Effects of Modified Constraint-Induced Movement Therapy on Movement Kinematics and Daily Function in Patients With Stroke: A Kinematic Study of Motor Control Mechanisms

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Background and Objective. Motor control of the upper extremity during unilateral and bimanual functional tasks and functional change during daily activities were evaluated in patients with stroke treated with modified constraint-induced movement therapy (mCIMT). Methods. In a pre-post randomized, controlled trial, 30 stroke patients received 2 hours of mCIMT or traditional rehabilitation (TR) for 3 weeks. Motor control of the upper extremity was evaluated using kinematic analysis in unilateral and bilateral tasks. Kinematic variables included spatial and temporal movement efficiency and type of movement control (preplanned control, representing well-learned movement, or feedback-guided control). Functional outcomes were evaluated using the Motor Activity Log (MAL) and the Functional Independence Measure (FIM). Results. Patients receiving mCIMT showed more temporally ($P_{0.013}$) and spatially ($P_{0.011}$) efficient movement and more preplanned movement control ($P_{0.009}$) during the bimanual task, and greater gains in FIM ($P_{0.004}$) and MAL scores (amount of use: $P_{<0.001}$, and quality of movement: $P_{0.012}$) than patients in the TR group. Patients receiving mCIMT produced more ballistic/preplanned reaching movement than did patients receiving TR ($P_{0.023}$) during the unilateral task; but there were no group differences in temporal or spatial efficiency in unilateral task performance. Conclusions. Relative to TR, mCIMT produced a greater improvement in functional performance and motor control. Improvement of motor control after mCIMT was based on improved spatial and temporal efficiency, apparently more salient during bimanual rather than unilateral task performance. This suggests that bilateral task performance should potentially be emphasized in kinematic study of changes in motor control after mCIMT.

Key Words: Cerebrovascular disease—Upper extremity—Kinematics—Rehabilitation—Activities of daily living.

Approximately 30% to 66% of stroke survivors report persistent impairment of upper extremity (UE) movement and are unable to use their affected arm in daily activities.1 Furthermore, patients with stroke are encouraged to perform tasks using their unaffected UE and progressively avoid using the affected UE, resulting in a learned nonuse phenomenon.2 Residual motor deficits in the UE and learned nonuse of the UE often lead to disability and permanent dependency on community care.3

Constraint-induced movement therapy (CIMT) and modified CIMT (mCIMT) have been advocated as means to improve movement of the UE and functional use of the affected limb among patients post stroke. CIMT and mCIMT involve restraint of the unaffected limb for an extended period and repeated task-specific training of the affected limb.4 Numerous studies in stroke patients have shown that CIMT/mCIMT can enhance performance of the affected UE during unilateral and bimanual functional tasks (e.g., flipping a light switch, putting on socks) assessed, for example, using the Motor Activity Log (MAL).5,6 Bonifer et al7 reported that CIMT primarily led to improvements in bimanual task performance despite that training was primarily unilateral.

Although studies have provided substantial evidence of the effectiveness of CIMT/mCIMT, they have not
clearly addressed what changes in motor control actually accounted for the therapeutic gains (or functional improvement) that are achieved. Elucidation of the motor control mechanisms underlying the effects of CIMT/mCIMT is of great interest and might inform the design of theoretically driven, effective interventions.

Alberts et al. used an assessment of force-producing capabilities to investigate the motor control mechanisms underlying CIMT. These authors and Page et al. suggest three-dimensional kinematic analysis is also a valid and reliable means to assess motor performance in high functioning stroke patients. Kinematic analysis enables the assessment of both spatial and temporal movement characteristics and might thereby provide insight into the motor control mechanisms underlying the effects of CIMT/mCIMT. One example is the control of reaching movements in stroke patients, the kinematics of which are well characterized. Healthy adults perform reaching movements skillfully, using preplanned movement control. In contrast, stroke patients perform reaching movements with reduced spatial and temporal efficiency and may control such movements using a more feedback-guided, homing-in control, an indication of a greater demand for error correction during reaching performance.

Temporal efficiency may be characterized by the movement time (MT), the time for execution of a reaching movement. Spatial efficiency may be characterized by total displacement (TD), the hand's path in a three-dimensional space. Increased spatial and temporal efficiency is characterized by reduced MT and TD. The type of control of reaching movements (i.e., preplanned vs. feedback-guided) can be determined as the percentage of MT where peak velocity occurs (PPV). A normal reaching movement is composed of one acceleration and one deceleration. During the deceleration phase, an online error correction of movement often occurs. PPV reflects percentage of MT for the acceleration phase. A higher PPV indicates a longer acceleration phase, suggesting less online error correction and more preplanned control of the reaching movements.

A recent case report used kinematic measures to evaluate the therapeutic efficacy of mCIMT and suggests the therapy may have increased motor control efficiency. The positive findings hold promise for further examination using a randomized controlled trial. In the present study, we investigated motor control and functional changes after mCIMT in patients post stroke. We chose to study performance outcomes on unilateral and bimanual tasks because both represent basic arm movements that are essential to daily life and human interaction with the surrounding environment. We evaluated the reaching movement because it is known to be sensitive to residual motor dysfunction in high-functioning stroke patients.
MAL and Functional Independence Measure (FIM) were used to detect the changes in the functional use of the affected limb during daily living.

We hypothesized that stroke patients receiving mCIMT, compared to patients receiving traditional rehabilitation (TR), would exhibit better motor control performance (shorter MT and TD, larger PPV) and achieve greater functional gains (higher FIM and MAL scores) in the affected UE during unilateral and bimanual tasks.

METHODS

Patients

Thirty patients post stroke (13 females; mean age, 53.99 years; range, 45-74 years) were recruited from the rehabilitation departments of 2 medical centers (Chang Gung Memorial Hospital and National Taiwan University Hospital). All patients signed informed consent forms approved by the Institutional Review Board. The patients were right-hand dominant before stroke by self-report and were 12-36 months (mean, 18.07 months) post onset of a first-ever cerebrovascular accident. All patients received independent examinations by a physiatrist and occupational therapist to determine their eligibility for inclusion: (1) able to actively extend at least 10 degrees at the metacarpophalangeal and interphalangeal joints and 20 degrees at the wrist, (2) considerable nonuse of the more affected UE (amount-of-use score < 2.5 on the MAL), (3) no serious cognitive deficits (score ≥ 70 on the modified Mini-Mental State Exam), (4) no balance problems sufficient to compromise safety when wearing the study’s constraint device, and (5) no excessive spasticity in any joint of the affected UE (shoulder, elbow, wrist, or fingers; Modified Ashworth Scale ≤ 2 in any joint). Figure 1 shows how the patients were randomized to groups. The demographic and clinical characteristics of the mCIMT group (n = 15) and the TR group (n = 15) were comparable (Table 1). All patients were blind to the study hypotheses.

<table>
<thead>
<tr>
<th>Table 1. Characteristics of Study Participants</th>
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<tbody>
<tr>
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<tr>
<td>mCIMT (n =15)</td>
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<tr>
<td>TR (n =15)</td>
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<tr>
<td>P Valuesa</td>
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<tr>
<td>Gender (M/F) 8/7</td>
</tr>
<tr>
<td>Age (mean [SD]) 54.66 (8.63)</td>
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<tr>
<td>Side of lesion (L/R) 9/6</td>
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<tr>
<td>Months after stroke (mean [SD]) 18.53 (6.92)</td>
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<tr>
<td>Modified Mini-Mental Exam (mean [SD]) 93.56 (8.21)</td>
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<tr>
<td>MAL (amount of use) (mean [SD]) .95 (.89)</td>
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<tr>
<td>Modified Ashworth Scale .34 (.30)</td>
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mCIMT = modified constraint-induced movement therapy; TR = traditional rehabilitation; UE = upper extremity; MAL = Motor Activity Log.

a. P associated with the χ² test for categorical variables and with the independent t test for continuous variables.

Figure 2. The experimental setup for the unilateral task.
press the desk bell, which was also located along the subject’s midsagittal plane (Figure 2). For the bimanual task, patients used the affected hand to open a 13.39 × 9.84 × 8.86-in. (length × width × height) drawer and used the unaffected hand to retrieve an eyeglass case inside (Figure 3). The patient rested the affected hand on the hand switch, which was in line with the affected shoulder, and rested the unaffected hand in line with the unaffected shoulder. They were instructed to use the affected hand to reach and pull the drawer and the unaffected hand to retrieve the eyeglass case inside the drawer recess (Figure 3).

Patients performed the 2 tasks at a comfortable speed. After a practice trial, 3 trials were performed. Only reaching movements of the affected hand were recorded during these tasks.

**Kinematic analysis.** During the 2 tasks, a 6-camera motion analysis system (VICON 370 3-D; Oxford Metrics Inc., Oxford, UK) was used in conjunction with a personal computer (IBM clone) to capture the movement of a marker attached to the styloid process of the patient’s ulna. For the unilateral functional task, 2 channels of analog signals were collected simultaneously; signal collection was linked to a pressure-sensitive hand switch and desk bell. Movement recording commenced when the hand moved off the hand switch and terminated when the hand pressed the desk bell. For the bimanual functional task, analog signal collection was linked to a pressure-sensitive hand switch, and 1 reference marker was attached on the drawer. Movement recording commenced when the hand moved off the hand switch and terminated when the reference marker attached on the drawer started to move. Movements were recorded at 60 Hz and digitally low-pass filtered at 5 Hz using a second-order Butterworth filter with forward and backward pass.

**Clinical assessment.** The MAL is a semistructured interview designed to obtain information about patient use of the affected limbs during 30 important activities of daily living (ADL). Patients used a 6-point amount-of-use (AOU) scale to rate the extent to which the arm was used and a 6-point quality of movement (QOM) scale to rate the quality of use of their affected arms.

The FIM (maximum score of 126) consists of 18 items grouped into 6 subscales measuring self-care, sphincter control, transfers, locomotion, communication, and social cognition ability. Each item is rated from 1 to 7 based on the required level of assistance necessary to perform the basic ADL (1 = complete assistance to perform basic ADL; 2 = maximal assistance; 3 = moderate assistance; 4 = minimal assistance; 5 = supervision; 6 = modified independence; and 7 = complete independence). The FIM has good interrater reliability, construct validity, and discriminant validity. A certified occupational therapist blind to study hypothesis and subject allocation was trained to administer the assessments.

**Intervention**

Subjects were individually randomized to the mCIMT or TR group with equal probability. In the mCIMT group, training was administered intensively 2 hours per day, 5 days per week, for 3 weeks. Training took place during regularly scheduled occupational therapy sessions, and all other routine interdisciplinary stroke rehabilitation proceeded as usual. mCIMT therapy concentrated on use of the affected limb during functional tasks chosen by patients and the treating therapist. It consisted primarily of a procedure termed shaping, which involved: (1) selecting functional tasks tailored to address the motor deficits of the affected hand, (2) increasing task difficulty in small steps when performance improved on more than 3 consecutive trials, and (3) providing immediate feedback when the task was successfully completed or movement speed and quality improved. Approximately 15 minutes of therapy was spent on normalization of muscle tone of the affected limb, as needed. During the 3-week period, the patients’ unaffected hands and wrists were placed in mitts every weekday for 6 hours identified as a time of frequent arm use.

The TR group received training matched to the mCIMT in duration and intensity of occupational therapy activities. Routine rehabilitation continued as usual. During each 2-hour therapy session, patients engaged in neurodevelopmental treatments emphasizing balance training, stretching of the affected limb, weight bearing with the affected limb, and fine-motor tasks in addition to practice on ADL with the less affected side.

**Data Analysis**

An analysis program coded by LabVIEW (National Instruments, Inc., Austin, TX) language was used to...
process the kinematic data. MT, TD, and PPV values were obtained. Because the task distance varied across subjects, MT and TD were normalized to correct for variations in reaching distance.

Analysis of covariance (ANCOVA), controlling for pretreatment differences, was used to compare the 2 groups’ improvement for each variable. Pretest performance (kinematic data and MAL/FIM scores) was the covariate, group was the independent variable, and posttest performance was the dependent variable. To index the magnitude of group differences in performance, the effect size \( r \) was calculated for each outcome variable. A large effect is represented by an \( r \) of at least 0.50, a moderate effect by an \( r \) of 0.30, and a small effect by an \( r \) of 0.10.

**RESULTS**

Consistent with the study hypotheses, stroke patients receiving mCIMT, compared to patients receiving TR, exhibited significantly better motor control performance (shorter normalized MT and TD, and larger PPV) in the affected UE during the bimanual task and achieved greater functional gains. Results of kinematic performance in the unilateral task were partially consistent with the hypotheses. The mCIMT group showed significantly larger PPV but did not exhibit significantly shorter normalized MT and TD than the TR group.

**Effects of mCIMT on Reaching Kinematics**

The effects of mCIMT on reaching kinematics in the unilateral functional task were statistically significant but modest. ANCOVA results showed that posttest performance on the kinematic measure of PPV was significantly higher in the mCIMT versus the TR group (\( F_{1,27} = 5.85, P = .023, r = 0.42 \)). Nonsignificant and small to moderate effects were found for the kinematic variables of normalized MT (\( F_{1,27} = 2.30, P = .14, r = 0.28 \)) and normalized TD (\( F_{1,27} = 0.89, P = .36, r = 0.18 \)). The mCIMT group showed more preplanned movement control after treatment than did the TR group, but there was no difference in spatial or temporal movement efficiency.

The effects of mCIMT on reaching kinematics of the affected UE were significant and moderate for the bimanual functional task. ANCOVA results showed significantly greater posttest performance for the mCIMT versus TR group on the kinematic measures of normalized MT (\( F_{1,27} = 7.14, P = .013, r = 0.46 \)), normalized TD (\( F_{1,27} = 7.53, P = .011, r = 0.47 \)), and PPV (\( F_{1,27} = 7.87, P = .009, r = 0.48 \)). After treatment, the mCIMT group showed greater temporal and spatial movement efficiency and more preplanned movement control than did the TR group.

**Effects of mCIMT on Clinical Measures**

mCIMT produced significant and moderate to large effects on MAL and FIM scores. There was significantly

### Table 2. Means and Standard Deviations of Performance on the Kinematic and Clinical Measures from Pretreatment to Posttreatment

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<thead>
<tr>
<th></th>
<th>Pretreatment</th>
<th>Posttreatment</th>
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<tbody>
<tr>
<td></td>
<td>mCIMT (n = 15)</td>
<td>TR (n = 15)</td>
</tr>
<tr>
<td>Kinematic variables</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unilateral task</td>
<td></td>
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<tr>
<td>Normalized MT</td>
<td>0.048 (0.020)</td>
<td>0.052 (0.024)</td>
</tr>
<tr>
<td>Normalized TD</td>
<td>1.49 (0.43)</td>
<td>1.51 (0.46)</td>
</tr>
<tr>
<td>PPV</td>
<td>37.08 (12.94)</td>
<td>34.01 (12.78)</td>
</tr>
<tr>
<td>Bimanual task</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalized MT</td>
<td>0.040 (0.023)</td>
<td>0.038 (0.014)</td>
</tr>
<tr>
<td>Normalized TD</td>
<td>1.59 (0.48)</td>
<td>1.24 (0.16)</td>
</tr>
<tr>
<td>PPV</td>
<td>35.11 (13.55)</td>
<td>33.63 (10.17)</td>
</tr>
<tr>
<td>Clinical measures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAL</td>
<td>.95 (.89)</td>
<td>1.11 (1.01)</td>
</tr>
<tr>
<td>AOU</td>
<td>1.21 (1.24)</td>
<td>1.33 (1.44)</td>
</tr>
<tr>
<td>QOM</td>
<td>99.60 (20.56)</td>
<td>95.93 (17.00)</td>
</tr>
</tbody>
</table>

mCIMT = modified constraint-induced movement therapy; TR = traditional rehabilitation; MT = movement time; TD = total displacement; PPV = percentage of total movement time to peak velocity; MAL = Motor Activity Log; AOU = amount of use; QOM = quality of movement; FIM = Functional Independence Measures.
greater improvement in AOU \((F_{1,27} = 20.19, P < .0001, r = 0.65)\) and QOM \((F_{1,27} = 7.25, P = .012, r = 0.46)\) of the affected arms during daily activities in the mCIMT group versus the TR group. In the mCIMT group, the affected UE was used for an average of 19 activities before treatment and 25 activities after treatment. In the TR group, the affected UE was used for an average of 17 activities before treatment and 22 activities after treatment. Posttreatment scores on the FIM were larger in the mCIMT versus TR group \((F_{1,27} = 10.11, P = .004, r = 0.52)\).

DISCUSSION

In this randomized controlled trial, mCIMT was associated with greater improvement in motor control of reaching and functional performance than TR. The kinematic results of this study extend those of the case report by Hakim et al\(^{17}\) to a randomized controlled trial and provide new information regarding the therapeutic mechanism of mCIMT from the motor control perspective. The results are consistent with the a priori hypotheses that mCIMT would produce a greater increase in spatial and temporal movement efficiency, a greater increase in the amount of preplanned control of reaching during the bilateral task, and greater functional gains in MAL and FIM scores than TR. During the unilateral task, mCIMT produced a greater increase in the amount of preplanned control of reaching movement than did TR, but there was no difference in the interventions' effects on spatial and temporal efficiency.

In comparison with TR, mCIMT produced more preplanned control, demonstrated by a higher PPV during the unilateral and bimanual tasks. This finding suggests the patients who underwent mCIMT used their affected UEs more spontaneously and automatically and aimed at the target more accurately, decreasing the need for online error correction. These improvements may relate to short-term learning changes at the central level. Intensive practice of the affected UE and restraint of the unaffected UE under a variety of functional tasks may provide opportunity for patients to explore optimal ways \(i.e.,\) more preplanned control) to achieve various functional tasks.\(^{32}\) Therefore, intensive practice may improve motor planning and promote experience-related adaptations of brain function, leading to more preplanned movement.\(^{4,32}\)

mCIMT produced greater temporal efficiency \(\text{(shorter MT)}\) and spatial efficiency \(\text{(shorter TD)}\) in the bimanual task than did TR, suggesting that the beneficial effects of mCIMT on the affected UE generalize to functional use of the affected UE during bilateral tasks. However, after mCIMT, there was no improvement in spatial and temporal efficiency on the unilateral task.

One possible reason for the superior performance of the affected arm during the bimanual versus unilateral task is that bimanual movements trigger interhemispheric disinhibition that may allow the activation of alternative recruitment pathways to improve movement efficiency of the affected arm.\(^{33,34}\) Because interextremity coupling may persist after damage to 1 hemisphere, another possibility is that a bimanual movement involving the unaffected UE might drive the activity of the affected limb more effectively than a unilateral movement with the affected UE, because bimanual movement involves undamaged parts of the brain in planning and execution.\(^{34,35}\) These postulates warrant further research.

The greater improvement of MAL scores in the mCIMT versus TR group, including the AOU and QOM scores, was consistent with previous findings.\(^{5,9}\) The substantial improvements in MAL scores suggest patients receiving mCIMT were more willing to engage their affected UEs and produced enhanced quality of movement. The finding that patients engaged in more spontaneous use of the affected UE after mCIMT is consistent with the kinematic finding of greater preplanned control after mCIMT.

FIM scores showed greater improvement in the mCIMT group versus the TR group, suggesting that patients in the mCIMT group better transferred the treatment effects to daily activities. Our findings regarding the FIM contrast with previous findings, which showed nonsignificant differences in FIM between mCIMT and control groups.\(^{39}\) A possible reason for this difference is that subjects in the study by Dromerick et al\(^{19}\) were older \(\text{(mean age, 66 years)}\) than those in the present study \(\text{(mean age, 51 years)}\). It is possible older subjects may have a reduced capacity to generalize learned motor function to daily activities.\(^{36}\)

Investigation of the extent to which mCIMT effects generalize is 1 possible target for further study. Future research might investigate the impact of mCIMT on the control of multistep unilateral movements or assess whether mCIMT produces beneficial effects on not only the performance of the affected UE during bilateral tasks but also on the coordination of UEs during bimanual tasks.

In conclusion, mCIMT was associated with greater improvement than TR in daily functioning but also in motor control. An additional interesting finding was the improvements in motor control after mCIMT encompassed more kinematic variables when patients performed bimanual tasks than unilateral tasks. Taken together, these findings provide some insight about the mechanisms that may be responsible for improved motor function of the affected UEs after mCIMT and suggest that bilateral task performance should potentially be emphasized in kinematic study of mCIMT.
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