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# Feasibility of Electromyography-Triggered Neuromuscular Stimulation as an Adjunct to Constraint-Induced Movement Therapy

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# Feasibility of Electromyography-Triggered Neuromuscular Stimulation as an Adjunct to Constraint-Induced Movement Therapy

**Background and Purpose.** The purpose of this case report is to explore the feasibility of electromyography-triggered neuromuscular stimulation (EMG-stim) as an adjunct to constraint-induced movement therapy (CIMT). **Case Description.** The patient was a 72-year-old man, 10 years poststroke, who did not meet traditional CIMT criteria. The EMG-stim was applied to the wrist extensors of the patient's weaker arm for one half of the CIMT training hours. **Outcomes.** The intervention was feasible for this individual. Improvements were observed in motor behavior, quality and amount of use, muscle activity, wrist range of motion, and reaction time of the more-affected extremity. These improvements were paralleled by a change in the size and location of the extensor digitorum communis muscle representation in the primary motor cortex, as measured by transcranial magnetic stimulation mapping. **Discussion.** These changes suggest that using EMG-stim as an adjunct to CIMT should be further investigated in individuals who have low functional abilities following stroke. [Fritz SL, Chiu YP, Malcolm MP, et al. Feasibility of electromyography-triggered neuromuscular stimulation as an adjunct to constraint-induced movement therapy. *Phys Ther.* 2005;85:428-442.]

**Key Words:** *Cerebrovascular accident, Electrical stimulation, Hemiplegia, Muscle performance.*

*Stacy L Fritz, Yi-Po Chiu, Matthew P Malcolm, Tara S Patterson, Kathye E Light*

## **Stroke is the most common disabling condition, with 30% to 66% of survivors losing functional ability in their more-affected arm and hand.**

**R**ecent advances, pairing 2 research-supported therapeutic approaches, appear to be promising for people with hemiparesis. Research evidence supports the use of constraint-induced movement therapy (CIMT), but many questions persist about who can benefit from this intervention.<sup>1-6</sup> Constraint-induced movement therapy is mainly used with people following stroke to increase the functional use of the neurologically weaker upper extremity, via massed practice (amount of practice time is greater than the amount of rest time) of hand and arm tasks, while restraining the lesser-involved upper extremity. The goals of CIMT are to overcome learned nonuse and to improve functional use of the more-affected upper extremity.<sup>1</sup> The results of CIMT studies have established lasting improvements of upper-extremity movement function.<sup>1-6</sup> The participants in most of these studies, however, were limited to those who were able to actively extend their wrist 20 degrees and fingers 10 degrees against gravity. The literature indicates that approximately 25% of people with stroke meet these criteria.<sup>7</sup> Participants who initially have lower recovery, who cannot meet these range-of-motion requirements, have had less improvement with traditional CIMT than patients with higher levels of motor ability.<sup>8</sup>

By engaging the hemiparetic limb in massed practice of functional tasks, CIMT is believed to alter the representation of this limb within the primary motor cortex.<sup>9</sup>

Studies of human and nonhuman primates have shown that the neural representation of hand muscles becomes enlarged as the subject is trained in the performance of a discrete motor skill.<sup>10-14</sup> Two studies using transcranial magnetic stimulation (TMS) have demonstrated activity-dependent neurological changes following CIMT in people with stroke who met the standard motor criteria.<sup>13,15</sup> Alterations in muscle representations, or motor maps, have not been studied in individuals with lower functional levels, or in concert with CIMT combined with electromyography-triggered neuromuscular stimulation (EMG-stim).

Pairing CIMT with EMG-stim may increase the therapeutic benefits to those individuals following stroke who do not qualify for CIMT due to limitations in active range of motion. Technological advances in microprocessors, as well as the monitoring capabilities of surface electrodes, have renewed interest in a procedure known as EMG-stim. Electromyography-triggered neuromuscular stimulation is an intervention that combines 3 modalities: functional electrical stimulation, biofeedback, and exercise. With this combination, EMG-stim is capable of facilitating movement of the hemiparetic upper extrem-

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Dr Fritz, Mr Chiu, and Dr Light provided concept/idea/protocol design. Dr Fritz, Mr Chiu, Dr Malcolm, and Dr Light provided writing. Dr Fritz, Mr Chiu, Dr Malcolm, and Ms Patterson provided data collection, and Dr Fritz, Mr Chiu, and Dr Malcolm provided data analysis. Dr Fritz provided project management and the patient. Dr Light provided fund procurement, facilities/equipment, and institutional liaisons. Ms Patterson and Dr Light provided consultation (including review of manuscript before submission).

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ity with patterned, repetitive, volitionally initiated exercises. Electromyography-triggered neuromuscular stimulation also provides cutaneous, proprioceptive, and electrical stimulation feedback, time-locked to attempted movements.<sup>16,17</sup> This technique, provided by the Automove 800,\* assists the function of the hemiparetic limb. The muscle contraction voluntarily generated by patients is assisted at a specific threshold by an electrical stimulation so that the wrist achieves a greater range of motion. Researchers<sup>16-19</sup> have indicated that EMG-stim can benefit movement of the upper extremity after both acute and chronic stroke. Cauraugh et al<sup>19</sup> reported improved function in patients with chronic stroke when using EMG-stim for 12 treatment sessions (30 minutes each) over a 2-week period.

Stroke is the most common disabling condition, with 30% to 66% of people who survive losing functional ability in their more-affected arm and hand.<sup>9,20</sup> The need for innovative rehabilitation is clear. Currently, the individuals with chronic stroke who have minimal control of their wrist 1 year following the stroke have limited options for rehabilitation. Electromyography-triggered neuromuscular stimulation has not been studied extensively, and, although available clinically, in our experience, it is rarely used. In addition, we are not aware that EMG-stim paired with CIMT currently is used in practice. Therefore, these combined interventions make this protocol experimental. We believe that this new protocol will augment functional improvements of the upper extremity in an individual with chronic stroke and minimal motor recovery. The purpose of this case report is to explore the feasibility and possible immediate benefits of using EMG-stim as an adjunct to CIMT. In addition, we describe the organization of muscle representations in the primary motor cortex following the intervention.

## Case Description

### *Patient Description/History Systems Review*

The patient ("DK") was a 72-year-old man, 10 years following left-brain stroke, with resultant hemiparesis of his dominant right hand and arm. He responded to posted information about stroke rehabilitation projects ongoing at our institution. After ensuring that he met the screening criteria via an initial telephone call, he signed an informed consent form and later completed a physical screen. DK reported that, at the time of stroke, he suddenly developed right-sided weakness while taking a bath; he had no reports of language or visual impairment. DK was independent in activities of daily living (ADL) and said that, although he primarily used his stronger hand, he was making attempts to use his

hemiparetic hand for activities such as turning on a light, opening doors, anchoring his tube of toothpaste, and shaking hands. DK complained of difficulty extending his fingers and his elbow. He was no longer able to drive, but was independent in using public transportation. DK worked occasionally as a consultant and lived with his wife, who was employed full-time. He attended college for 3 years. His initial Frenchay Activities Index score was 32. Frenchay Activities Index scores range from 15 (inactive) to 60 (highly active).<sup>21</sup> DK's stated goal for the program was to recover more use of his affected arm and hand. He appeared motivated and excited about the therapy.

### *Examination, Evaluation, and Diagnosis*

DK's stroke was categorized as a probable large-vessel disruption of the left middle cerebral artery resulting in an ischemic stroke. During physical screening, a marked increase in tone (the resistance of a muscle being passively lengthened) was noted, with flexor tone being greater than extensor tone in both the upper and lower affected extremities. The increased tone was defined as increased resistance to passive stretch when compared with the less-affected side. He ambulated with increased stance time on the unaffected lower extremity, genu recurvatum, initiation of swing with a hip hike, stance initiated on the ball of his foot, and lateral trunk shift, but did not complain of difficulties maintaining balance.

He met the initial screening criteria:

- Slight wrist extension from a fully flexed position.
- Finger extension, in 2 fingers, at one joint.
- Stroke more than 9 months previously.
- No serious uncontrolled medical complications.
- Able to follow directions (Mini-Mental Status Examination score of at least 24/30).
- Not currently participating in skilled therapeutic interventions.

DK was unable to actively extend his fingers and wrist to meet the traditional minimum motor criteria of 20 degrees of wrist extension and 10 degrees of extension of 2 fingers and the thumb. He had approximately 10 degrees of active wrist extension and slight extension of 2 fingers and a thumb at the proximal interphalangeal (PIP) joint, but little to no movement at the metacarpophalangeal (MCP) joint. Minimum motor criteria were tested with the forearm supported on the edge of a table and the wrist in a passively flexed position over the edge of the table.

DK demonstrated passive insufficiency of the finger flexors. Thus, when his wrist was passively extended, his fingers flexed at the PIP and MCP joints. He had full passive range of motion of the upper extremity, with the

\* Daumeter A/S, Kildemosevej 13, DK-5000 Odense C, Denmark.



**Table 1.**  
Subsection and Total Change Scores for the Fugl-Meyer Measurement of Physical Performance

Fugl-Meyer Test	Pretest	Posttest	Maximum Potential Score
Passive range of motion	23	24	24
Pain	24	24	24
Sensation	4	4	4
Proprioception	8	8	8
Reflex	4	4	4
Flexor synergy	9	11	12
Extensor synergy	5	5	6
Combining synergies	2	2	6
Out of synergy	0	0	6
Normal reflex activity	0	0	2
Wrist stability	5	7	10
Hand	10	10	14
Coordination	3	3	6
Total	97	102	126

**Table 2.**  
Subsection and Total Change Scores for the Stroke Impact Scale

	Pretest	Posttest	Possible
Motor	107	117	140
Memory	35	35	35
Emotional	29	33	45
Speech	35	35	35
Social	34	38	40
Total	240	258	295

exception of slight limitation in wrist extension. He was able to actively flex and abduct his shoulder greater than 90 degrees, but not without elbow flexion, indicating a flexor synergy. His arm posture while standing included minimal shoulder abduction, a slightly flexed elbow, and flexed fingers at all joints. His flexor synergy increased with effort. His light touch sensation was intact (he reported no difference in the feeling of a cotton swab between his affected and unaffected arms), and he had no complaints of pain with active or passive movement. DK's initial Fugl-Meyer Measurement of Physical Performance<sup>22</sup> and Stroke Impact Scale (SIS)<sup>23</sup> scores are reported in the "Outcomes" section (Tabs. 1 and 2). His Mini-Mental Status Examination score was 29/30. He had no complaints of fatigue or pain.

#### Preintervention Testing

Preintervention testing was performed the 2 days prior to the start of training by a physical therapist who had established intrarater reliability across tests. This was done by testing people without known pathology or impairments on consecutive days to establish reliability. The testing consisted of the following:

1. Behavioral tests: Fugl-Meyer Measurement of Physical Performance,<sup>22</sup> the timed and functional ability rating scale of the Wolf Motor Function Test (WMFT),<sup>4,6,24,25</sup> Actual Amount of Use Test (AAUT),<sup>4,6,24,25</sup> and Box and Block Test<sup>26</sup> (see Tab. 3 for test descriptions).
2. Questionnaires: Motor Activity Log (MAL)<sup>4,6,24,25</sup> and SIS<sup>23</sup> (see Tab. 3 for test descriptions).
3. Electromyography (EMG) testing of co-contraction patterns of wrist flexors and extensors. A ballistic isometric task and a reciprocation task to measure co-contraction pattern of wrist flexors and extensors was used to assess changes in wrist control.
4. Transcranial magnetic stimulation in combination with CIMT. This combination of interventions offers a unique opportunity to study neurologic changes in people with stroke. Transcranial magnetic stimulation is a noninvasive neuroimaging technique that has the ability to "map" hand and arm representations in the motor cortex.

We used the reciprocation task to measure the co-contraction pattern of the wrist flexors and extensors. The patient was seated in a straight-back chair in front of a table with adjustable-height legs. The forearm and wrist being tested were positioned and stabilized in a trough so that the upper extremity was in 0 degrees of shoulder flexion, 20 degrees of shoulder abduction, and 90 degrees of elbow flexion. The forearm was in mid-position, and the hand was placed on the table without ulnar or radial deviation. Velcro straps<sup>†</sup> and additional foam padding provided stabilization and comfort.

The reciprocation task for the wrist extensors and flexors was first practiced with the less-affected side to ensure understanding of the motor task. The patient was then instructed to follow the designated metronome speed (0.67–0.83 Hz) by producing 10 reciprocal isotonic contractions of the wrist extensors and flexors with the affected upper extremity. Electromyographic activity was recorded using 4 pairs of preamplified surface electrodes<sup>‡</sup>—2 pairs for the wrist flexors (flexor carpi radialis [FCR] and flexor carpi ulnaris [FCU]) and 2 pairs for the wrist extensors (extensor carpi radialis brevis [ECRB] and extensor digitorum communis [EDC]). Each recording electrode consisted of 2 silver-silver chloride 1-cm-diameter electrodes embedded in an epoxy-mounted preamplifier system (×35) whose centers were spaced 2 cm apart. The sampling rate was 1,000 and the overall gain was set at 1,000. The EMG data were filtered with a low-frequency cutoff of 20 Hz to reduce

<sup>†</sup> Velcro USA Inc, 406 Brown Ave, Manchester, NH 03103.

<sup>‡</sup> Therapeutics Unlimited, 2835 Friendship St, Iowa City, IA 52240.

**Table 3.**Description of Behavioral Tests and Questionnaires Used as Dependent Measures<sup>a</sup>

Test	Descriptions	What Is Being Measured?	Reliability
<b>Behavioral tests</b>			
Fugl-Meyer test <sup>22</sup>	Designed for use in rehabilitation settings for people who have sustained a stroke. For this report, only the UE portion of this test was included.	Measures percentage of recovery of a person following stroke (range of motion, ability to move in and out of synergy, reflexes, grasping, and coordination)	Interclass correlation coefficient=.96
Wolf Motor Function Test (WMFT) <sup>4,6,23,24</sup>	A series of 15 timed tasks and 2 strength tasks. The test starts with testing shoulder movement tasks and progresses distally to fine-motor skills, ending with multijoint, functional tasks.	Measures quality of movement, time to complete tasks, or amount of weight lifted or grasped (dynamometer)	Interrater reliability=.95-.97
Actual Amount of Use Test (AAUT) <sup>4,6,23,24</sup>	The patient was asked to perform a series of functional tasks designed as an orientation to the therapy. He was videotaped, unknowingly but with prior consent, so that his quality of movement and amount of use could later be assessed.	Spontaneous use and quality of use of affected UE	Interrater reliability=.93
Box and Block Test (BBT) <sup>25</sup>	The test box is placed lengthwise across a standard-height table. 100 blocks (2.5-cm cubes) are in the compartment positioned on the testing side of the seated patient. Given 1 min to move as many blocks, one at a time, from one compartment to the other.	Grasp, transport, and release of small blocks. Outcomes include number of blocks transported.	Test-retest reliability tested at 6-mo intervals=.94 and .98.
<b>Questionnaires</b>			
Motor Activity Log (MAL) <sup>4,6,23,24</sup>	The MAL is a structured interview that incorporates the patient's perception about how he performed 30 functional tasks at home.	Person's perception of "how well" and "how much" he or she uses the more-affected UE	The "how well" section interrater reliability=.94
Stroke Impact Scale (SIS) <sup>26</sup>	Questions are asked about impairments and disabilities resulting from stroke and how the stroke has affected quality of life. Divided into 5 main subsections: motor, memory, emotional, speech, and social. The patient rates recovery from stroke on an ordinal scale of 1 to 5.	Evaluates how stroke has affected a person's life and health	Test-retest reliability of the domains ranged from .70 to .92 (except for reliability of the emotion domain, which was .57)

<sup>a</sup> UE=upper extremity.

possible noise from artifact movement during the task. Data of muscle onset time from the EMG recordings and measurements of range of motion in the wrist obtained with a custom-made rigid potentiometric goniometer were collected for each reciprocal wrist extension and flexion movement. The "muscle onset time" was determined as the time period between the beginning and end of muscle EMG activity. *Muscle activation* was defined as greater than 2 standard deviations of EMG activity from the baseline.

The percentage of muscle co-contraction time, overlapping time with both flexors and extensors active, and averaged muscle activity (root mean square) were calculated.<sup>27</sup> The peak-to-peak amplitude of wrist flexion and extension range of motion was averaged, and clarity of bursting activity of wrist flexors and extensors was evaluated.

For the ballistic isometric task, the patient remained in the same position as described for the reciprocation task. He was asked to perform 15 isometric contractions of



wrist extension to measure the efficiency of force generation of the wrist extensors. He received a verbal cue followed by a visual signal. The times between the 2 cues were randomized to range between 1 and 3 seconds in order to prevent anticipation. He extended his wrist as forcefully and as quickly as possible against the force transducer. He then was told to immediately relax. The electromyograph (with electrodes placed on the EDC and ECRB) and force transducer were used to collect the data from the wrist extensors of the affected limb. A load cell (MLP-25<sup>§</sup>) was used on the hemiparetic arm of the patient to detect the force output. The force transducer was applied at the center of the palm, which was at the middle position between the third metacarpal head and wrist joint along the axis of third metacarpal bone. The position of the force transducer was 45 degrees away from the horizontal plane. Data from the electromyograph and the force transducer were collected from 15 trials, and data for the top 3 trials were averaged for analysis. The data obtained for reaction time, premotor time latency, peak force amplitude, and time to the peak force were analyzed.

Transcranial magnetic stimulation is a neurophysiologic technique that may be used to investigate the organization and excitability of the corticospinal system that subserves voluntary movement. This technique is believed to indirectly activate corticospinal neurons by directly activating interneurons in the motor cortex.<sup>28</sup> When applied to the primary motor cortex, TMS generates a motor-evoked potential (MEP), which may be quantified and qualified by means of EMG. Transcranial magnetic stimulation has a spatial resolution of 5 mm<sup>29</sup> and a temporal resolution on the order of a few milliseconds. We used TMS to assess physiological activity of the affected primary motor cortex prior to and immediately following the CIMT intervention. Three primary assessments were made using TMS: identification of the motor-cortex representation of 3 muscles in the affected upper extremity (motor-cortex mapping), assessment of the excitatory threshold of the affected motor cortex (motor threshold), and assessment of locational shifts of the representation.

The "motor map" represents the area of the primary motor cortex that may produce a muscle response following TMS. This measure was used to assess brain plasticity that coincides with CIMT. Transcranial magnetic stimulation was used to generate a motor map by stimulating at various points over the primary motor cortex while monitoring for an evoked muscle response using EMG.<sup>30</sup> A motor map was created for 2 muscles in the forearm and one muscle in the hand of the hemiparetic limb. The motor map area was calculated as the

number of stimulating positions that evoked a muscle response. Changes in the area of the motor map measured before and after CIMT were compared.

During the testing session, the patient was comfortably seated in a reclining dental chair. Passive, bipolar surface-EMG electrodes were prepared with conductive gel and then applied, in a belly-tendon arrangement, over the first dorsal interosseous muscle (FDI), EDC, and FCR. The FDI abducts the index finger and flexes it at the MCP joint and extends the interphalangeal joints. The EDC is the primary MCP joint extensor and is also important for wrist stabilization during hand manipulations. The FCR is a primary wrist flexor that is also important for wrist stabilization. These muscles were studied in the hemiparetic upper limb for both testing sessions. Correct placement of the electrodes was verified by asking DK to contract the muscle while one author (MPM) monitored the online EMG record for visible muscle activation. The interelectrode distance was fixed at 20 mm for all muscles.

All TMS stimulation points were recorded in reference to the vertex of the skull (Cz). The Cz was marked as the intersection of the nasion-inion and interaural lines. Measurement of these lines was recorded to ensure consistent location of the Cz across testing sessions. Stimulation was delivered using a Magstim Rapid magnetic stimulator<sup>||</sup> with a 5-cm mean loop diameter, figure-eight-shaped, magnetic coil. The technique for stimulation was performed as described by Wassermann et al.<sup>30</sup> The coil handle was oriented sagittally, with the handle pointing posteriorly and the magnetic coil situated tangential to the skull. Stimulation was delivered over the affected hemisphere, which was contralateral to the affected arm. With the stimulator set at its maximum output and with the patient relaxed, the optimal point for stimulation was identified and recorded in relation to the Cz. The *optimal point* was defined as the stimulating position that elicited the largest-amplitude MEPs. Once the optimal point was determined, motor threshold was assessed in a stepwise fashion at that position. *Motor threshold* is defined as the lowest stimulation intensity that elicits discernable MEPs in at least 5 of 10 consecutive stimulations using an oscilloscope gain of 50  $\mu\text{V}/\text{cm}$ .<sup>30</sup>

To account for initial heightened arousal levels or startle responses, several trial stimulating runs were performed prior to the final assessment of motor threshold. The investigator (MPM) then marked a 5- $\times$ -5-cm grid centered at the optimal point (25 spots, separated by 1 cm). With the stimulator set at 115% of the motor threshold, 5 stimuli were delivered to each spot at a

<sup>§</sup> Transducer Techniques Inc, 42480 Rio Nedo, Temecula, CA 92590.

<sup>||</sup> The Magstim Company Ltd, Spring Gardens, Whitland, Carmarthenshire, Wales, United Kingdom SA34 0HR.



frequency of 1 Hz. The responses from these stimuli were averaged online. After all grid positions were stimulated, the grid was extended, if necessary, until the area from which the MEPs were elicited was surrounded by stimulated sites that did not elicit MEPs discernible at an oscilloscope display gain of 200  $\mu\text{V}/\text{cm}$  in any muscle. We selected this lower oscilloscope gain during motor mapping to prevent data clipping. Electromyography signals were recorded simultaneous to TMS, band-pass filtered at 2 to 10 kHz, amplified, and rectified with a Viking II electromyograph.\* Audio feedback from the electromyograph was routinely monitored to ensure muscle relaxation. Mapping the motor cortex in this manner has previously demonstrated good test-retest reliability (intraclass correlation coefficient=.86) (Malcolm et al, unpublished research).

Motor map-area was expressed as the number of positions on the stimulating grid, which produced an observable MEP. Shifts in the motor map were represented by a change in location of the optimal point in reference to the fixed vertex.

#### *Postintervention Testing*

Postintervention testing was completed on the 2 days following the 14-day intervention. The same tests were performed as during the preintervention testing.

#### **Intervention**

DK received CIMT for 6 hours a day. This intervention included intensive therapy involving functional task practice with progressive task complexity using EMG-stim (3 of the 6 hours) for 2 weeks. His lesser-involved hand remained in a constraint mitt for the duration of the therapy (14 days). DK was evaluated over a 2-day period. He began training the next day and continued for the next 10 consecutive weekdays. As much as possible, during the training, DK was not permitted to use the constrained hand during performance of a task. The goal was to wear the mitt 90% of awake hours, and removal of the mitt was allowed for specifically agreed-on tasks such as toileting and the use of water or other liquids. A behavioral contract was written between the trainer and patient regarding agreements about mitt use, task effort, activity logs, and home diaries. Trainers were physical therapists, occupational therapists, and trained technicians. The patient was strongly encouraged to continue to use his weaker hand during activities throughout the day and while at home. He was asked, on a daily basis, to rate how much and how well he used his hand using the MAL. While at home, the patient maintained a home diary documenting activities and mitt time. During the weekends, there were no assigned tasks,

but DK was instructed to continue to wear his mitt and maintain a home diary.

The CIMT activities were chosen or adapted from a task menu (Tab. 4), and an activity log was kept to demonstrate what tasks had been attempted and how the tasks were progressed during training. The CIMT consisted of a set of tasks to be performed with the affected upper extremity, such as picking up pencils, moving beans from one container to another, stacking blocks, and using utensils. As DK improved in performance, the complexity and difficulty of the tasks were increased in an attempt to continue to challenge him. As DK became more successful, the tasks were changed in various dimensions, such as by adding a time component, increasing the degrees of freedom, incorporating multi-joint tasks, increasing the height or distance at which the task was performed, or increasing the number of choices or the pattern complexity. Examples of this task progression are given in Table 4. The tasks were functional in nature, but were modified so that they were simple enough to allow some success for a patient with minimal finger and hand control (see Tab. 5 for an example of a typical day of therapy). The CIMT activities that were matched with EMG-stim focused primarily on wrist extension, grasp, and release.

The EMG-stim device was worn for 3 nonconsecutive hours of the 6 hours of therapy. The trainer removed the stimulator when the task being performed did not require added wrist extension provided by the EMG-stim. The stimulator also was removed when the patient requested a break from the stimulation and during meal times. The trainer documented the times the stimulator was used until 3 hours of EMG-stim was achieved. The methods for the EMG-stim were similar to those reported by Cauraugh et al.<sup>19</sup> Attempts were made to localize electrode placement to the EDC and extensor carpi ulnaris (ECU) muscle, but ultimately placement was at a location where the best wrist extension was accomplished.

As the patient attempted to lift his hemiparetic wrist and fingers, the level of muscle activation in the extensor muscles was monitored using the Automove 800 surface electrodes (diameter=50 mm). The patient was instructed to initiate wrist and finger extension until a target threshold level of voluntary EMG activity was achieved. When the threshold was achieved, the surface electrodes became a stimulator. The neuromuscular electrical stimulation assisted the wrist extensors to reach a functional range of motion, which was task-dependent. Each muscle contraction, stimulated by the biphasic electrical stimulation (50 Hz), lasted 10 seconds, plus a 1-second ramp up and 1-second ramp down, and the intensity was set to tolerance (14–29 mA).

\* Nicolet Biomechanical, PO Box 44451, Madison, WI 53744-4451.



**Table 4.**

Activities Were Chosen or Adapted From This Task Menu, Which Includes Examples of the Progression of Tasks

Task	Task Description	Progression
Picking up sticks	Place wooden colored sticks in front of patient; pick up each stick one at a time and place in can	Use pincher fingers only; move sticks further away
Sorting beans	Sort colored beans and place in container	Place container higher up
Moving blocks	Remove block box from the maze and place in correct position	Lift box higher up; use proper grasp
Stacking cones	Pick up cones one at a time and stack on top of each other	Use pincher fingers to grasp; stack on higher surfaces
Connect Four <sup>a</sup>	Pick up pieces and place in slot	Pincher grasp; lift arm without assistance
Transferring golf balls	Pick up golf balls from egg crate and move to container	Use only thumb and forefinger; move to higher surface
Nuts and bolts	Unscrew and screw each bolt using thumb and forefinger	Using smaller bolts, add time limit
Ring toss	Grasp rings and remove, replace on pole	Drop rings or toss rings onto pole
Play-Doh <sup>b</sup>	Separate Play-Doh and form figures; practice cutting with knife	Mashing with entire hand; proper cutting form
Eating lunch	Assist with preparing, eating, and cleaning up after lunch	Progress to preparing and eating as much as possible with affected hand
Sliding checkers	Place forefinger on checker and slide out as far as possible	Slide as far out, hitting a target
Etch A Sketch <sup>c</sup>	Use fingers to draw on the Etch A Sketch	Use thumb and forefinger only in both directions
Clothespins	Use pincher fingers to clip and remove pins from pole	Go as high up as possible; maintain trunk alignment
Computer typing	Use fingers to type on keyboard	Move keyboard out further; use one finger
Stacking cans	Grasp cans and stack	Move to higher levels; increase speed

<sup>a</sup>Milton Bradley Co, Springfield, MA 01101.<sup>b</sup>Hasbro Industries Inc, 1027 Newport Ave, Pawtucket, RI 02861.<sup>c</sup>The Ohio Art Company, 1 Toy St, Bryan, OH 43506-0111.

Across a total set of 60 trials (2 blocks of 30 trials) the Automove unit automatically adjusted the target threshold level either higher (successful attempts at reaching the target level) or lower (unsuccessful attempts) so that patient was constantly challenged to voluntarily generate more EMG activity before onset of the electrical stimulation. A 15-second rest period followed each successful trial.

### Outcomes

One purpose of this report was to investigate the feasibility of using EMG-stim as an adjunct to CIMT. In terms of safety and adherence, the patient was able to complete the protocol safely and met most of the adherence requirements. DK was able to participate in 10 days of CIMT for 6 hours a day. He tolerated the EMG-stim 3 hours a day for the 10 days without complaints of pain or signs of skin irritation. DK's adherence to mitt usage, however, was 65%. This poor adherence may have been due to the low level of hand function. He needed to remove the mitt more often than people with higher functional levels to successfully accomplish ADL. In addition, the patient did not have constant assistance or caregiver supervision because his wife was employed full time.

DK's task performance improved from before intervention to after intervention across all of the motor behavior tests. Table 1 presents a breakdown of each section of the Fugl-Meyer Measurement of Physical Performance and the changes in scores from before to after intervention. The changes demonstrate improvements in the flexor synergy subcomponent and the wrist stability subcomponent. More specifically, improvements were noted in shoulder retraction, shoulder external rotation, and wrist stability. The wrist stability component assesses the patient's ability to maintain wrist extension against resistance while extending the elbow.

Table 6 demonstrates DK's improvement on the WMFT for each task. Although he did not improve in all tasks, his improvement was substantial in some tasks such as "lift can" and "flip cards." Figure 1 depicts the overall change in WMFT timed scores from before to after intervention. In addition, DK improved from 2.5 on the functional rating of the WMFT during preintervention testing to a score of 2.73 following the intervention. The functional rating scale of the WMFT is defined under "Quality Scale" in the footnote of Figure 2, it is the same as the AAUT "Quality Scale" (the functional rating scale

**Table 5.**

Example of a Typical Day of Constraint-Induced Movement Therapy Activities, Including Time Electromyography-Triggered Neuromuscular Stimulation (EMG-stim) Is On and Off

Minutes of EMG-stim	Time of Day	Typical Day of Treatment
Off	9:00 AM	Range of motion, stretch, EMG-stim setup
15	9:10 AM	Placing and removing rings on a stand on table
20	9:25 AM	Picking blocks off of table and placing them into appropriate-sized hole
20	9:45 AM	Stacking and unstacking cans from table
Off	10:05 AM	Stretching hand
	10:15 AM	Bathroom break (mitt removed)
25	10:25 AM	Picking up golf balls and placing into egg carton
Off	10:50 AM	Playing Connect Four <sup>a</sup> (placing checkers into a vertically place game board)
	11:25 AM	Screwing nuts onto secured bolts
	11:55 AM	Lunch (mitt off to finish food—15 min)
25	12:30 PM	Pushing checkers across a checker board
25	12:55 PM	Taking large blocks out of a box and placing on a table
Off	1:20 PM	Turning knobs on an Etch A Sketch <sup>b</sup>
	1:40 PM	Break (bathroom), took walk (mitt off)
35	2:00 PM	Scooping beans out of a bowl
15	2:35 PM	Taking cones from the table and stacked on the floor
Off	2:50 PM	Removing EMG-stim, continued with cones
Total EMG-stim=180 min	3:00 PM	Home

<sup>a</sup> Milton Bradley Co, Springfield, MA 01101.

<sup>b</sup> The Ohio Art Company, 1 Toy St, Bryan, OH 43506-0111.

**Table 6.**

Wolf Motor Function Test Change Scores Per Item

Task	Pretest	Posttest	Change
Forearm to table	1.4	0.9	0.5
Forearm to box	3.2	1.7	1.5
Extend elbow	12.7	13.3	-0.6
Extend elbow (0.45 kg [1 lb])	1.1	0.8	0.3
Hand to table	1.7	1.4	0.3
Hand to box	1.6	1.2	0.4
Reach and retrieve	0.9	0.9	0.0
Lift can	120.0	4.0	116.0
Lift pencil	2.8	2.9	-0.2
Lift paper clip	2.9	2.2	0.7
Stack checkers	21.9	8.7	13.2
Flip card	90.8	13.7	77.1
Turn key in lock	24.0	25.7	-1.7
Fold towel	28.7	8.3	20.4
Lift basket	5.7	5.4	0.3
Weight to box	2.0	4.0	-2.0
Grip force	8.6	7.6	1.0

of the WMFT identical to the "Quality Scale" of the AAUT).

Slight improvements were made in both amount and quality of use of the more-affected extremity for the AAUT. Refer to Figure 2 for DK's improvements before and after training for the AAUT, indicating an increase in spontaneous use and quality of use of the affected extremity. The amount of use scale and the quality scale for the AAUT are defined in the footnote of Figure 2.<sup>4,6,24,25</sup>

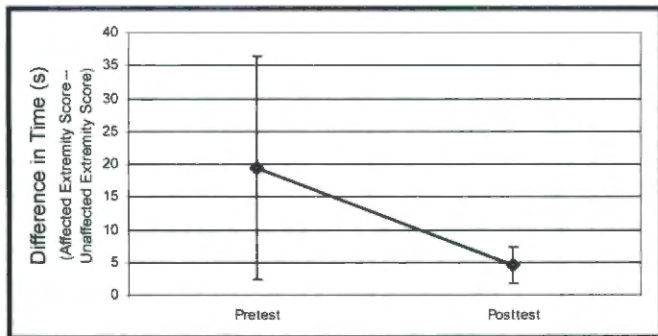
DK also demonstrated improvements on the Box and Block Test. During preintervention testing, he was able to move 13 blocks in 1 minute. During postintervention testing, he was able to move 20 blocks in 1 minute.

DK's performance on the MAL improved. His MAL amount score increased from 0.85 (using his hand very rarely) to 1.76 (sometimes using the weaker hand, but doing most activities with his stronger arm). His MAL quality score also improved from 1.02 (weaker hand is not helpful at all) to 1.70 (weaker hand is of some use, but it is moved very slowly and with difficulty or it needs some help from the stronger arm).

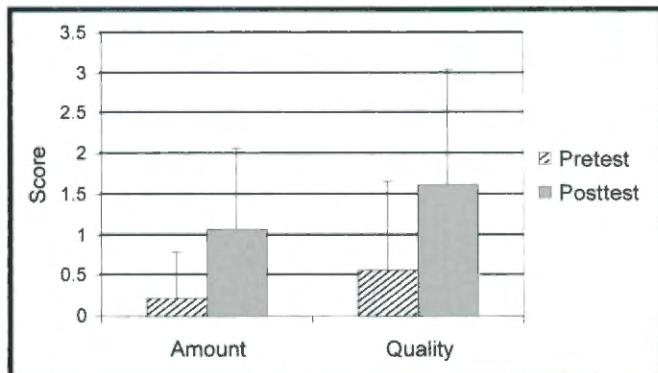
DK improved his scores on the SIS. His score on each subscale of the SIS is outlined in Table 2. Additionally, his perceived level of recovery of his more-affected arm and hand improved from 40% to 65% (Fig. 3). The perceived level of recovery is assessed by the last question on the SIS, in which the patient responds to the following question: "On a scale of 1 to 100, with 100 representing full recovery and 0 representing no recovery, how much has your most-affected arm and hand recovered from your stroke." This question has been modified for use in CIMT studies to focus on the arm and hand, whereas in the original SIS, the question addresses overall recovery from a stroke.

After CIMT, with EMG-stim as an adjunct, during the reciprocation task, the muscle co-contraction time remained 100% for both speeds on the affected side because the sustained muscle activities without silent baseline were still found throughout the task. Muscle activation in both speeds, however, demonstrated clearer bursting activity at the wrist muscles, especially





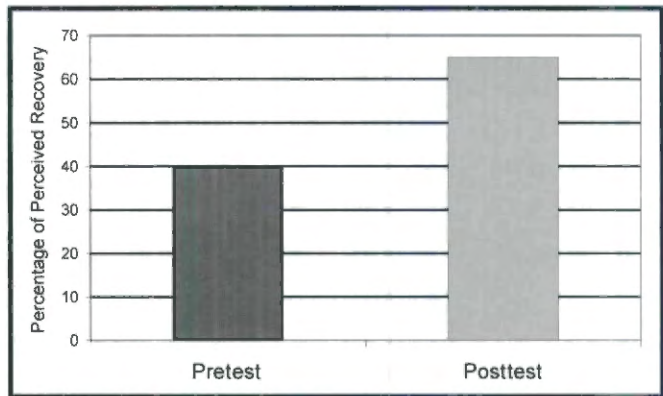
**Figure 1.** Mean change ( $\pm$ SD) in Wolf Motor Function Test scores from before to after testing.



**Figure 2.** Mean scores for the Actual Amount of Use Test from before testing to after testing. Vertical bar is the standard deviation across test items. Amount scale: 1—patient moves arm during task, but use of arm is rudimentary and nonfunctional; 2—patient uses arm to carry out task and the use of the affected arm is functional at some level, uses involved arm 20% of time task is performed. Quality scale: 0—did not attempt task with involved arm; 1—involved arm was moved, but unable to perform task (very poor); 2—performed task very slowly or with difficulty, needed more than 2 attempts, needed assistance from stronger arm, or the task was modified (poor); 3—performed task slowly or with synergy (fair); 4—almost normal, just not as fast or accurate; 5—appears normal.

the wrist extensors (Fig. 4). In addition, the EMG activity of the FCU showed an intermittent twitching pattern that was different from the EMG activity of other muscles. Averaged muscle activity did not change substantially at either speed. Wrist range of motion improved from 9.9 to 17.9 degrees for the medium speed and from 12.8 to 14.1 degrees for the slower speed.

Following CIMT, during the ballistic isometric task, the patient's reaction time on the affected side improved from 229 to 190 milliseconds. There was no change for the premotor time from before to after testing. The peak force decreased from 0.31 to 0.18 N. The torque of wrist joint decreased from  $1.3 \times 10^{-2}$  to  $7.6 \times 10^{-3}$  N·m. The time to peak force was slightly longer after training (from 998 milliseconds to 1,188 milliseconds). The test indicated an improvement in reaction time with no



**Figure 3.** Score for perceived recovery section of the Stroke Impact Scale from before to after testing.

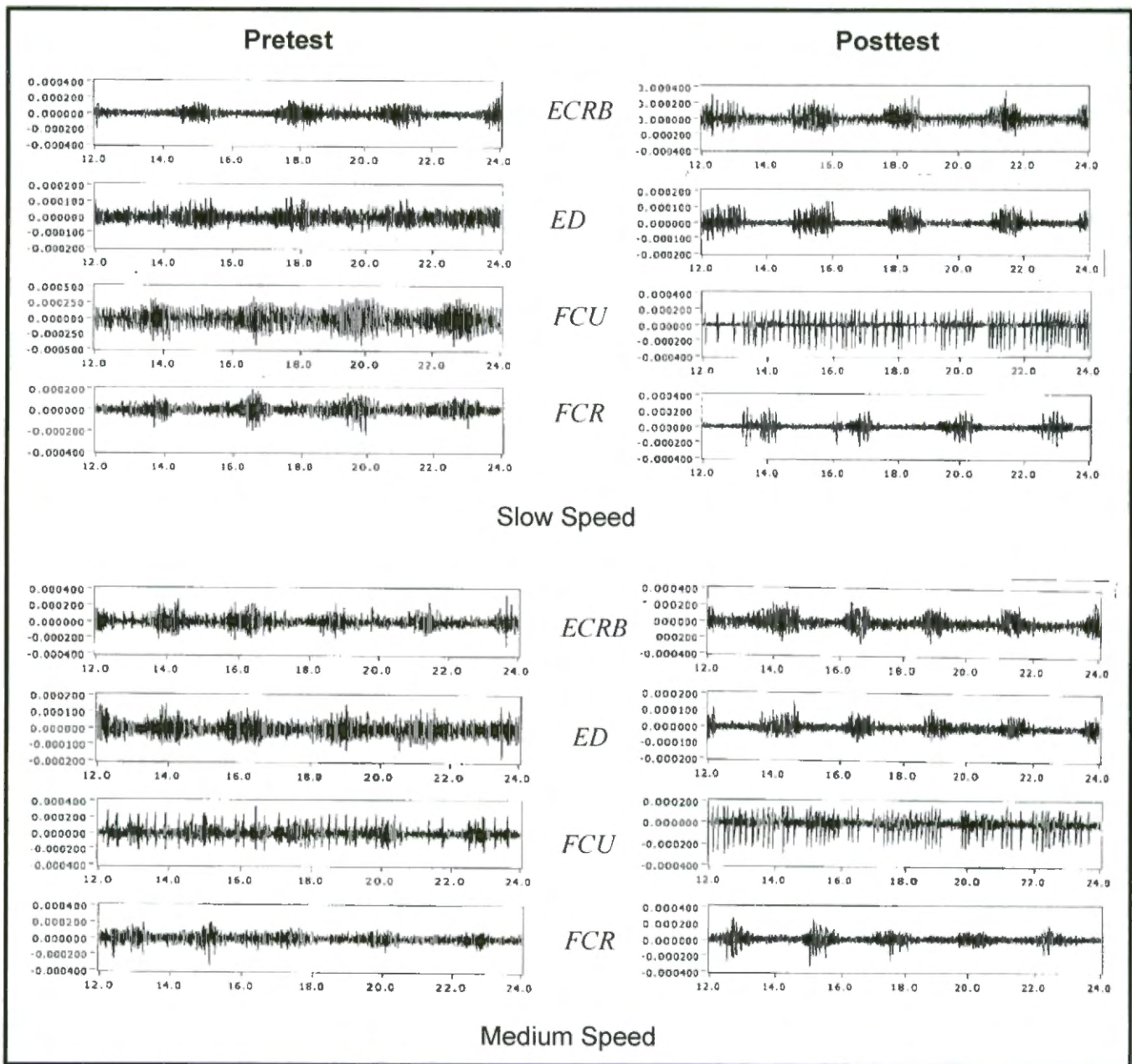
positive changes (desirable improvement) in peak force and time to peak force.

Motor map area and location of the optimal point, which is the stimulating position that elicited the largest-amplitude MEPs, for both preintervention and post-intervention TMS testing sessions are depicted in Table 7. Schematic representations of preintervention and postintervention motor maps are presented in Figure 5. The area of the EDC map increased from 12 to 16 active positions following CIMT. The FCR map area decreased slightly, whereas the FDI map area increased slightly. The location of the optimal stimulating point shifted laterally following therapy for all muscles, but especially for the EDC representation. Although motor threshold increased slightly from 80% before testing to 85% after testing, this small difference represents a nonsubstantial change and indicates relative stability in overall corticospinal excitability.

## Discussion

Rehabilitation researchers have yet to identify a truly effective intervention for upper-limb hemiparesis.<sup>8</sup> Thus, rehabilitation professionals continually search for improved approaches, and new treatment methods, such as CIMT, are often accepted before the relevance of the therapy to a specific group of people is clearly understood. An intervention, for example, may be limited to people who meet certain criteria, although its effectiveness with other people is unknown. For instance, people with DK's ability were not included in traditional CIMT because it was believed that more movement was needed to be successful with this type of therapy and that a person needed to be able to meet minimum motor criteria. An example of this is limiting participation in CIMT studies to people who meet certain wrist and finger range-of-motion requirements. DK had some use of his dominant right hand and arm prior to participating in the rehabilitation program. He did not have enough movement, however, to meet traditional CIMT





**Figure 4.** Muscle-activation pattern (electromyography [EMG] raw data) at 2 speeds (upper row: slow speed, lower row: medium speed) during the reciprocation task in 4 muscles: extensor carpi radialis brevis (ECRB), extensor digitorum (ED), flexor carpi ulnaris (FCU), and flexor carpi radialis (FCR). The left column shows pretest EMG activity. The right column shows posttest EMG activity.

requirements. The purpose of this case report was to demonstrate the feasibility of using EMG-stim as an adjunct to traditional CIMT for a patient who did not meet the requirements of wrist and finger extension.

The patient demonstrated improvements on the Fugl-Meyer Measurement of Physical Performance, WMFT, AAUT, Box and Block Test, MAL, and SIS. The changes in the scores could be due to a variety of factors. The scores could reflect improvements in speed of movement, improved grasp and release, increased spontaneous use of the affected arm, and improved perceived

recovery of hand and arm function. The patient may have performed better after intervention simply because he has performed these tests previously. Changes also may have been due to learned nonuse or, as shown with TMS, to changes in use-dependent cortical plasticity. The significance of improvements, however, is questionable. Although DK showed definite improvements on many of the assessments, the functional significance related to the amount of improvement may be unclear. That is, difficulty exists relating how the standardized assessments translate into real-world function. Although DK reported increased use on the MAL, this score could



**Table 7.**  
Motor Map Area and Location of the Optimal Point for Both Preintervention and Postintervention Transcranial Magnetic Stimulation Testing Sessions

<b>Motor map area (no. of active positions)</b>			
<b>Muscle<sup>a</sup></b>	<b>Preintervention</b>	<b>Postintervention</b>	<b>Change</b>
EDC	12	16	+4
FCR	22	20	-2
FDI	10	12	+2

<b>Optimal point location</b>			
<b>Muscle</b>	<b>Preintervention</b>	<b>Postintervention</b>	<b>Change</b>
EDC	5 lateral, 1 posterior	7 lateral	Shifted 2 cm lateral, 1 cm anterior
FCR	5 lateral, 1 posterior	6 lateral, 1 posterior	Shifted 1 cm lateral
FDI	5 lateral, 1 posterior	6 lateral, 1 anterior	Shifted 1 cm lateral, 2 cm anterior

<sup>a</sup> EDC=extensor digitorum communis, FCR=flexor carpi radialis, FDI=first dorsal interosseous.

have been artificially heightened because he had just finished therapy. He, however, did make improvements across all the motor tasks.

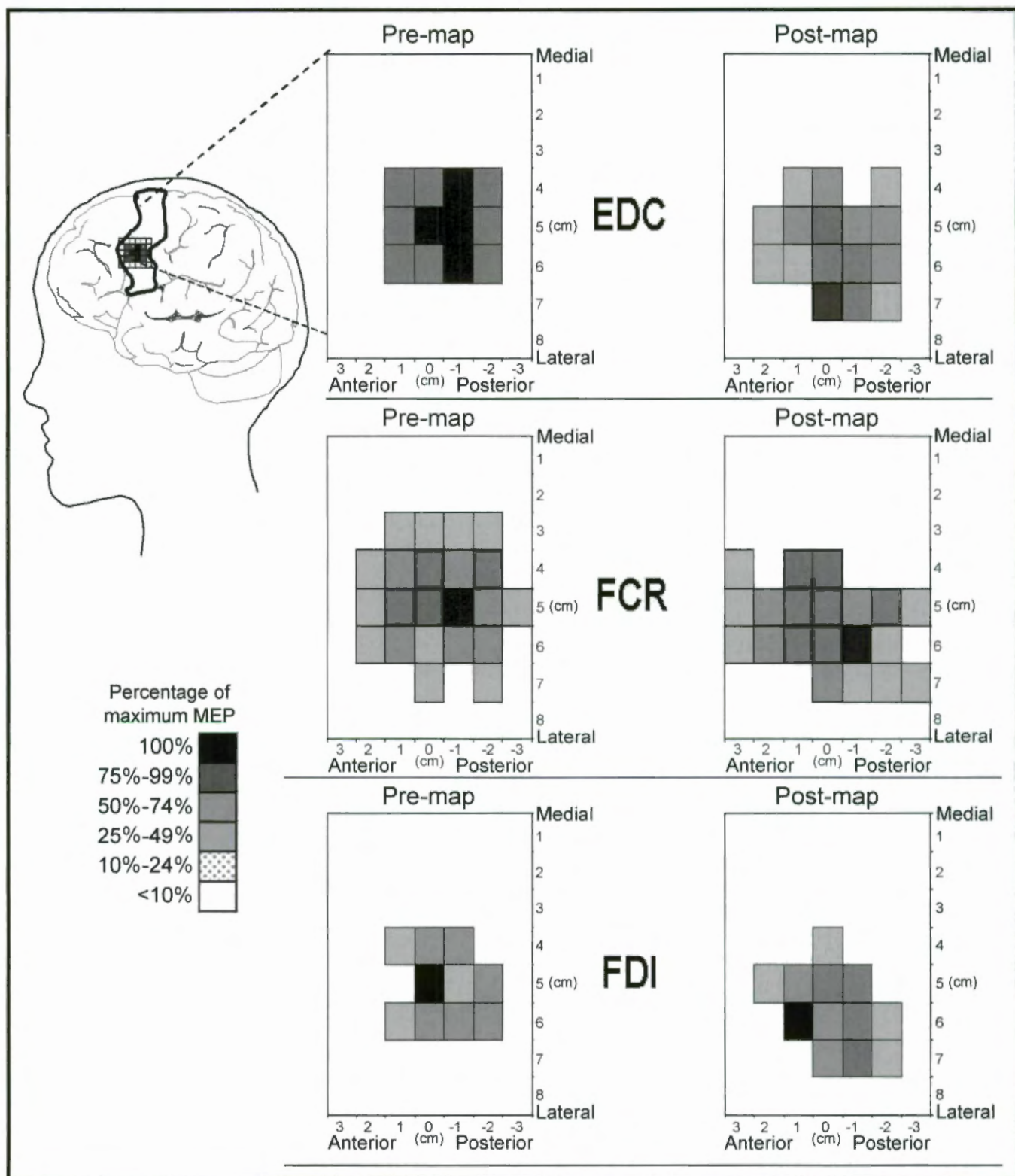
Although DK said he was motivated to participate in the CIMT program, he did not wear his mitt as much as requested or as previously reported in other CIMT literature.<sup>4,6-8</sup> DK's failure to don the mitt as instructed may have been due to his lower level of function. While at therapy, his mitt was on for an average of 5.25 hours out of the total 6 hours (88%). While at home, he reported wearing the mitt 65% of waking hours. The trainers continually tried to encourage increased mitt time; however, due to DK's limited amount of movement and limited help from a caregiver, this was difficult to achieve.

The changes seen in some of the behavior tests and questionnaires should be further explained. DK's improvement on the timed portion of the WMFT can be attributed mostly to the change in scores of 4 specific activities: lifting a can, stacking checkers, flipping cards, and folding a towel. The time required for these activities decreased substantially from the preintervention testing. An original study investigating CIMT showed improvements of the WMFT time scores by 90%.<sup>31</sup> DK showed a greater than 400% decrease in time on the WMFT. Although this improvement seems remarkable, caution is needed because this report describes the outcomes for one individual and improvements from CIMT can vary considerably among individuals.<sup>32</sup> DK did show substantial gains in time to complete a task following this 2-week intervention; however, there was little change in his scores on the functional ability scale of the WMFT. This outcome may have been due to the fact that DK exhibited synergy during both pretest and posttest measurements in most of the task completions. If synergy is present, the highest functional ability score that can be received is 3, meaning that the movement is

somewhat influenced by synergy. DK exhibited changes in both quality and amount of use of the more-affected extremity on the AAUT. Although these improvements were small, they could be defined as functional. These improvements could be interpreted to mean that DK rarely used his weaker arm for any task prior to therapy and that he attempted to use his arm on approximately half of the given tasks during the AAUT after therapy.

DK demonstrated improvements on the motor component, the social component, and the percentage of perceived recovery of the SIS. The increases in reported motor scores are of interest because these scores are from DK's point of view. For example, he reported improvements not only in hand and arm function, but also in gait and balance. Prior to therapy, he said that climbing stairs and getting in and out of a car were "somewhat difficult" for him; however, following intervention, he rated these activities as "not difficult at all." Possibly, the demand of keeping a schedule and reporting to therapy every day for 6 hours resulted in increased confidence in these balance tasks. In addition, his social subscale score increased from 34 to 38. This improvement may reflect being more comfortable in social situations, possibly as a result of the intensive 6 hours per day of therapy. Finally, DK rated his most-affected arm and hand as 40% recovered prior to therapy. Following therapy, this rating increased to 65%. This change in perceived level of recovery demonstrates that he believed he improved with this intervention, and pictured his arm and hand as more recovered overall.

The benefits of EMG-stim were well demonstrated in Cauraugh et al<sup>19</sup>; however, differences in clinical dependent measures in their study were limited to the Box and Block Test, in which individuals who received EMG-stim improved an average of 129%. DK demonstrated an improvement of 65% on the Box and Block Test, but he also had improved scores on the Fugl-Meyer Measure-



**Figure 5.**

Motor cortex representation for the extensor digitorum communis (EDC), flexor carpi radialis (FCR), and first dorsal interosseus (FDI) muscles. The shaded squares represent stimulation positions that elicited a motor-evoked potential (MEP) of interest. The stimulating positions were located 1 cm apart and are referenced in relation to the vertex of the skull. The shading in each square indicates the mean MEP area elicited at each stimulating point as a percentage of the largest MEP elicited in each muscle. Maps on the left were recorded prior to constraint-induced movement therapy (CIMT); those on the right were recorded following the 2-week intervention. Note the enlargement of the EDC map following CIMT.



ment of Physical Performance. No improvement was demonstrated on the Fugl-Meyer test in the study by Cauraugh et al. More of DK's improvements were noted across other clinical measures and questionnaires not included in the cited study.<sup>19</sup> DK showed improvements across different domains, including impairments, functional limitations, and disabilities.

*Muscle co-contraction* can be defined as the temporal (or simultaneous) overlap of agonist and antagonist muscle contractions. Co-contraction is normal when learning a new motor skill and when stability is required. Controlled co-contraction during active movement is an important feature of motor function because it provides postural stability of a body part. For example, when a person drinks a glass of water, the co-contraction of wrist flexors and extensors provides stability of movement. People with a stroke, however, usually have abnormal muscle co-contraction, which interferes with achieving their movement goal.<sup>33,34</sup>

In the reciprocation task, DK's muscle-bursting activity demonstrated a clearer pattern following the training. His wrist active range of motion also improved. In the ballistic task, only reaction time improved after training. Most parameters, such as timing of muscle activation and force generation, did not improve. Although cause and effect cannot be determined from a case report, hypotheses can be developed. The results from the EMG portion may be attributed to the main focus of the intervention: repetition of movement over quality of movement. Force generation requires appropriate muscle recruitment (ie, sequence and timing of muscle activation) and coordinated force modulation.<sup>35</sup> In our protocol, however, intensive training with massed practice mainly emphasized intensity of practice rather than reconstruction of movement patterns.

The motor cortex representations for each muscle changed in both size and location following the intervention. These changes were only slight in the FCR and the FDI; however, the EDC representation demonstrated a relatively substantial lateral shift and increase in absolute area. The finding of an increase in map size fits with the findings of studies that have demonstrated neural changes following repetitive use. For example, Pascual-Leone et al<sup>36</sup> examined changes in the primary motor cortex hand representation over a 5-day period in participants without known pathology or impairments as they learned a skilled movement task. As the participants became more skilled in a 5-finger piano exercise, the size of the motor cortex hand representation increased. Similar reports have demonstrated that the brain hemisphere affected by stroke also is capable of activity-dependent reorganization. Liepert et al<sup>12</sup> reported that the size of the motor representation for a thumb muscle

increased following CIMT. Such rapid changes in cortical maps likely represent the unmasking of weak or secondary synaptic connections and are driven by concentrated practice.<sup>37</sup>

We also found a lateral shift of all motor maps, suggesting that the representations for these muscles may have "invaded" the adjacent facial muscle representation. Nudo et al<sup>14</sup> noted that intrinsic and extrinsic hand muscle maps shifted both laterally and medially in a group of squirrel monkeys following intensive upper-extremity practice. Similarly, in individuals who recovered from stroke, lateral shifts<sup>38</sup> and medial shifts,<sup>13</sup> or extensions of representations involved in finger movement, were found. The locational changes demonstrated in referenced studies and the optimal point shifts in DK, suggest that, in addition to the enlargement of excitable cortical areas, a new maximum may have developed adjacent to the former one.<sup>13</sup>

DK demonstrated neurological alterations in primarily the EDC representation. This finding lends support to the notion that EMG-stim may help to increase the capacity of wrist and finger extensors in performing functional tasks. By increasing the capacity for movement, the stimulation may allow the individual to use the affected limb with the purpose and intensity needed to drive changes in neural systems that subservise movement. This needs to be investigated in a randomized study to determine the accuracy of this statement.

In summary, an intensive therapy program such as this can be frustrating. DK often exhibited and verbalized frustration with wearing the mitt and performing the activities. Although he acknowledged his frustration, he also noted the changes that occurred in how much and how well he could use his weaker hand and arm. Although motivation was not measured, DK demonstrated motivation, even after 10 years, to regain more use of his hand and arm. Future studies should incorporate measures of motivation to help in determining outcomes following therapy.

Although it is unknown whether EMG-stim in addition to CIMT was more beneficial than CIMT alone, this case report demonstrated that this intervention was feasible and appeared to be helpful for an individual 10 years following stroke. Future studies incorporating this protocol would provide insight into the effectiveness of such an intervention. Whether EMG-stim in addition to CIMT is more beneficial than CIMT alone for people who have low functional ability needs to be determined. Data are currently being collected, with more participants, comparing this intervention with traditional CIMT. This study will include participants with low functional ability who do not meet minimum motor criteria.



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