Case Report

Combined Use of Repetitive Task Practice and an Assistive Robotic Device in a Patient With Subacute Stroke

Background and Purpose. This case report describes a training program comprising repetitive task practice (RTP) and robotic therapy for a patient with subacute stroke and resultant impaired upper-extremity function. **Case Description.** A 63-year-old man with right-sided hemiplegia resulting from a hemorrhagic stroke received a combined intervention of RTP and robotic therapy for 4 hours per day for 3 weeks. Clinical and kinetic evaluations were performed before and after intervention. **Outcomes.** Following the combined intervention, clinical improvements in hand function were observed, maximum grip force decreased slightly, and interlimb coupling decreased. **Discussion.** An intervention of RTP with robotic therapy may be an effective method to improve upper-extremity function following stroke. Furthermore, the case suggests that improvements in strength are not necessary for improved dexterous function, provided that a minimal level of strength is present. [Frick EM, Alberts JL. Combined use of repetitive task practice and an assistive robotic device in a patient with subacute stroke. *Phys Ther*. 2006;86:1378–1386.]

Key Words: *Forced use, Rehabilitation, Robotic therapy, Stroke, Upper extremity.*

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This case report describes the application of repetitive task practice with adjunct use of a robotic device in an individual with upper-extremity hemiplegia.

Approximately 80% of people with stroke will have some degree of upper-limb involvement.[1] It is not surprising, therefore, to find a large amount of research in recent decades on the rehabilitation of upper-limb impairments in patients with stroke. Until recently, improvements in motor function were believed to be greatest during the first 6 months following stroke, with little to no progress after 6 to 12 months. Some studies that have examined intensive interventions have challenged this expected course of recovery, with patients more than 12 months poststroke showing improved motor function.[2–5] Intensive interventions usually require extensive one-on-one time with a therapist.

One approach that is gaining acceptance in the management of upper-extremity (UE) motor impairment following stroke is constraint-induced movement therapy (CI therapy). Clinical studies with CI therapy have shown that it can increase motor function in patients with both subacute and chronic stroke.[6–8] Studies that have utilized transcranial magnetic stimulation (TMS) have further shown a strong association between CI therapy and motor cortical reorganization.[9] In a 2001 preliminary study in which TMS was used, Liepert et al[10] found that the motor output maps on the affected sides of patients in the subacute stage of stroke were larger following a week of forced use combined with conventional physical therapy, such as Bobath techniques or teaching of compensatory activities with the less-impaired UE, when compared with a week of conventional physical therapy alone. Similarly, with repetitive task practice (RTP) intervention, the patient focuses on using the more-affected hand as in CI therapy, but the less-affected hand is not physically constrained.[8,11] Repetitive task practice has been shown to be effective in improving UE motor performance in patients with chronic stroke.[12] Although promising, interventions such as CI therapy and RTP are expensive forms of rehabilitation because of their intense nature, which requires a great deal of time and extended interaction between the patient and a trained rehabilitation specialist. Current CI therapy protocols calls for patients to participate in therapy sessions 6 hours per day for 10 days.[11] In a recent survey,[13] many therapists and patients expressed concern about traditional CI therapy, with 68% of the therapists saying that they thought it would be "difficult" or "very difficult" to carry out the CI therapy protocol. Furthermore, 85% of the therapists speculated that most facilities did not have adequate resources to administer CI therapy.

In an effort to create an alternative form of treatment, a limited number of robotic devices have been developed.[14] Studies on supplemental robotic treatment suggest that these devices can improve recovery in patients with acute and chronic stroke.[15,16] Many of these systems, however, are not yet suitable for widespread use due to size, cost, and complexity of operation. Furthermore, it is unclear whether these systems offer any unique advantages over conventional therapy.

For a device to be applicable in clinical and home settings, it must be relatively inexpensive, easy to operate, and compact. One assistive robotic device with the potential to be used with RTP or CI therapy is the Hand Mentor (HM) system.* This device uses a pneumatic muscle to extend the wrist and fingers. The framework contains potentiometers, force-sensing resistors, and surface electromyography (EMG) recording electrodes to provide for a variety of intervention modalities. The use

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of this device or similar systems in combination with a reduced amount of RTP or CI therapy may provide a more cost-effective and equally therapeutic form of treatment than RTP or CI therapy alone.

The primary aim of this case report is to describe a 3-week training program using an assistive robotic device in conjunction with RTP to improve functional independence and UE function in motor and somatosensory tasks in a patient with subacute stroke. A secondary aim is to characterize the changes in grasping force control for each limb after this combined intervention.

Case Description

Patient History and Characteristics

The patient was a 63-year-old, right-handed man who had a hemorrhagic stroke in the left thalamus 7 months prior to our intervention. The patient was recruited from the Emory University Center for Rehabilitation Medicine. Although Emory University is currently recruiting patients for an ongoing randomized clinical trial, this patient did not meet the inclusion criteria for this larger study due to his dialysis regimen. Informed consent was obtained in accordance with the local institutional review board.

The patient had a history of hypertension and end-stage renal disease. He was taking medication to control hypertension and was receiving biweekly dialysis at the time of the intervention. The patient had right hemiparesis. In the majority of patients with stroke, both sides are affected, although one side typically is more affected than the other side. We therefore refer to the patient's "less-affected" and "more-affected" sides in this case report. Motor inclusion criteria from a previous CI therapy study[17] were applied in the selection of the patient. The patient was able to actively extend his wrist more than 10 degrees and was able to actively extend the metacarpophalangeal and interphalangeal joints of his thumb and at least 2 additional digits. All movements were performed from a resting position on a supported surface 3 times in 1 minute. He was able to ambulate independently, could balance for 2 minutes without support, had no excessive pain in the more affected limb, and was discharged from all forms of physical rehabilitation. The patient did have sensory impairment on the more involved side. He was not able to detect a difference up to 3 cm during a 2-point discrimination test. Although he was right-side dominant, he performed most activities of daily living (ADL) such as writing using the less-affected side. The patient attempted to use the more-affected side at home in ADL. However, many tasks, especially those requiring bimanual UE use, required assistance. He used the more-affected side primarily for stabilization in bimanual tasks and gross movements such as pointing. The patient was unable to effectively write, feed himself, and perform grooming activities with the more-affected side. The patient's function had plateaued approximately 2 months prior to beginning this intervention.

Instruments

Clinical outcome measures included the Wolf Motor Function Test (WMFT), the Fugl-Meyer Assessment of Motor Recovery (FMA), and the Stroke Impact Scale (SIS). Grip force data were collected using the Gripper System[†]; 3 single-axis Entran force transducers[‡] were used to measure maximal grip force under unimanual and bimanual conditions.

The WMFT is a 17-item instrument consisting of 15 timed performances and 2 strength (muscle force-generating capacity) measures that quantifies UE movement ability in people with mild to moderate stroke.[18] Tasks are sequenced from proximal to distal joint movements and gross to fine motor skills, and then combining all joint movements in functional tasks.[19] Fifteen tasks are performed as quickly as possible, with the final time score equaling the median time required for all timed tasks performed. Morris et al[18] used intraclass correlation coefficients (ICCs) to examine interrater reliability and the Cronbach alpha to examine internal consistency of the WMFT scores in patients with chronic stroke. The ICCs for interrater reliability were .97 or greater for performance time and .88 or greater for functional ability. Cronbach alphas for internal consistency were .92 for both performance time and functional ability in test 1 and .86 for performance time and .92 for functional ability in test 2.[18] The ICCs for test-retest reliability were .90 for performance time and .95 for functional ability.[18]

The FMA assesses several dimensions of impairment to examine for the presence of synergistic and isolated movement patterns and grasp[20] and has been used in CI therapy studies.[17,21] The test scores sensation, motor function, and coordination using a 3-point ordinal scale (0=cannot perform, 1=can perform partially, 2=can perform fully) with a maximum score of 66. The instrument has yielded data showing test-retest reliability (total=.98, subtests=.87–1.00),[22] interrater reliability (Pearson r=.984 for the UE component),[22] and construct validity.[23]

The SIS is a disease-specific instrument that contains 64 items that test over 8 domains: strength, hand function, combined basic and instrumental ADL, mobility, memory and thinking, communication, social participation,

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‡ Entran Devices Inc, 10 Washington Ave, Fairfield, NJ 07004-3877.

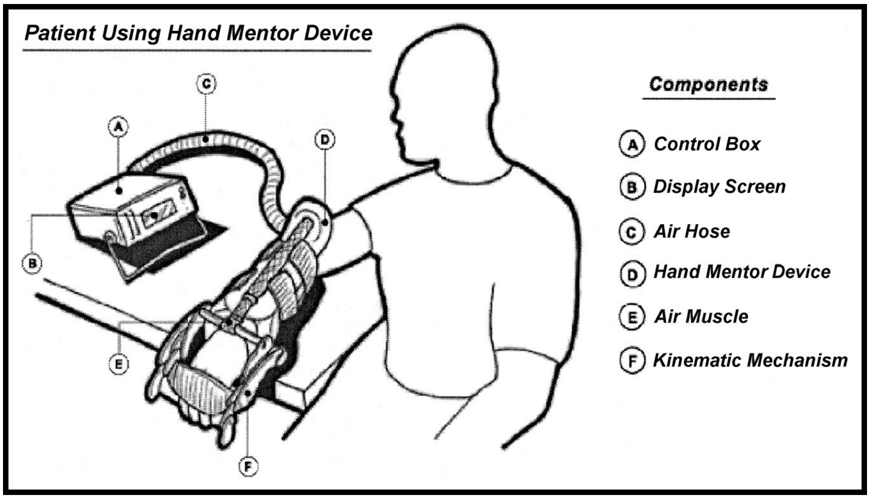

Figure 1.
Illustration of experimental setup.

Table 1.
Actual Time Spent in Each Training Protocol

Protocol	Time (hr)
Repetitive task practice	14.3
Hand Mentor	10.2
Spasticity reduction	2.6
Flexion-extension strengthening	4.6
Electromyographic muscle recruitment	3.1

and emotion. Each domain is scored from 0 to 100, with higher scores associated with greater function. These domains were found to be responsive to change due to ongoing stroke recovery.[24] The instrument has been shown to yield reliable data, with ICCs of each of the 8 domains ranging from .70 to .92.[24] Duncan et al[24] examined validity by comparing SIS scores with data obtained with existing stroke measures and found ICCs ranging from .44 to .84.

Maximum grip force data were collected under unimanual and simultaneous bimanual conditions. The patient was instructed to produce his maximum grip force using his best precision grip. Data from 3 maximum trials, 10 seconds each, were collected in the following order: unimanual maximum grip force with the less-impaired hand, unimanual maximum grip force with the more-impaired hand, and simultaneous bimanual maximum. A rest period of approximately 2 minutes was provided after each trial. The greatest force during the 10-second trial was considered the maximum.

Intervention

The intervention consisted of 2 concurrent components: RTP and HM training. Each component was performed for 2 hours of each 4-hour session. The patient was trained 3 days per week for 3 weeks for a total of 9 sessions. The intervention was initiated during the second visit because the first visit was reserved for a baseline evaluation. A post-intervention evaluation was performed 4 days following the final session. All training and evaluations took place at the Motor Control Laboratory at Georgia Institute of Technology.

Activities during the RTP intervention were varied within each session and between sessions to challenge all UE movements (finger dexterity, pronation/supination, elbow flexion/extension, shoulder flexion/extension/abduction). Examples of tasks included transporting marbles from the hand to the fingertips, stacking cans, and drawing circles. Task difficulty was increased as the patient became proficient in order to continue to challenge him. All tasks were performed solely with the more-affected hand, although no physical constraint was placed on the less-affected hand. Verbal instructions were provided prior to each task, with coaching and encouragement provided throughout the training. All activities were timed and recorded so a complete record could be kept on the total time spent on RTP.

During the HM training portion of each session, the patient was seated comfortably with the more-affected (right) arm resting on a foam pad on the table with the HM device attached (Fig. 1 illustrates the components of the HM system and the typical configuration). The LCD display on the HM device faced the patient, allowing him to receive feedback on his performance, which varied on a trial-by-trial basis depending on which program was selected. Biofeedback such as EMG has been shown to be an effective training approach for patients with stroke.[25–27] Feedback provided by the system included wrist position, wrist flexor resistive torque, and EMG readings of extensor activity. Surface EMG electrodes were placed over the common extensor group on the upper forearm. The position of the HM device relative to bony landmarks and electrode position was recorded and used to ensure consistent placement across sessions.

The HM device had 7 preprogrammed programs from which to select. Three of the programs were termed "anti-spasticity settings." These programs provided a long, continuous stretch of varying time durations (program duration was 30, 60, or 90 seconds) as the hand was slowly brought up into extension and held. The degree to which the hand was brought up was regulated by the

Table 2.
Time Taken to Complete Each Task on the Wolf Motor Function Test (WMFT) With Absolute Change and Percentage of Change

Task	Pretest	Posttest	Absolute Change	Percentage of Change
WMFT (time in seconds)				
Forearm to table	1.3	1.1	0.2	12.5
Forearm to box	2.0	1.6	0.3	17.3
Extend elbow	1.4	1.0	0.4	27.0
Extend elbow (weight)	1.4	1.2	0.2	12.6
Hand to table	1.4	1.5	−0.1	−9.3
Hand to box	1.2	1.3	−0.1	−7.6
Reach and retrieve	1.3	1.1	0.3	18.7
Lift can	3.7	3.8	−0.1	−2.7
Lift pencil	5.6	2.5	3.1	54.8
Lift paper clip	10.8	3.5	7.3	67.7
Stack checkers	15.7	12.0	3.6	23.2
Flip cards	18.9	15.6	3.3	17.3
Turn key in lock	18.4	8.4	10.0	54.2
Fold towel	18.7	10.4	8.3	44.6
Lift basket	4.4	4.3	0.1	2.7
Mean of timed tasks	7.1	4.6	2.4	34.6
Weight to box (lb)	12	12	0	0
Grip force (kg)	16.3	18.0	1.7	9.3

force-sensing resistors within the HM device's framework that responded to increased torque, indicative of stretch on the muscle or spasticity. Recent research on lower-limb spasticity indicates that prolonged stretching with feedback multiple times per week can lead to improvements in passive range of motion, maximum voluntary contraction, and stiffness.[28] The angle of the wrist is provided during the anti-spasticity protocols as feedback. Two of the programs were wrist and finger flexion-extension strengthening protocols. One of these 2 programs required the patient to extend the wrist to maximum extension. The second of these 2 programs required the patient to extend the wrist to a maximum and then to try to reach maximum wrist flexion. While performing either of the strengthening protocols, the patient received feedback on the amount of force produced in the form of a vertical bar on the LCD display screen.

The final 2 programs used EMG readings from electrodes placed on the extensors in the forearm with the aim to work on muscle recruitment. During these programs, the HM system signaled the patient to begin extending the wrist and fingers. A vertical bar on the LCD display screen indicated the relative EMG signal. The patient was instructed to try to increase the height of the bar through increased active extension of the wrist and fingers. The programs were varied within sessions and between sessions. All 3 types of training were performed during each session. No formal decision tree was used to determine time spent in each program. Program selection depended on the patient's level of interest and using those programs that seemed to best target the patient's deficits.

Training Summary

The patient completed all 9 treatment sessions over 3½ weeks. Patient illness necessitated 2 sessions to be rescheduled. Table 1 presents the amount of actual "working" time spent in each therapy protocol. The table does not include time spent for setup or patient rest breaks. The time spent using the robotic device is further broken down by the different programs used; the patient spent the majority of the training time using the flexion/extension and EMG muscle recruitment programs. The spasticity protocol did not prove sufficiently demanding because this patient had only minor spasticity but was used at the beginning of each training session prior to using the more challenging protocols. The patient reported feeling more "warmed-up" following the passive stretch provided by the spasticity protocols. Overall, slightly less time was spent using HM training compared with RTP training due to occasional malfunctioning of the device.

Outcomes

Clinical Outcome Measures

The pretest and posttest scores for each item of the WMFT for the more-affected limb are provided in Table 2. Following the intervention, there was a 2.44 point (34.6%) improvement in the median time of all timed tasks on the WMFT. The largest absolute and percent changes were noted in the tasks that involve hand dexterity (lifting a pencil, lifting a paper clip, stacking checkers, turning a key in a lock, and folding a towel).

There was a 7-point improvement on the motor and coordination portion of the FMA. A 2-point improvement was seen with proprioception, while light touch proprioception did not change (score of 0 before and after intervention). The patient remained unable to detect a difference up to 3 cm during a 2-point discrimination test. Pretest and posttest data are provided in Table 3. For the SIS, improvement was seen in multiple areas, including hand function, strength, and ability to perform ADL (see Tab. 4 for subsection scores).

Table 3.
Fugl-Meyer Assessment of Motor Recovery Scores Before and After Intervention[a]

Component	Pretest Score	Posttest Score	Absolute Change
Joint motion (24)	24	23	−1
Joint pain (24)	24	24	0
Light touch proprioception (4)	0	0	0
Proprioception (8)	2	4	2
Motor and coordination (66)	44	51	7
Reflexes (4)	4	4	0
Flexor synergy (12)	9	10	1
Extensor synergy (6)	3	4	1
Movement combining synergies (6)	4	5	1
Movement out of synergy (6)	4	3	−1
Wrist (10)	6	8	2
Hand (14)	10	13	3
Coordination/speed (6)	4	4	0
Total (126)	94	102	8

[a] Total score possible shown in parentheses.

Table 4.
Stroke Impact Scale Scores Before and After Intervention[a]

Component	Pretest Score	Posttest Score	Percentage of Change
Physical function			
Hand function	25	50	25
Strength	38	63	25
Activities of daily living	53	60	7
Mobility	75	61	−14
Social participation	66	66	0
Communication	86	71	−15
Memory and thinking	75	68	−7
Emotion	50	50	0

[a] Maximum possible score of 100.

Grip Force Data

Pretest and posttest grip force for the more-affected and less-affected limbs under unimanual maximum efforts are shown in Figure 2. No improvement was seen in the maximum force produced by the more-affected hand following the intervention. The average maximum values for both unimanual and bimanual grasp are provided in Figure 3 for preintervention and postintervention conditions. The average of the maximum values produced over 3 trials was lower for the more-affected side (21.57 N compared with 16.43 N) following treatment. The maximum grip force of the less-affected hand was much closer to that of the more-affected hand during the pretest than during the posttest.

Representative force-time profiles during the simultaneous bimanual conditions are shown in Figure 4. Inspection of preintervention data shows that while the more-affected hand had similar maximum grip force values compared with unimanual gripping, the less-affected hand had much lower values. Furthermore, a clear coupling between the profiles of the more-affected hand and the less-affected hand can be seen, with the pattern of the force being very similar. Postintervention data show that, although the maximum grip force of the affected hand did not improve, the grip force of the less-affected hand of 55.8 N during bimanual gripping was higher than the unimanual average maximum grip force of 47.5 N. A coupling in the force-time profiles is also no longer as apparent. Figure 5 illustrates the grip force for the more-affected limb as a function of force produced by the less-affected limb. Pretest data are represented by the solid line, and posttest data are represented by the dotted line. The relationship between the 2 hands is greater during the pretest levels (slope of the regression line is 0.76, while slope between hands at the posttest was 0.13). These data suggest that there was a greater degree of coupling between the 2 limbs prior to the combined intervention.

Discussion

The aim of this case report was to describe the changes in clinical and kinetic data in a patient with subacute stroke with sensory loss who participated in a 3-week therapy program that combined RTP with use of a robotic assistive device. The outcomes suggest that the combined program led to improvements of clinical outcome measures as well as an altered gripping strategy while trying to achieve maximum grip force under bimanual conditions.

Clinical Outcomes

The WMFT data showed an improvement in UE function, especially for those activities requiring distal hand function. Eight of the 17 component tasks of the WMFT showed very little improvement between the pretest and the posttest. Six tasks, however, showed improvements ranging from 23.2% to 67.7% from pretest to posttest. Five of those 6 tasks require fine control of distal musculature. The mean of all of the timed tasks decreased from pretest to posttest, indicating that a combined intervention improves UE function. Consistent with the WMFT data, greater changes in hand-

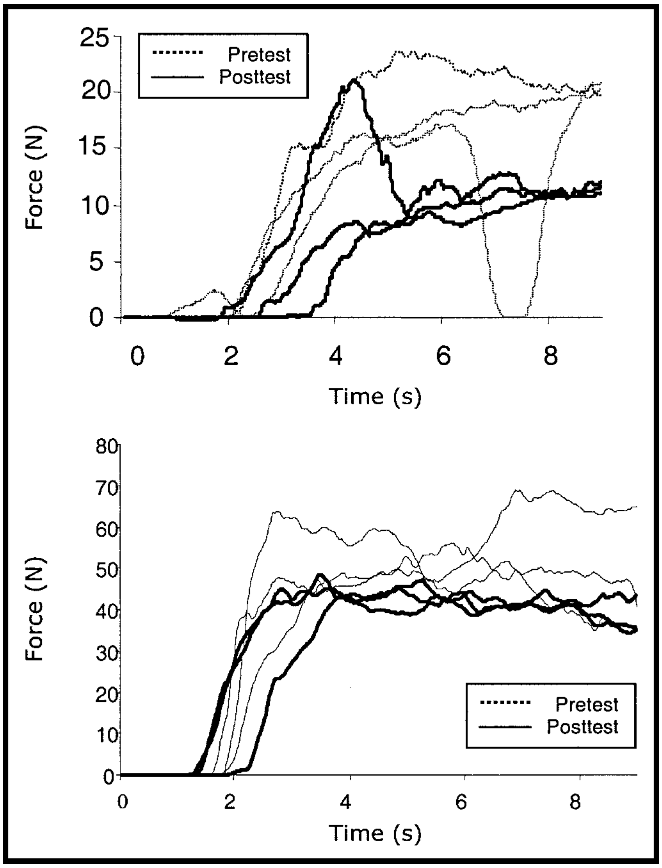

Figure 2.
(Top) Pretest (dotted lines) and posttest (solid lines) grip force profiles during unimanual maximum grip for the more-affected limb. (Bottom) Pretest (dotted lines) and posttest (solid lines) grip force profiles during unimanual maximum grip for the less-affected limb.

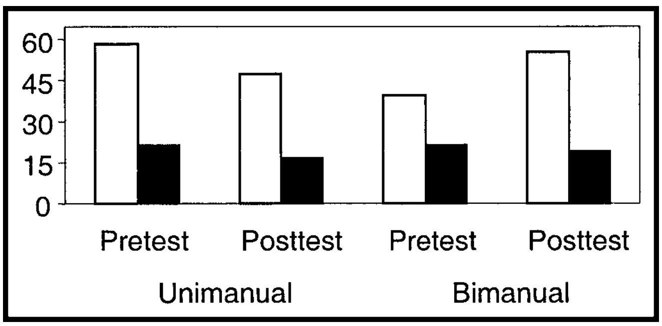

Figure 3.
Average maximum grip force for the less-affected hand (unfilled bars) and the more-affected hand (filled bars) in unimanual and bimanual conditions. Pretest and posttest results are shown.

related domains were observed in the FMA and SIS data. Previous investigations of CI therapy have shown similar results of an improvement in UE function as assessed by clinical outcome scales.[6,7]

These are the first data that show an improvement in distal UE function following a program of reduced RTP combined with use of a robotic assistive device such as the HM. The improvement in motor function was seen without any associated improvement in sensation of the UE. This outcome is similar to the results of a study by van der Lee and colleagues[29] comparing forced-use therapy with a reference therapy based on neurodevelopmental treatment. The only patients in that study who achieved notable improvement were those patients with sensory disorders, suggesting that patients without sensory disorders had already reached the upper limit of dexterous ability. Although motor function certainly relies a great deal on sensation, these data suggest that the central nervous system, with intensive rehabilitation, is capable of compensating for a loss in sensory function. This is interesting to note considering that the original research done by Taub[30] on the learned nonuse theory was performed with monkeys that had undergone deafferentation leading to sensory, but not motor, deficits. Further research is needed to determine exactly what role sensory loss has in stroke rehabilitation.

The degree to which RTP or HM usage contributed to the improvements in UE motor function is unclear. Both modalities have aspects that could contribute to improvements in distal hand function. The HM device has protocols that require the patient to produce somewhat accurate wrist and finger flexion and extension movements, which may allow the patient to get the hand into a more functional position to perform dexterous actions. The repetitive nature of RTP, with its focus on common movements of the hand and arm and the use of motor learning techniques (eg, breaking down of tasks into meaningful parts and practicing each part, increasing movement difficulty, and providing feedback), probably contributed to improved function. A randomized, blinded preliminary trial is currently under way to determine the effect of each of these treatment modalities in patients with subacute stroke.

Grip Force

Maximum unimanual precision grip force decreased slightly in the more-affected hand following RTP therapy and HM training. Despite this loss in maximum grip force, the smoothness of the force-time profiles produced by this limb during unimanual and simultaneous bimanual trials improved. During the pretest bimanual conditions, there was an apparent coupling of grasping forces between the more-affected and less-affected hands. Under bimanual conditions, the grip force of the less-affected hand was coupled with the grip force produced by the more-affected hand (eg, as reflected by a similar force-time profile in both limbs and a lower maximum force in the less-affected limb compared with the force achieved during unimanual maximum testing of the less-affected limb). Following the combined RTP and HM intervention, the degree of coupling between the limbs appears to have been reduced (based on lower

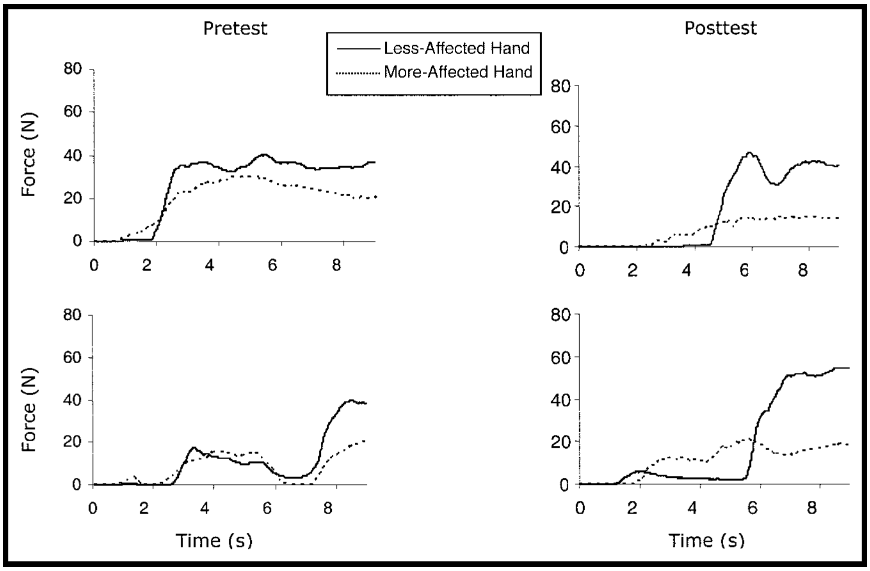

Figure 4.
Representative force-time profiles of 2 trials for the less-affected hand (solid lines) and the more-affected hand (dotted lines).

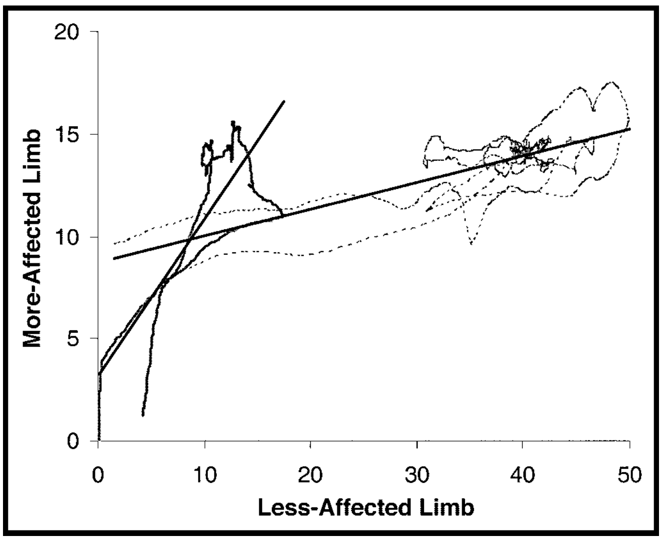

Figure 5.
Force-time profiles of the more-affected limb as a function of force produced by the less-affected limb during pretest (solid lines) and posttest (dotted lines) trials.

slope values when force produced by the more-affected limb was expressed as a function of force produced by the less-affected limb). These data suggest that the more-affected limb was no longer driving or limiting the performance of the less-affected limb.

Previous studies[31–34] have examined the relationships between grip force of the more-affected hand and UE function as measured by various clinical tests. The researchers concluded that grip force is closely associated with motor performance, which would seem to contradict the findings from this case report. Canning and colleagues[35] examined the relative contribution of strength and dexterity to overall UE function during the first 6 months following stroke. They found that the largest contribution to function during this acute period was made by the shared component of strength and dexterity, with strength also making an additional separate contribution to function. They suggested that the separate contribution of strength was present because, without at least enough strength to move against gravity, it is not possible to perform ADL. Alberts and colleagues[21] suggested a similar scenario that successful performance of daily activities does require a minimum level of strength; however, fine motor tasks involving the distal musculature rely more on the ability to control muscle forces with precision than on absolute strength. Therefore, applying this idea to our patient, who was in a subacute stage of recovery and had already achieved a moderate level of strength, UE function was influenced more by an improvement in force control rather than overall strength.

Conclusions

A combined therapy program appeared to improve UE function in a patient with stroke as changes in WMFT, FMA, and SIS were observed. Although the results are promising, they are limited by the case report design of this project. However, we are not aware of any other published CI therapy or RTP study that has exposed patients to less than 18 hours of RTP over the course of 3 weeks and shown an improvement in UE motor function.

References

1 *Heart Disease and Stroke Statistics: 2005 Update.* Dallas, Tex: American Heart Association; 2005.

2 Byl N, Roderick J, Mohamed O, et al. Effectiveness of sensory and motor rehabilitation of the upper limb following the principles of neuroplasticity: patients stable poststroke. *Neurorehabil Neuro Repair.* 2003;17:176–191.

3 Miltner WH, Bauder H, Sommer M, et al. Effects of constraint-induced movement therapy on patients with chronic motor deficits after stroke: a replication. *Stroke.* 1999;30:586–592.

4 Wolf SL, Lecraw D, Barton L, Jann B. Forced use of the hemiplegic upper extremities to reverse the effect of learned nonuse among chronic stroke and head-injured patients. *Exp Neurol.* 1989;104:125–132.

5 Taub E, Miller N, Novack T, et al. Technique to improve chronic motor deficit after stroke. *Arch Phys Med Rehabil.* 1993;74:347–354.

6 Miltner WHR, Bauder H, Sommer M, et al. Effects of constraint-induced movement therapy on patients with chronic motor deficits after stroke. *Stroke.* 1999;30:586–592.

7 Page SJ, Sisto S, Johnston MV, et al. Modified constraint-induced therapy in subacute stroke: a case report. *Arch Phys Med Rehabil.* 2002;83:286–290.

8 Wolf SL, Blanton S, Baer H, et al. Repetitive task practice: a critical review of constraint-induced movement therapy in stroke. *Neurologist.* 2002;8:325–338.

9 Park SW, Butler AJ, Cavalheiro V, et al. Changes in serial optical topography and TMS during task performance after constraint-induced movement therapy in stroke: a case study. *Neurorehabil Neuro Repair.* 2004;18:95–104.

10 Liepert J, Uhde I, Graf S, et al. Motor cortex plasticity during forced-use therapy in stroke patients: a preliminary study. *J Neurol.* 2001;248:315–321.

11 Mark VW, Taub E. Constraint-induced movement therapy for chronic stroke hemiparesis and other disabilities. *Restor Neurol Neurosci.* 2002;22:317–336.

12 Sterr A, Freivogel S. Motor improvement following intensive training in low-functioning chronic hemiparesis. *Neurology.* 2003;61: 842–844.

13 Page SJ, Levine P, Sisto S, et al. Stroke patients' and therapists' opinions of constraint-induced movement therapy. *Clin Rehabil.* 2002; 16:55–60.

14 Fasoli SE, Drebs HI, Stein J, et al. Robotic therapy for chronic motor impairments after stroke: follow-up results. *Arch Phys Med Rehabil.* 2004;85:1106–1111.

15 Lum PS, Burgar CG, Shor PC, et al. Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke. *Arch Phys Med Rehabil.* 2002;83:952–959.

16 Reinkensmeyer DJ, Emken JL, Cramer SC. Robotics, motor learning, and neurologic recovery. *Ann Rev Biomed Eng.* 2004;6:16.11–16.29.

17 Winstein CJ, Miller JP, Blanton S, et al. Methods for a multisite randomized trial to investigate the effect of constraint-induced movement therapy in upper extremity function among adults recovering from a cerebrovascular stroke. *Neurorehabil Neuro Repair.* 2003;17: 137–152.

18 Morris D, Uswatte G, Crago J, et al. The reliability of the Wolf Motor Function Test for assessing upper extremity function after stroke. *Arch Phys Med Rehabil.* 2001;82:750–755.

19 Murphy MA, Roberts-Warrior D. A review of motor performance measures and treatment interventions for patients with stroke. *Topics in Geriatric Rehabilitation.* 2003;19(1):3–42.

20 Fugl-Meyer A, Jaasko L, Leyman I, et al. The post stroke hemiplegic patient: a method for evaluation of physical performance. *Scand J Rehabil Med.* 1975;7:13–31.

21 Alberts JL, Butler AJ, Wolf SL. The effects of constraint-induced therapy on precision grip: a preliminary study. *Neurorehabil Neuro Repair.* 2004;18:250–258.

22 Duncan PW, Propst M, Nelson SG. Reliability of the Fugl-Meyer assessment of sensorimotor recovery following cerebrovascular accident. *Phys Ther.* 1983;63:1606–1610.

23 Di Fabio RP, Badke RB. Relationship of sensory organization to balance function in patients with hemiplegia. *Phys Ther.* 1990;70: 542–548.

24 Duncan PW, Wallace D, Lai SM, et al. The Stroke Impact Scale version 2.0: evaluation of reliability, validity, and sensitivity to change. *Stroke.* 1999;30:2131–2140.

25 Schleenbaker RE, Mainous AG III. Electromyographic biofeedback for neuromuscular reeducation in the hemiplegic stroke patient: a meta-analysis. *Arch Phys Med Rehabil.* 1993;74:1301–1304. Comment in 1994;75:1023.

26 Wolf SL, Baker M, Kelly J. EMG biofeedback in stroke: effect of patient characteristics. *Arch Phys Med Rehabil.* 1979;60:96–102.

27 Wolf SL, Binder-Macleod S. Electromyographic biofeedback applications to the hemiplegic patient: changes in upper extremity neuromuscular and functional status. *Phys Ther.* 1983;63:1393–1403.

28 Selles R, Li X, Lin F, et al. Feedback-controlled and programmed stretching of the ankle plantarflexors and dorsiflexors in stroke: effects of a 4-week intervention program. *Arch Phys Med Rehabil.* 2005;86: 2330–2336.

29 van der Lee JH, Wagenaar RC, Lankhorst GJ, et al. Forced use of the upper extremity in chronic stroke patients. *Stroke.* 1999;30:2369–2375.

30 Taub E. Somatosensory deafferentation research with monkeys: implications for rehabilitation medicine. In: Ince LP, ed. *Behavioral Psychology in Rehabilitation Medicine: Clinical Applications.* Baltimore, Md: Williams & Wilkins; 1980:371.

31 Boissy P, Bourbonnais D, Carlotti MM, et al. Maximal grip force in chronic stroke subjects and its relationship to global upper extremity function. *Clin Rehabil.* 1999;13:354–362.

32 Heller A, Wade DT, Wood VA, et al. Arm function after stroke: measurement and recovery over the first three months. *J Neurol Neurosurg Psychiatry.* 1987;50:714–719.

33 Mercier C, Bourbonnais D. Relative shoulder flexion and handgrip strength is related to upper limb function after stroke. *Clin Rehabil.* 2004;18:215–221.

34 Sunderland A, Tinson D, Bradley L, Hewer RL. Arm function after stroke: an evaluation of grip strength as a measure of recovery and a prognostic indicator. *J Neurol Neurosurg Psychiatry.* 1989;52:1267–1272.

35 Canning CG, Ada L, Adams R, O'Dwyer NJ. Loss of strength contributes more to physical disability after stroke than loss of dexterity. *Clin Rehabil.* 2004;18:300–308.