The Effect of Robot-Assisted Therapy and Rehabilitative Training on Motor Recovery Following Stroke

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**Background:** We used MIT-Manus, a robot designed to provide interactive, goal-directed motor activity for clinical neurologic applications.

**Objective:** To test whether this robotic manipulation of the impaired limb influenced motor recovery in patients with hemiplegia.

**Methods:** Sequential patients with a history of a single stroke and hemiplegia (N=20) hospitalized on the same acute care rehabilitation floor were enrolled in a standard rehabilitation program supplemented by either robot-aided therapy or sham robot-aided therapy. These 2 groups were comparable in age, initial physical impairment, and time between onset of the stroke and enrollment in the trial. Patients, clinical team members, and the clinical evaluator were blinded to the treatment group assignments. Standardized assessment tools measured outcomes.

**Results:** Impairment and disability declined in both groups between hospital admission and discharge. The robot-treated group showed a greater degree of improvement in all 3 measures of motor recovery, and the change in motor status measured in the proximal upper limb musculature was significant (P=.002). No adverse events resulted from robot-assisted therapy.

**Conclusions:** These results suggest that robotic manipulation of the impaired limb may favorably add to recovery following stroke and that robotics may provide new strategies for neurologic rehabilitation.

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The traditional goal of rehabilitation medicine is to promote functional adaptation. However, recent evidence suggests that genuine restoration of neurologic function may be attainable following stroke and that the rehabilitation environment may play a role in restoration. Positron emission tomographic studies have shown that relative oxygen metabolism in the cerebral cortex of the nondiseased, ipsilateral cortical hemisphere increases coincident with motor recovery in some stroke patients with hemiplegia. Combined with clinicopathologic observations that have suggested ipsilateral corticospinal involvement in the motor recovery process, these data indicate a potential for neuron plasticity in the adult cerebral cortex. Pilot experiments have shown that amphetamine injection coupled with repetitive physical training can improve motor outcome in laboratory animals with brain infarction, indicating that experience has a role in accelerating motor recovery. Similar observations have been reported in human studies. Intracortical microstimulation studies indicate that adjacent cortical tissue assumes lost motor function following experimentally induced stroke in primates and that the degree of reorganization of undamaged cortex is significantly influenced by rehabilitative training. Such findings indicate the potential for functional plasticity in the adult human cerebral cortex and suggest that the rehabilitation environment may influence that process.

A cornerstone of neurorehabilitation of patients following a stroke relies on physical therapy practice philosophies that claim to restore neurologic control, rather than merely use compensatory techniques to ameliorate disability. However, claims that physical therapy restores neurologic control remain unproven. Physical medicine approaches vary dramatically from one another in philosophy, and in practice the therapies administered vary greatly between patients and between therapists. No definitive therapy has emerged and there are no controlled studies, to our knowledge, that have
PATIENTS AND METHODS

Twenty sequential patients with hemiplegia admitted to the same medical ward and team of the Burke Rehabilitation Hospital, White Plains, NY, 3 weeks (+1 week) after a single stroke were recruited for this study. The protocol was approved by the institutional review board of the Burke Rehabilitation Hospital and the Committee Overseeing Use of Human Experimental Subjects of the Massachusetts Institute of Technology, Cambridge. Written informed consent was obtained from all patients. Patients were stratified on the basis of impairment to robot-aided therapy or the control group (sham robot therapy). Patients and the medical and rehabilitation team providing clinical care were blinded to group assignment.

All patients were examined by the same therapist at baseline and then biweekly. The Functional Independence Measure (FIM) scale was used to assess functional performance. The FIM has become the standard functional status instrument for US rehabilitation hospitals and has established internal consistency and discriminative capability. Motor impairment was measured with the upper extremity subsection of the Fugl-Meyer Scale (F-M), a tool with established validity and reliability designed to provide an assessment of a variety of motor signs in hemiparesis, including deep tendon reflexes, tremor, range of motion, and balance, as well as synergy-based motor capabilities across a limited number of joints. Based on an expanded F-M, a motor status scale (MSS) was developed to increase the number of assessed muscle groups in the paretic limb. The goal was to generate a quantitative measure of motor control (accuracy) and the proportion of isolated volitional muscle activity involved in each movement. The MSS score was a sum of all movement scores (0, no movement; 1, partial or uncontrolled movement; and 2, complete, controlled movement) obtained for 10 shoulder movements and 4 elbow/forearm movements; movement scores only were separately tabulated for 3 wrist movements and 12 hand movements. The MSS was prospectively applied to all patients before and after participation in the experimental protocol.

Because the robot-aided exercise program focused on shoulder and elbow musculature, a motor power (MP) score was generated by assessing power in the biceps, triceps, and anterior and lateral deltoid muscles (0, no contraction; 1, trace contraction; 2, active movement possible with gravity eliminated; 3, antigravity strength; 4, reduced function but adequate to overcome some resistance; and 5, normal strength; plus and minus scoring was permitted, increasing the score by 0.4) and summing individual muscle grades, for a maximum score of 20. This scoring system has been used in other therapeutic trials for motor impairment.

All patients received conventional therapy from the same team of therapists. The experimental group received an additional 4 to 5 hours per week of robot-aided therapy with MIT-Manus, a robot prototype designed and built at the Massachusetts Institute of Technology for clinical neurologic applications. This therapy consisted of goal-directed, robot-assisted arm movement; a customized, interactive, computer-generated video program provided visual and auditory feedback to the patient. If the arm was paralyzed, limb movement was initially passive, and as motor function returned, the interactive robot required the initiation of motor activity by the patient. The patient's hand and wrist were held in a rigid support affixed to the robotic arm and therapy consisted of flexion, extension, and rotational movements across elbow and shoulder joints.

The control group had weekly to biweekly contact with the robotic device. During these sessions, the patients actively moved the robotic arm and were able to observe the response on the video monitor. The robotic device was also used to record strength and quality of movement. Patients and rehabilitation therapists were blinded to the treatment group.

Statistical analysis was performed with the SPSS-PC statistical software package (SPSS Inc, Chicago, Ill.). A 1-tailed t test was used to compare changes between hospital admission and discharge FIM, F-M, MSS, and MP scores in patients who received robot-aided therapy and their lesion-matched controls. Complications potentially related to physical activity, such as bursitis, tendinitis, and the shoulder-hand syndrome, were recorded.

examined the effect of withholding rehabilitation therapies after stroke.

Although the impact on functional restoration is ill-defined, it has become standard practice, perhaps for reasons of compassion rather than any scientific basis, to attempt to decrease spasticity and facilitate functional motor abilities by moving a patient's flaccid paralyzed limb through the complete range of motion excursions or by assisting the patient who is not totally paralyzed to exercise a weakened limb.

In this pilot study we tested whether a new technology designed to provide quantifiable and reproducible physical activity could affect motor outcome when this therapy was added to a standard program for stroke neurorehabilitation. Stroke patients actively or passively interacted with a robotic arm that applied a precise degree of force, velocity, duration, and repetition of movement in a stereotyped pattern. Movement activities were goal directed and the robotic system supplied the patient with visual, auditory, and tactile feedback concerning the accuracy of movement throughout each therapy session. The robotic system provided a form of therapy that conceptually resembles a widely accepted physical therapy approach. Robot-aided therapy sessions supplemented an acute stroke rehabilitation program. The goals were to determine whether supplemental, intensive, and reproducible physical therapy provided by the robot improved patients' outcomes as measured by changes in pain, motor strength, quality of movement, and motor recovery in portions of the limb not exercised by the robot.

RESULTS

CLINICAL CHARACTERISTICS OF CONTROL AND EXPERIMENTAL GROUPS

The clinical characteristics and admission-discharge assessment scores are summarized in Table 1 and Table 2. The control group included 6 men and 4 women and the
### Table 1. Control Group Characteristics and Assessment Scores

<table>
<thead>
<tr>
<th>Sex/Age, y/D</th>
<th>Type of Stroke</th>
<th>F-M (Maximum Score=66)</th>
<th>FIM (Maximum Score=126)</th>
<th>Motor Power (Maximum Score=20)</th>
<th>MSS (Maximum Score=40)</th>
<th>Complications</th>
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</thead>
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<tr>
<td>F/69/R</td>
<td>R small DWM (s)</td>
<td>56/49</td>
<td>72/114</td>
<td>13.2/12.4</td>
<td>39/35</td>
<td>Yes</td>
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<td>M/72/R</td>
<td>R large DWM (s)</td>
<td>9/23</td>
<td>73/102</td>
<td>2.6/8.8</td>
<td>13/16</td>
<td>Yes</td>
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<tr>
<td>M/71/L</td>
<td>R large DWM (s)</td>
<td>8/17</td>
<td>94/111</td>
<td>5.8/7.4</td>
<td>17/22</td>
<td>No</td>
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<tr>
<td>M/64/R</td>
<td>R entire MCA (sc)</td>
<td>4/13</td>
<td>72/98</td>
<td>0.6/8</td>
<td>13/12</td>
<td>Yes</td>
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<td>F/70/R</td>
<td>R brain stem</td>
<td>26/66</td>
<td>78/99</td>
<td>9.8/12.8</td>
<td>30/38</td>
<td>No</td>
</tr>
<tr>
<td>M/59/R</td>
<td>R entire MCA (sc)</td>
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<td>53/82</td>
<td>0.0/0</td>
<td>11/18</td>
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<td>M/58/R</td>
<td>L small DWM (s)</td>
<td>4/8</td>
<td>64/93</td>
<td>10.8/16</td>
<td>10/6</td>
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<td>68/82</td>
<td>0.0/0</td>
<td>10/6</td>
<td>Yes</td>
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<td>R small DWM (s)</td>
<td>19/41</td>
<td>67/65</td>
<td>6.4/8.4</td>
<td>16/20</td>
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<tr>
<td>M/66/R</td>
<td>R small DWM (s)</td>
<td>4/18</td>
<td>85/95</td>
<td>4.8/8</td>
<td>16/16</td>
<td>Yes</td>
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</table>

*D indicates disabled limb; F-M, Fugl-Meyer Scale; FIM, Functional Independence Measure; MSS, motor status scale; SHS, shoulder-hand syndrome; DWM, deep white matter; s, subcortical lesion; sc, cortical and subcortical lesion; and MCA, middle cerebral artery.

### Table 2. Experimental Group Characteristics and Assessment Scores

<table>
<thead>
<tr>
<th>Sex/Age, y/D</th>
<th>Type of Stroke</th>
<th>F-M (Maximum Score=66)</th>
<th>FIM (Maximum Score=126)</th>
<th>Motor Power (Maximum Score=20)</th>
<th>MSS (Maximum Score=40)</th>
<th>Complications</th>
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<tbody>
<tr>
<td>M/45/R</td>
<td>L wedge MCA (c)</td>
<td>22/21</td>
<td>78/112</td>
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<td>15/24</td>
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<td>F/87/R</td>
<td>L small DWM (s)</td>
<td>21/38</td>
<td>67/92</td>
<td>7.4/7.4</td>
<td>18/17</td>
<td>No</td>
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<tr>
<td>F/88/R</td>
<td>L ACA/MCA (c)</td>
<td>24/54</td>
<td>72/87</td>
<td>1.6/6.6</td>
<td>8/66</td>
<td>Yes</td>
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<tr>
<td>F/54/L</td>
<td>L wedge MCA (c)</td>
<td>8/27</td>
<td>64/91</td>
<td>1.8/6.4</td>
<td>5/16</td>
<td>No</td>
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<td>M/57/L</td>
<td>R small DWM (s)</td>
<td>47/64</td>
<td>87/119</td>
<td>16.8/17.4</td>
<td>3/6</td>
<td>No</td>
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<tr>
<td>F/66/R</td>
<td>R large DWM (s)</td>
<td>4/4</td>
<td>68/98</td>
<td>0.1/6</td>
<td>3/5</td>
<td>Yes</td>
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<tr>
<td>M/45/R</td>
<td>R large DWM (s)</td>
<td>1/24</td>
<td>64/99</td>
<td>0.0/0</td>
<td>2/15</td>
<td>No</td>
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<td>M/52/R</td>
<td>R entire MCA (sc)</td>
<td>4/8</td>
<td>87/103</td>
<td>0.0/0</td>
<td>2/14</td>
<td>Yes</td>
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<td>M/68/R</td>
<td>R brain stem</td>
<td>6/9</td>
<td>71/91</td>
<td>2.2/2.2</td>
<td>4/8</td>
<td>No</td>
</tr>
<tr>
<td>M/62/R</td>
<td>R wedge MCA (c)</td>
<td>34/53</td>
<td>72/94</td>
<td>7.4/12.8</td>
<td>21/34</td>
<td>No</td>
</tr>
</tbody>
</table>

*D indicates disabled limb; F-M, Fugl-Meyer Scale; FIM, Functional Independence Measure; MSS, motor status scale; SHS, shoulder-hand syndrome; MCA, middle cerebral artery; c, cortical lesion; DWM, deep white matter; s, subcortical lesion; ACA, anterior cerebral artery; ellipses, no data available; and sc, cortical and subcortical lesion.

Experimental group included 5 men and 5 women. The mean (±SD) age of patients in the control group was 63.3±10.6 years and in the experimental group was 58.5±8.3 years (P=.28). Control patients were admitted to the Burke Rehabilitation Hospital 3.3±1.2 (SD) weeks and were discharged 9.8±2.6 (SD) weeks after stroke; experimental patients were admitted 2.8±1.1 (SD) weeks and discharged 9.2±2.5 (SD) weeks after stroke.

The mean (±SD) baseline admission FIM score in the control group was 70.90±14.02 and in the experimental group, 73.0±8.47 (P=.69). Similarly, no statistically significant differences in mean (±SD) baseline F-M or MP scores were apparent (F-M: control group, 13.8±16.64; experimental group, 17.10±15.18 [P=.65]; MP: control group, 4.42±4.50; experimental group, 4.12±3.46 [P=.89]).

The mean (±SD) baseline proximal MSS score for the control group was 15.80±11.52 and for the experimental group was 8.22±7.34 (P=.11). The mean (±SD) wrist MSS score was 1.8±1.93 for the control group and 1.33±1.87 for the experimental group (P=.60). The mean (±SD) baseline hand MSS score was 8.20±12.47 for the control group and 6.56±11.75 for the experimental group (P=.77).

Results of neuroimaging studies showed an intraparenchymal hemorrhage in 3 control and 2 experimental patients and bland infarcts in 7 control and 8 experimental patients. Middle cerebral artery distribution strokes were present in 3 patients in the control group and 4 patients in the experimental group. Large, deep, white matter strokes occurred in 2 patients from each group, while small, deep, white matter strokes (small perforator distribution) were evident in 4 control and 2 experimental patients. One brain stem stroke occurred in each group, and 1 experimental patient had an anterior cerebral artery infarct with posterior extension, producing arm weakness.

**ANALYSIS OF CHANGES BETWEEN ADMISSION AND DISCHARGE**

Both groups showed improvement between hospital admission and discharge. The FIM, a scale that measures functional adaptation and often relies on training an unimpaired limb to perform compensatory tasks, did not
show a change in degree of improvement between groups. The control group had a mean (±SD) increase in FIM scores of 25.7±12.25 and the experimental group had an increase of 25.6±7.23 (P=.59).

Motor power and F-M scores also improved in both groups. A trend favoring the experimental group occurred in proximal motor strength improvement (P=.10) between control group MP scores (2.30±2.45) and experimental group MP scores (3.88±2.89). The mean (±SD) change in the control group F-M score was 10.10±11.63, and in the experimental group F-M score, 14.10±9.70 (P=.21). The F-M is relatively insensitive to small but visible changes in isolated movement and motor control, particularly in proximal upper limb muscle groups. For this reason, the MSS was developed, based on an expansion of the F-M, to document these motor changes.

The MSS, examining the accuracy and degree of isolation of movement across joints, was separately calculated for portions of the limb that were directly involved in the robotic exercise program (shoulder, forearm, and elbow) and for more distal regions (wrist and hand). The experimental group showed a statistically significant degree of improvement in proximal MSS scores (P=.002). The mean (±SD) increase in proximal MSS scores was 1.8±3.34 for the control group and 4.44±5.90 for the experimental group. The MSS was also measured in the wrists and hands, regions not directly exercised by the robot; although a greater degree of improvement was also seen in the experimental group, it was not significant (wrists, P=.29; hands, P=.36).

Frequency of pain or shoulder-hand syndrome in the paretic arm did not differ between groups. Joint or tendon pain occurred in 7 control and 5 experimental patients (P=.36), and shoulder-hand syndrome occurred in 3 control and 4 experimental patients (P=.66).

These results cannot determine whether a robotic device is superior to standard means of administering therapy. The device lacks the compassionate human aspect of physical therapy, the effects of which cannot be discounted. However, no adverse events were associated with its use and it has certain potential advantages over traditional physical therapy. For example, computerized robotic devices can precisely standardize the therapy delivered, potentially providing a graded exercise program that adjusts to patient response on a continuous basis. The robot is capable of delivering a precise regimen of active and passive physical therapy coupled with multisensory (visual, tactile, and auditory) feedback. The MIT-Manus robot has the capability not only of administration of a therapeutic exercise regimen, but also of online patient assessment and analysis. Ultimately, mechanical devices may represent a cost-effective adjunct to standard rehabilitation therapy.

A larger study with a long-term follow-up is needed to confirm the results of this pilot study and to determine whether gains are maintained after acute rehabilitation has ended. Examination of a larger cohort stratified by lesion site as well as disability will be required to examine which patients respond best and the type of therapy most applicable to specific lesions.

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REFERENCES