-to-point movements outside. In particular, movements executed outside the training workspace were slower (MV), less accurate (MD), less efficient (nPL) and less smooth (SM) than those within. Previous studies suggest that central nervous system plans voluntary movements starting from a set of stereotyped sub-movements, which represent an "alphabet" of primitive movements [15], [16]. Different movements can be generated by using different sets of sub-movements. Roherer et al. [17], [18] showed that movement smoothness increases during stroke recovery, and that sub-movements become larger, fewer and more blended. Our results extend these studies by showing that movement smoothness, together with other robotic variables, does not generalize outside the training workspace. Given the limited number of subjects, our study should be considered as preliminary and further investigations are required. Nevertheless, the additional information about generalization we obtained could be very useful for the planning and optimization of treatment.  

VI. REFERENCES