Comparison of Finger Tracking versus Simple Movement Training via Telerehabilitation to Alter Hand Function and Cortical Reorganization after Stroke

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**Objective.** To compare 2 telerehabilitation training strategies, repetitive tracking movements versus repetitive simple movements, to promote brain reorganization and recovery of hand function. **Methods.** Twenty subjects with chronic stroke and 10 degrees of voluntary finger extension were randomly assigned to receive 1800 telerehabilitation trials over 2 weeks of either computerized tracking training (track group) with the affected finger and wrist involving temporospatial processing to achieve accuracy or movement training (move group) with no attention to accuracy. Following movement training, the move group crossed over to receive an additional 2 weeks of tracking training. Behavioral changes were measured with the Box and Block test, Jebsen Taylor test, and finger range of motion, along with a finger-tracking activation paradigm during fMRI. **Results.** The track group showed significant improvement in all 4 behavioral tests; the move group improved in the Box and Block and Jebsen Taylor tests. The improvement for the track group in the Box and Block and Jebsen Taylor tests did not surpass that for the move group. A consistent group pattern of brain reorganization was not evident. The move group, after crossing over, did not show further significant improvements. **Conclusion.** Telerehabilitation may be effective in improving performance in subjects with chronic stroke. Tracking training with reinforcement to enhance learning, however, did not produce a clear advantage over the same amount of practice of random movements. Two weeks of training may be insufficient to demonstrate a behavioral advantage and associated brain reorganization.

A n important question in stroke rehabilitation is whether recovery is influenced more by forced use versus forced learning. Repetitive use of the paretic limb during simple movements may not optimize the conditions for recovery. Research in rodents, primates, and healthy humans suggests that precision-demanding tasks that challenge motor-learning processes create richer conditions for change.

We questioned whether the improved finger movement and changed brain reorganization demonstrated in an earlier study involving finger-tracking training in stroke was due to the repetitive movement or to the cognitive processing engaged to produce accurate movements, as both conditions were convolved. Consequently, the primary purpose of the present study was to compare 2 training strategies in promoting brain reorganization and recovery of hand function in subjects with stroke: finger movement tracking that involved temporospatial processing to achieve accuracy versus the practice of simple finger movements that required no attention to accuracy.

A 2nd question in the current study concerned the venue of training. As communication technology has advanced, an unconventional method of rehabilitation has emerged that may allow rehabilitative training to continue remotely following discharge from acute care. This method is called telehealth, defined here as therapy from a distance directed by a computer and telecommunication. We questioned whether behavioral improvements and associated brain reorganization could be accomplished in the subject’s own home using a self-administered, computerized finger-tracking training program with occasional teleconferencing with a remote therapist. Our overall hypothesis was that subjects receiving home-based finger-tracking training would experience greater change in finger control and brain reorganization compared to subjects receiving home-based simple finger movement training.

Key Words: Stroke—Hand—fMRI—Motor learning—Telemedicine.
METHODS

Subjects

Twenty subjects with stroke were randomly assigned to either a track group or move group. Individual characteristics are summarized in Table 1. Figure 1 shows the flow chart summarizing the subject inclusion at the different stages of the study. The mean age (±SD) for the track group was 65.9 ± 7.4 years, and for the move group, it was 67.4 ± 11.8 years (nonsignificant difference). The mean time from stroke onset to entry was 42.5 ± 24.3 months in the track group and 35.6 ± 26.1 months in the move group (nonsignificant difference). A neurologist identified the location of infarct from MR images and also classified the infarct as either cortical or subcortical. The preferred hand prior to stroke was indicated. The mean time from stroke onset to entry was 67.4 ± 11.8 years (nonsignificant difference).

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None of the subjects had a history of stroke, head trauma, or severe brain injury. None had Mini-Mental State Examination scores ranging from 24 to 30.10 All subjects had sufficient cognition to perform the training and testing. All had Mini-Mental State Examination scores of 25 or higher, except 1 subject with a score of 21, who was still deemed appropriate to participate. The maximal score for Mini-Mental State Examination is 30, with normal scores ranging from 24 to 30.10

Inclusion criteria were poststroke duration of at least 12 months, 30 to 80 years of age, satisfactory corrected vision to recognize the full tracking target and cursor movement, at least 90 deg of passive extension-flexion movement at the index finger metacarpophalangeal (MP) joint of the paretic hand (no contracture), and at least 10 deg of active movement at this joint. Exclusion criteria were indwelling metals or medical implants incompatible with functional magnetic resonance imaging (fMRI), pregnancy, and claustrophobia. Subjects with subtle kinesthesia deficits, evidenced by impaired ability to detect 10-deg passive extension-flexion movements at the MP joint with eyes closed, were included in the study. All subjects were able to detect larger amplitude (>10 deg) movements. Subjects were recruited by advertising in a local newspaper and through announcements at local stroke support group meetings. This study was approved by the institution’s Committee on the Use of Human Subjects in Research. All subjects signed a statement of informed consent.

Training: Track Group

Subjects in the track group received finger and wrist tracking training in their own homes. This training was done independent of any direct supervision by the therapist. The training equipment consisted of a laptop computer (Dell Latitude 600, Dell, Round Rock, TX) with customized tracking software. At the completion of the pretest (below), the subject watched a video showing the training setup procedures. The subject practiced the setup once under the supervision of the therapist, and then the subject performed 5 or 6 trials to become familiar with the training. After this orientation, the subject took the equipment home.

The subject began a training session by securing custom-made electrogoniometer braces to each hand. One size was used for all subjects, and the fit was adjustable with Velcro hand straps and moldable metallic bands that secured around each person’s wrist (Fig. 2). Each brace included 2 potentiometers (ETI Systems Inc., Carlsbad, CA): one signaling extension/flexion movement at the index finger MP joint and the other signaling extension/flexion movement at the wrist. The voltage signal representing joint motion was directed to the training computer through an analogue-to-digital converter that sampled the signal at 100 Hz. These devices were designed so that accurate placement by the subject at home was not required, that is, there was no need to align anatomical joints with the potentiometers. The device output was repeatable, with electrical noise below 1 pixel on the display screen. As demonstrated through mathematical calculations using the link geometry, the device output approximated, but was not linearly related to, joint angle, particularly at extreme angles. However, the function of the devices used for the training sessions did not require a linear joint angle measure, only a means to control the screen cursor with joint motion. For training, the subject sat in front of the computer screen with forearms resting on the chair’s armrests. At each training session, subjects followed brief prompts on the screen to record the active range of motion at each joint, which were then used to set the extension/flexion limits for the tracking waveforms that followed. Figure 2 shows the training setup.

The program required the subject to perform 180 tracking trials per day for 10 days. The 180 trials were divided into 60 different blocks with 3 consecutive trials per block that were completed over 2 to 8 h depending on rest breaks determined by the subject. To make the telerehabilitation training flexible to each person’s schedule and energy level, and thereby promote compliance, we did not control the distribution of the rest breaks.

The 60 training blocks came from a host set of 100 blocks. A given block did not repeat until the full 100 blocks had been experienced. Possible waveforms included square, sawtooth left, sawtooth right, triangle, or variable sine. Frequencies were 0.2, 0.4, or 0.6 Hz. Trial durations were 5, 10, or 15 s. For example, a 0.4 Hz frequency during a 10-s trial duration involved 4 cycles of extension-flexion movements, each lasting 2.5 s. The peak flexion amplitude of a given target waveform was set at either 0%, 15%, or 30% of the subject’s full range
### Table 1. Subject Characteristics

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Stroke Duration (months)</th>
<th>Infarct Classification (Cortical or Subcortical) and Location</th>
<th>Paretic Side</th>
<th>Preferred Hand</th>
<th>Prestroke MMSE</th>
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<tbody>
<tr>
<td>1</td>
<td>Track</td>
<td>M</td>
<td>62</td>
<td>69</td>
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<td>R</td>
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<td>79</td>
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<td>Subcortical – right corona radiata</td>
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<td>R</td>
<td>R</td>
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<td>36</td>
<td>Cortical – right fronto-parietal cortex</td>
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**Track Group Summary**

<table>
<thead>
<tr>
<th>M:F (Frequency/Mean ± SD)</th>
<th>Cortical:Subcortical</th>
<th>R:L (Frequency/Mean ± SD)</th>
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</thead>
<tbody>
<tr>
<td>9:1 65.9 ± 7.4 42.5 ± 24.3</td>
<td>5:5</td>
<td>5:5 10:0 27.1 ± 2.6</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Stroke Duration (months)</th>
<th>Infarct Classification (Cortical or Subcortical) and Location</th>
<th>Paretic Side</th>
<th>Preferred Hand</th>
<th>Prestroke MMSE</th>
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<tbody>
<tr>
<td>11</td>
<td>Move</td>
<td>M</td>
<td>78</td>
<td>58</td>
<td>Subcortical – right internal capsule</td>
<td>L</td>
<td>R</td>
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<tr>
<td>12</td>
<td>Move</td>
<td>M</td>
<td>55</td>
<td>16</td>
<td>Subcortical – left corona radiata</td>
<td>R</td>
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<tr>
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<td>72</td>
<td>70</td>
<td>Subcortical – right corona radiata</td>
<td>L</td>
<td>R</td>
<td>26</td>
</tr>
<tr>
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<td>Move</td>
<td>M</td>
<td>65</td>
<td>13</td>
<td>Cortical – right fronto-parietal cortex, corona radiata</td>
<td>L</td>
<td>R</td>
<td>30</td>
</tr>
<tr>
<td>15</td>
<td>Move</td>
<td>M</td>
<td>85</td>
<td>14</td>
<td>Cortical – left posterior frontal cortex, corona radiata</td>
<td>R</td>
<td>R</td>
<td>30</td>
</tr>
<tr>
<td>16</td>
<td>Move</td>
<td>F</td>
<td>77</td>
<td>14</td>
<td>Subcortical – right internal capsule, putamen</td>
<td>L</td>
<td>L</td>
<td>30</td>
</tr>
<tr>
<td>17</td>
<td>Move</td>
<td>F</td>
<td>49</td>
<td>82</td>
<td>Cortical – right frontal cortex, corona radiata</td>
<td>L</td>
<td>R</td>
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<tr>
<td>18</td>
<td>Move</td>
<td>M</td>
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<td>44</td>
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<tr>
<td>19</td>
<td>Move</td>
<td>M</td>
<td>73</td>
<td>28</td>
<td>Subcortical – right corona radiata, internal capsule, thalamus</td>
<td>L</td>
<td>R</td>
<td>28</td>
</tr>
<tr>
<td>20</td>
<td>Move</td>
<td>F</td>
<td>54</td>
<td>17</td>
<td>Subcortical – right corona radiata, extreme capsule, claustrum, insula</td>
<td>L</td>
<td>R</td>
<td>30</td>
</tr>
</tbody>
</table>

**Move Group Summary**

<table>
<thead>
<tr>
<th>M:F (Frequency/Mean ± SD)</th>
<th>Cortical:Subcortical</th>
<th>R:L (Frequency/Mean ± SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6:4 67.4 ± 11.8 35.6 ± 26.1</td>
<td>3:7</td>
<td>2:8 9:1 28.6 ± 1.6</td>
</tr>
</tbody>
</table>

Stroke duration = time from stroke onset to entrance into study; MMSE = Mini-Mental State Examination (no units); M = Male; F = female; R = Right; L = Left.
Figure 1. Flow chart showing the number of subjects at each stage of the study.
(0% = full flexion), and the peak extension amplitude was set at 70%, 85%, or 125% of full range (100% = full extension). Thus, if the subject could extend the joint 60 deg from the fully flexed position, and the designated tracking protocol involved flexion/extension limits of 15%/85% of the available range, respectively, the flexion limit of the tracking target would be 9 deg above the fully flexed position and the extension limit would be 9 deg below the fully extended position. The condition of 125% was included, even though it exceeded the subject’s active extension range, to stimulate the subject to strive for further extension range.

The paretic hand was used for 90% of the blocks and the nonparetic hand for 10%. For a given hand, the joint used during tracking was either the index finger MP joint (50%) or the wrist (50%).

Hand position was varied to create either stimulus-response compatibility or incompatibility in the task. Finger or wrist extension always produced upward movement of the cursor on the screen, but the position of the hand was varied between pronation, neutral, and supination. The pronated position was the compatible position, as upward finger or wrist extension produced upward cursor movement on the computer screen. With the hand neutral between pronation and supination, finger or wrist extension occurred in the horizontal plane but produced vertical cursor movement. With the hand supinated, downward finger or wrist extension produced upward cursor movement. Incompatibility was included because spatial processing has been shown to be a potent factor influencing excitability of the primary motor area in primates.

Figure 2. Training setup for a subject in the track group. The computer screen shows a “sawtooth right” target waveform and tracking response. Cartoons at bottom prompt which hand (right or left), joint (finger or wrist), and position (pronated, supinated, or neutral) to use. A flashing light-emitting diode on the electrogoniometer also assists subject in recognizing which joint to use (in this case, the right index finger metacarpophalangeal joint). The Web camera above the screen is turned on with a switch on the white box to show an image of the subject to the remote therapist simultaneous with the subject seeing an image of the therapist on screen. A cellular phone with speaker adaptation allows verbal communication with the therapist while video conferencing over the regular telephone line. With the keyboard covered for simplicity, pressing the red button on the black box starts, pauses, or ends a training session.
During a trial, the cursor swept automatically from left to right across the screen while the subject extended and flexed the proper joint to track the cursor as accurately as possible along the target waveform. Next, the computer displayed a pause screen for a time equal to the duration of the preceding trial. After the 3rd trial of a given block, the computer showed the icon prompts for the next block of 3 trials.

Knowledge or results (KR)\(^\text{14}\) was provided during the pause at the end of each trial with a computer-calculated accuracy score.\(^\text{15}\) Although Anderson and others\(^\text{16}\) found better retention of motor skill in healthy subjects with a less frequent schedule of KR, we chose every trial because we believed it helped to keep these subjects with stroke motivated. Knowledge of performance (KP)\(^\text{14}\) was presented less frequently. KP consisted of a computer-generated text comment describing a feature to correct in the tracking behavior. Algorithms were written to detect such behaviors as undershooting the target, lagging/leading the target, or a declining range of extension movement during the last quarter of the trial compared to the first quarter. If values exceeded a certain threshold, based on values derived from healthy subjects during pilot testing, a comment was displayed to the subject identifying the error along with a suggestion for improvement. For given tracking protocols, the threshold for eliciting KP comments was held constant across training sessions and across subjects. The schedule of KP, however, was faded, occurring at the end of every 2nd block for the 1st day and declining to every 20th block by the end of the 10th day. This schedule was based on the principle that excessive extrinsic feedback interferes with one’s own intrinsic error detection capability, which can disrupt learning.\(^\text{17}\) When KP did occur, it was for only the preceding trial. Included with the KP was a brief motivational comment that encouraged continued effort.

Teleconferencing was used to reinforce a human interaction and therapeutic relationship between the subject and the therapist, albeit from a distance. This technology consisted of a cellular phone and a Web camera that operated over the Internet connection using the subject’s telephone line. This equipment was issued to each subject along with the training computer. The therapist contacted the subject about 5 times in total over the 10 training sessions using a cellular phone and Web camera. Also, the therapist had a pager and was available to answer specific questions if the subject called. When the subject activated the Internet connection by turning on the switch on the white box, the therapist and patient could see each other on their respective computer screens. The therapist and patient could see each other on the computer screen in a 128 × 96 pixel window. Video imaging was transmitted at 3 frames/s. This system did not show the actual tracking effort of the subject, nor did it transmit the performance records to the therapist. These records were retrieved from the computer when the subject returned to the laboratory for the posttest.

Training: Move Group

Subjects in the move group received finger and wrist movement training in their own homes. The setup and procedures for determining the range of motion for each joint were the same as for the track group. The number of blocks, trials per block, duration of each trial, and rest between trials were the same as for the track group. During a movement trial, the screen showed a sweeping cursor but it did not show a target or response. The subject was instructed to move the proper joint into extension and flexion using a range that approximated their full limits and a rate that approximated 0.4 Hz, as instructed at orientation. Neither KR nor KP was provided to the subject. Motivational comments were provided by the computer with the same frequency given to the track group but were not based on prior performance. Also, teleconferencing occurred with the same frequency. At the completion of the 10 days (1800 move trials), the posttest was given, after which move subjects crossed over to receive 10 additional days of tracking training.

Testing

For track and move subjects, testing occurred before (pretest) and after (posttest) training. Additionally, track subjects received a follow-up test 3 months after the posttest to check for retention and move subjects received a crossover test after 10 days of tracking training. All tests were identical and consisted of a Box and Block test, Jebsen Taylor test, finger range of motion test, and finally a finger tracking test simultaneous with fMRI. As the poststroke duration was at least 12 months for all subjects, we did not establish a baseline of stable motor recovery with multiple pretests prior to initiation of treatment.

*Box and Block test.* For this test, subjects grasped 2.54 cm\(^3\) blocks from one side of a divided box with the tip of the index finger and tip of the thumb of the paretic hand and released the block on the opposite side of the box. Subjects performed three 60-s trials of grasping and releasing as many blocks as possible, one at a time.\(^\text{18}\)

*Jebsen Taylor test.* For each testing point, subjects performed 1 trial of the following components of the Jebsen Taylor test\(^\text{19}\): 1) turning over cards, 2) picking up small objects (e.g., pennies, paper clips), 3) stacking checkers, 4) picking up beans with a spoon, 5) turning...
over large empty cans, and 6) turning over large weighted cans. We did not use the handwriting component of this test, because not all subjects used their paretic hand for handwriting before the stroke. Each test was timed separately, and the dependent measure was the total time to complete all tests. Although the original Jebsen Taylor test did not include a time limit, we set a maximal allowable time for completing any given component at 180 s.

**Finger range of motion test.** An electrogoniometer was attached to the paretic hand with the potentiometer centered at the MP joint of the index finger. The voltage signal from this potentiometer was directed to the test computer through an analogue-to-digital converter (Interactive Structures, Inc., Bala-Cynwyd, PA) that sampled the signal at 60 Hz. To determine the range of motion at the index finger, subjects were instructed to make a fist followed by maximum extension of the index finger. The subject held the finger at the peak of each motion for approximately 3 s, and the investigator pressed a key on the computer to automatically record the voltage signal, which was then converted into an angular value (degrees).

**Finger movement tracking test.** Accuracy of tracking movements of the index finger was measured during fMRI. The electrogoniometer remained attached to the subject’s paretic hand. A 2nd electrogoniometer was placed on the nonparetic hand but was used only to monitor for mirror movements.20 Subjects were positioned supine inside a 3 Tesla magnet (see below). Head movements were minimized through stabilization pads inside the head coil. A mirror was mounted to the head coil to allow subjects to view a target waveform that the computer displayed on a projection screen. The paretic arm was adducted to the chest. The elbow was flexed to 45 deg, and the hand was propped in the pronated position near the hip, neutral between extension and flexion of the wrist, using foam pads. With this position, finger extension and flexion occurred in the vertical plane. Subjects were instructed to move only the paretic fingers (long, ring, and little fingers were allowed to move with the tracking index finger) and nothing else. Subjects wore earplugs and headphones to dampen the magnet noises and allow for communication with the investigators.

The tracking test consisted of six 1-min phases alternating between Rest and Track conditions: Rest1, Track1, Rest2, Track2, Rest3, Track3. For all phases, the computer displayed a sinewave target (0.4 Hz) along with the corresponding prompt, “Rest” or “Track,” at the bottom of the screen. The peak-to-peak amplitude was the same at pretest and posttest. The lower (flexion) peaks were set at 15% of the subject’s available finger range of motion, with the subject’s full flexion defined as 0% of the range and the subject’s full extension defined as 100%. The upper (extension) peaks were set at 150%. Thus, at pretest, the extension peaks exceeded the subject’s available range but allowed for improved tracking accuracy at posttest if the subject’s extension range of motion improved following training. For each Track phase, the cursor swept from left to right across the screen and the subject attempted to track the target as accurately as possible with careful extension and flexion movements. For each Rest phase, the subject watched the cursor sweep across the screen but executed no finger movements. Two 1-min practice trials occurred before entering the magnet, and a 10-s practice trial occurred again inside the magnet. If necessary, vision was corrected using appropriate lenses inserted into plastic frames. Investigators visually monitored for extraneous movements in the subject throughout the tracking test, plus any subtle mirror movements in the nonparetic index finger were detected with the 2nd electrogoniometer identified above. Subjects who showed such movements were not included in the fMRI analysis, and this occurred for two subjects in the track group.

Tracking accuracy was quantified with an accuracy index defined as

\[
\text{Accuracy index} = 100\left(1 - \frac{E}{P}\right)
\]

Where \(E\) is the root-mean-square (rms) error between the target line and the response line and \(P\) is the magnitude of the subject’s target pattern, calculated as the rms difference between the sinewave and the midline separating the upper and lower halves of the sinewave. The maximum possible score is 100%. Negative scores occur when the response line falls on the opposite side of the midline from the target.

**fMRI**

Anatomical and functional images were acquired using a whole-body 3 Tesla magnet (Magnetom Trio, Siemens, Munich, Germany) equipped with a standard head coil. A high-resolution (1 mm\(^3\)), \(T_1\)-weighted, 3D anatomical image dataset (3D FLASH, \(T_{\text{R}} = 20\) ms, \(T_{\text{E}} = 30\) deg, total acquisition time = 10:44 min) was acquired over the entire brain to identify appropriate landmarks and serve as a template upon which functional images would be overlaid. Functional images were obtained while the subject performed the tracking test and consisted of \(T_{\text{E}}\)-weighted functional MR images of the BOLD (blood oxygen–level dependent) signal with a slice thickness of 3 mm, which were obtained in the transverse plane using a gradient echo EPI sequence (\(T_{\text{R}} = 30\) ms, \(T_{\text{E}} = 3000\) ms, \(FA = 80\) deg, \(FOV = 192 \times 192\) mm with a matrix size of \(64 \times 64\) leading to a resolution of \(3 \times 3 \times 3\) mm). The total imaged volume extended from the superior pole of the
cortex to a depth of 108 mm in 36 interleaved slices. A block fMRI design was used whereby 145 MR scans were acquired for a total scan time of 7:15 min, which covered the time for all the alternating rest/track phases plus the 3 to 4 s between each condition needed to toggle the computer display from one phase to the next.

Analysis

fMRI analysis. Brain Voyager (Brain Innovation B.V., Maastricht, the Netherlands) software was used for fMRI data preprocessing and analysis. Functional images were preprocessed to correct for head motion artifacts, differences in slice scan time acquisition, and temporal linear trends. The 3D functional volume was aligned with the corresponding 3D anatomical volume, and both were normalized to standard Talairach space. The change in BOLD signal intensity (percentage) between the track and rest conditions was analyzed separately for every subject using a general linear model (GLM) with 7 predictors. One predictor was the track condition. Three predictors accounted for translational movement of the head in sagittal, coronal, and transverse planes, and the remaining 3 predictors accounted for rotational movement in the same 3 planes. These last 6 predictors were entered as covariates in the model and served to exclude the effect of any movement artifact in the variability of BOLD signal.

For each subject, regions of interest encompassing the primary motor area (M1), supplementary motor area (SMA), and premotor cortex (PMC) in each hemisphere were drawn manually according to landmarks described earlier. The primary somatosensory area (S1) was also drawn and included the gray matter comprising the entire postcentral gyrus.

Once the regions of interest were drawn, statistical analyses were conducted to identify voxels with significantly greater BOLD signal intensity during the track phases compared to rest. For this, a GLM analysis was carried out to compare the boxcar model of alternating rest-track phases (including the projected hemodynamic response) with the observed BOLD signal data. The voxels were deemed active if they surpassed the threshold of a false determination rate of less than 0.01. The raw volume of activation for each region of interest was quantified as the total number of active voxels. However, raw voxel count is prone to physiological variations in BOLD signal; thus, voxel count for each region of interest was normalized in 2 ways. First, relative volume of activation for each region of interest was calculated as follows:

\[
\text{Relative Volume} = \frac{\text{Voxel count}_{\text{specified region}}}{\text{Voxel count}_{\text{M1+S1+PMC+SMA}}} \times 100.
\]

Second, volumes of activation for a given region of interest were compared between hemispheres by using the laterality index, calculated as:

\[
\text{Laterality Index} = \frac{\text{Voxel count}_{\text{ipsilesional}} - \text{Voxel count}_{\text{contralateral}}}{\text{Voxel count}_{\text{ipsilesional}} + \text{Voxel count}_{\text{contralateral}}}.
\]

where ipsilesional refers to the stroke hemisphere contralateral to the performing paretic hand and contralateral refers to the nonstroke hemisphere ipsilateral to the performing paretic hand.

Besides exploring the volumes of activation during track phases, we were also interested in studying the change in BOLD signal intensity during the track phases versus rest. Thus, for each cluster of active voxels, we calculated an intensity index as the percentage increase in signal intensity during Track above Rest:

\[
\text{Intensity index} = \frac{\text{Intensity}_{\text{Track}} - \text{Intensity}_{\text{Rest}}}{\text{Intensity}_{\text{Rest}}} \times 100,
\]

where \(\text{Intensity}_{\text{Track}}\) is the average BOLD signal intensity during Track phases and \(\text{Intensity}_{\text{Rest}}\) is the average BOLD signal intensity during Rest phases.

Statistical analysis. Behavioral and fMRI data at pretest and posttest were analyzed statistically with a 2-factor (group × test) analysis of variance (ANOVA) with repeated measures. Post hoc analysis examining for baseline differences between groups was done with 2-sample \(t\) tests. Examination for change from pretest to posttest was done with preplanned paired \(t\) tests. We compared results from posttest to follow-up within the track group and from posttest to crossover within the move group using paired \(t\) tests. Statistical significance was set at \(P < 0.05\).

RESULTS

Examination of the tracking records retrieved from the training computers confirmed that each subject did exert effort on each trial, evidenced by the response trace. Only on rare trials (<1%) did subjects fail to execute movement throughout the entire trial. We observed that the move subjects generally selected a higher rate of movement than the track subjects. To estimate the difference, we visually counted the movement repetitions for all subjects on all trials of 2 training sessions (total = 360 trials). The mean (±SD) of the total number of movement repetitions for the move group was 13.0 (±4.9), compared to 5.5 (±0.8) for the track group (Mann-Whitney \(U\), \(P = 0.002\)). Figure 3 illustrates this difference in movement repetitions for 1 subject in the move group doing movement training (before crossover) and tracking training (after crossover).
Behavioral

For all measures below, there was no significant difference between groups at pretest. For the Box and Block measure, the ANOVA revealed significant effects for test ($P < 0.001$) and interaction ($P = 0.02$). From pretest to posttest, as shown in Figure 4A, the track group improved from a mean ($\pm SE$) of 23.9 (±4.4) to 25.9 (±5.5) blocks ($P = 0.03$) and the move group showed greater improvement from 31.7 (±4.9) to 36.6 (±5.9) blocks ($P < 0.001$). For the track group, 8 subjects returned for a follow-up test and their performance was unchanged at 28.9 (±5.2) blocks, indicating that the benefit from pretest to posttest was retained. For the move group, 9 subjects crossed over to receive tracking training. Their performance at crossover was unchanged at 37.9 (±7.3), indicating that the tracking training following their movement training did not result in additional improvement.

For the Jebsen Taylor test, a significant test effect ($P = 0.002$) was found but there was no evidence of differences between groups. From pretest to posttest (Fig. 4B), the track group improved from 218.6 (±49.1) to 154.3 (±31.5) s ($P = 0.01$) and the move group improved from 144.8 (±31.5) to 92.2 (±21.9) s ($P = 0.03$). Performance in the track group at follow-up was 154.9 (±42.2) s, and in the move group at crossover, it was 98.6 (±34.4) s, which were not significantly different from their respective posttests.

For finger range of motion, significant effects were found for test ($P = 0.02$) and interaction ($P = 0.03$). From

Figure 3. Finger movement responses of 1 subject from the move group at trial #M1179 of movement training (A) and in the same subject, following crossover, at trial #T1179 of tracking training (B). During (A), the subject saw only a blank screen and produced 26 extension-flexion movements. During B, the subject saw the 8 cycles of the target square wave and the response trace and produced 8 extension-flexion movements. (On the $y$-axis, 0% represents full flexion and 100% represents full extension for each subject.)
pretest to posttest (Fig. 4C), the track group improved from 64.5 (±10.8) to 86.5 (±8.4) deg (P = 0.004), whereas the move group showed a nonsignificant change from 76.5 (±12.9) to 77.7 (±5.4) deg. Performance in the track group at follow-up was 82.8 (±10.0) deg, and in the move group at crossover, it was 78.9 (±6.3) deg, which was not different from their respective posttests.

For finger tracking, a trend toward significance was found for interaction (P = 0.07). From pretest to posttest (Fig. 4D), the track group improved from −30.3% (±5.2) to −6.9% (±6.6) (P = 0.02), whereas the move group showed a nonsignificant change from −27.6% (±5.2) to −29.1% (±5.5). Performance in the track group at follow-up was −1.65%, which was not different from their posttest. For the move group at crossover, however, tracking accuracy increased to −8.14% (±9.2) (P = 0.06).

Imaging

For the relative volume of activation in the ipsilesional hemisphere, M1 showed group (P = 0.05) and interaction (P = 0.05) effects, PMC showed test (P = 0.04) and interaction (P = 0.04) effects, and SMA showed interaction (P = 0.03). From pretest to posttest (Fig. 5), M1 for the track group showed a trend toward increased activation (P = 0.07), whereas SMA showed a significant decrease (P = 0.008). For the move group, PMC showed a trend toward increased activation (P = 0.08). In the contralesional hemisphere, there were no significant findings for any region.

For the laterality index data during the finger tracking test, interaction was significant in the M1 (P = 0.04) and approached significance in the S1 (P = 0.06). Figure 6 shows that the laterality index in the M1 decreased.
significantly from pretest to posttest for the move group ($P = 0.04$), indicating a shift away from ipsilesional toward contralesional activation, whereas it increased for the track group, although not significantly. Similarly, in the S1, the decrease for the move group approached significance ($P = 0.06$), whereas the increase for the track group was not significant.

For the intensity index in the ipsilesional hemisphere, the M1 showed test ($P = 0.004$) and interaction ($P = 0.05$) effects, whereas only test effects were found for the S1 ($P = 0.03$) and PMC ($P = 0.04$), with no evidence of group differences. From pretest to posttest (Fig. 7), the decrease in intensity for the M1 in the move group was significant ($P = 0.03$), whereas the decrease for the track group was not. PMC showed a trend toward a significant decrease ($P = 0.06$) for the track group but not for the move group. However, after crossover, the move group showed an increased intensity ($P = 0.004$). In the contralesional hemisphere, trends toward a test effect were found in the M1 ($P = 0.07$) and PMC ($P = 0.07$). Figure 7 shows that the decrease for the move group was significant ($P = 0.05$) but not for the track group. The changes from posttest to follow-up and posttest to crossover were nonsignificant except for the contralesional M1 in the move group, which showed a significant increase ($P = 0.05$) in intensity.

Figure 8 shows for 1 subject in the track group the improvement in tracking responses and corresponding MR scans from pretest to posttest, with a shift toward greater ipsilesional activation.

Figure 9 shows for 1 subject in the move group the tracking responses and MR scans at pretest, posttest, and post-crossover. In contradistinction to the results of Figure 8, the laterality index for the M1 showed strong ipsilesional (0.85) activation at pretest, shifting to contralesional (~0.39) activation at posttest, and even greater contralesional activation (~0.44) at crossover, despite the improved tracking accuracy.

**DISCUSSION**

This study examined in subjects with stroke whether telerehabilitation emphasizing temporospatial processing during movement training would be more effective in improving hand function and brain reorganization than movement training without such processing. The difference in training was the mental effort required to
perform the assigned task. Both groups performed repetitive manual movements, but the track group presumably had to engage greater motor and cognitive resources to produce accurate movements. Although we did not quantify the difference in effort, subjects in the track group consistently reported that the task was fatiguing, whereas subjects in the move group did not. The results showed that telerehabilitation for both groups was effective in producing functional gains, but a clear advantage for those who performed more temporospatial processing (track group) did not materialize. The track group did show greater improvements in tracking accuracy and finger range of motion, but because this group trained with tracking and also trained to increase their range of motion (using tracking protocols with amplitudes at 125% of their range), these gains over the move group were expected. In transferring skill to more functional tasks (Box and Block, Jebsen Taylor tests), the improvements for the track group did not surpass those for the move group. In the Box and Block test, the improvement for the track group was small (2 blocks), and although statistically significant, this change may not be clinically significant. The improvement was actually greater for the move group. Despite the behavioral improvements in both groups, a consistent pattern of brain reorganization linked to these gains was not evident.

We based our hypothesis of greater gains in the track group on studies that had shown a pattern of more brain reorganization following motor tasks with active cognitive processing compared to motor tasks without such processing. The mechanisms underlying these changes were not determined but may be related to trophic factors in the brain responding to both physical and cognitive activity. Such studies point to the possibility of neurochemical mechanisms predicated as much or more on motor learning as on physical activity per se to promote neuroplasticity associated with skills learning.

Two reasons may explain why we did not find an advantage with motor learning training in the track group over the more simple training in the move group. First, although we “yoked” our track subjects and move subjects so that they had the same number of training trials and total training time, differences within training trials occurred. The number of extension/flexion movements produced by move subjects during any given trial was not controlled, and this was important to remove temporal processing from the task in the move group. Instead, move subjects were instructed at orientation to perform movements at a “comfortable” rate that we demonstrated. Nonetheless, move subjects produced extension and flexion movements at a significantly higher frequency than the track group (Fig. 3). Repetitive movement training by
itself has been shown to improve manual performance in stroke,\(^2^9\) and the possibility exists that the greater number of extension/flexion finger movements in the move group could have offset the temporospatial processing advantage in the track group.

Second, the treatment dosage (total trials), duration (total time), and distribution of rest in the track group may not have been adequate to promote the necessary brain reorganization for consolidation of learning. The total trials devoted to finger tracking training in this study was 900, whereas our earlier work,\(^5\) which did show significant brain reorganization, involved 1200 trials. Also, the duration of training in that study was 4 weeks, compared to 2 weeks in the present study. Karni and others\(^3^0\) showed that brain reorganization during motor learning is dependent on the duration of training in normal subjects. Finally, the distribution of rest time between practice was more compressed in the current study compared to our earlier work. Ofen-Noy and others\(^3^1\) suggested that the amount of practice may not be as important to learning as the “passage of time” between practice, and Savion-Lemieux and Penhune\(^3^2\) emphasized that spacing of rest between practice is important to allow time to process and encode ongoing task information. Thus, as we took advantage of the convenience of telerehabilitation training in the subject’s own home by intensifying the training into a shorter duration with less time between training sessions, we may have

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**Figure 7.** Means (± standard error) of intensity index in the ipsilesional and contralesional primary motor area (M1), primary somatosensory area (S1), premotor cortex (PMC), and supplementary motor area (SMA) for track and move groups across tests. \(a\) = trend toward significant decrease from pretest \((P = 0.06)\); \(b\) = significant decrease from pretest \((P = 0.03)\); \(c\) = significant increase from posttest to crossover \((P = 0.004)\); \(d\) = significant decrease from pretest \((P = 0.05)\); \(e\) = significant increase from posttest to crossover \((P = 0.05)\).
violated as yet unknown biologic rules important for skills learning after stroke. As a result, the observed functional gains in the track group may not have reached their full potential.

In assessing fMRI activity during paretic hand function following training, Feydy and others described “focusing” as the gradual restriction of neural activation to the ipsilesional hemisphere and “recruitment” as the extension of activation to the contralesional hemisphere. Ward and others studied patients with stroke longitudinally and found that patients with lesser recovery were more likely to recruit a greater number of brain regions, including contralesionally. They suggested that the more expanded and intense activation in patients

Figure 8. Sample tracking responses for 1 subject from the track group tracking with paretic left index finger (0 deg = maximum flexion). Accuracy improved from –20.07% at pretest to 45.01% at posttest. Representative brain activation maps (1 slice) show mainly contralesional activation in the primary motor (M1) and primary somatosensory (S1) areas (green arrows mark central sulcus) at pretest (M1 laterality index = –0.50 and S1 laterality index = –0.53), shifting in the direction toward more ipsilesional activation at posttest (M1 laterality index = –0.03 and S1 laterality index = –0.18).
Figure 9. Sample tracking responses for 1 subject from move group tracking with paretic right index finger (0 deg = maximum flexion). Tracking accuracy was –21.39% at pretest and –33.01% at posttest and improved to 26.4% at crossover. Brain activation maps show mainly ipsilesional activation in the primary motor area (M1) (green arrows mark central sulcus) at pretest (M1 laterality index = 0.85), shifting to contralesional activation at posttest (M1 laterality index = –0.39) with further progression to contralesional activation at crossover (M1 laterality index = –0.44).
with poorer recovery was due to their need to pay closer attention to the motor task.

Our fMRI results show evidence of training-induced focusing. For intensity index (Fig. 7), a significant decrease occurred in the ipsilesional M1, S1, and PMC from pretest to posttest, but this decrease was not specific to either group. However, in the relative volume of activation for the ipsilesional M1, PMC, and SMA, we did find significant interaction between groups from pretest to posttest. In particular, the trend with tracking training toward a significant increase in the M1 proportion of total activation in this hemisphere, combined with the significant decrease in the SMA proportion, may represent an early expression of training-induced focusing of cortical activation. But longer training time with more trials or more rest between training sessions may be needed to reveal a more causal link between brain reorganization and training-induced improvements in behavior.

A further expression of training-induced focusing of cortical activation is suggested by the change in laterality index in the M1 and S1. Significant interaction between groups from pretest to posttest was found in both regions, but this difference in response was due primarily to the precipitous decrease in volume of ipsilesional activation in the move group. Although the volume of ipsilesional activation in the M1 and S1 did increase in the track group, it was not significant, as it was in our earlier study, and the possible reasons may again relate to differences in dosage, duration, or distribution of rest. The move group’s precipitous change from ipsilesional activation toward contralesional activation in the M1 and S1 was conspicuous. Different patterns of brain reorganization exist following stroke, and the possibility exists that training with simple movements may promote predominantly contralesional M1 and S1 activation, whereas more difficult tracking training may promote predominantly ipsilesional activation. A number of studies have shown that with evoked or voluntary activity of the paretic hand, greater contralesional cortical activation (i.e., ipsilateral to the paretic hand) is associated with poorer function and that with improved recovery, there is a shift toward ipsilesional activation. Such contralesional activation, through exaggerated interhemispheric inhibition, may actually interfere with excitability of the ipsilesional hemisphere, and studies have shown that disruption of the contralesional M1 with repetitive transcranial magnetic stimulation can improve paretic hand function. Thus, further studies are needed to determine whether certain training procedures are more apt to promote brain reorganization in the ipsilesional hemisphere versus the contralesional hemisphere and whether such orchestration influences recovery.

A further conspicuous feature in the move group was their absence of change in Box and Block, Jebsen Taylor, and finger range of motion performance (Fig. 4A-C) following crossover. In our previous study, the control group showed significant functional improvement after crossing over to receive tracking training. The notion that move subjects here had reached a ceiling effect after movement training seems doubtful, as scores were still far below normal. Mathiowetz and others reported for healthy males and females 65 to 69 years of age that the mean (±SD) Box and Block scores were 68.4 (±7.1) and 72.0 (±6.2) blocks, respectively, for the right hand and 67.4 (±7.8) and 71.3 (±7.7) blocks, respectively, for the left hand.

The possibility exists that the movement training may actually have prevented further functional gains from the tracking training that followed closely. For example, several clinical studies suggested that bidirectional synaptic plasticity and thresholds for long-term potentiation and depression can be affected by evoking cortical motor responses and by voluntary movements that precede an action. Perhaps, then, the absence of improvement in the move group following crossover resulted from its recent history of intensive practice prior to the tracking training. Clearly, the conditioning methods and the time course between conditioning and measurement differed between the present study and experiments designed to test the limits of synaptic plasticity. The possibility, however, that overly intensive conditioning (training) blocks synaptic plasticity and motor learning remains unexplored in stroke recovery studies.

We believe that telerehabilitation can offer a valuable method for promoting further recovery from stroke, in part because of the convenience of practice at home at a time and intensity that befits a person’s own poststroke medical and psychological conditions. As more details are discovered in stroke on such factors as forced use versus forced learning, optimal schedules of practice with rest, contextual interference, and reinforcement, as well as best dose-response intensity curves for training, the adaptability and flexibility of training availed through telerehabilitation may lessen impairments and disability.

ACKNOWLEDGMENTS

This work was supported by the National Institute on Disability and Rehabilitation Research (U.S. Department of Education #H133G020145-04) and the National Institutes of Health (National Center for Research Resources #M01-RR00400 and Biomedical Technology Research Resources #P41-R008079).
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