

Two Coupled Motor Recovery Protocols Are Better Than One

Electromyogram-Triggered Neuromuscular Stimulation and Bilateral Movements

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Background and Purpose—Overcoming chronic hemiparesis from a cerebrovascular accident (CVA) can be challenging

for many patients, especially after the first 12 months after the CVA. With the use of established motor control theories,

the present study investigated electromyogram (EMG)-triggered neuromuscular stimulation and bilateral coordination training.

Methods—Twenty-five CVA subjects volunteered to participate in this motor recovery protocol study. Subjects were

randomly assigned to 1 of 3 groups: (1) coupled protocol of EMG-triggered stimulation and bilateral movement (n_10);

(2) EMG-triggered stimulation and unilateral movement (n_10); or (3) control (n_5). All participants completed 6

hours of rehabilitation during a 2-week period according to group assignments. Motor capabilities of the wrist and

fingers were evaluated on the basis of 3 categories of motor tasks in a pretest-posttest control group design.

Results—Significant findings for the (1) number of blocks moved in a functional task, (2) chronometric reaction times to

initiate movements, and (3) sustained muscle contraction capability all favored the coupled bilateral movement training

and EMG-triggered neuromuscular stimulation protocol group. In addition, the unilateral movement/stimulation group

exceeded the control group in the number of blocks moved and rapid onset of muscle contractions.

Conclusions—This new evidence is convincing in that subjects in the coupled protocol group were able to demonstrate

enhanced voluntary motor control across 3 categories of tasks. Chronic hemiparesis decreased considerably in the wrist

and fingers as CVA patients expanded their motor repertoire. (*Stroke*. 2002;33:1589-1594.)

Key Words: cerebrovascular accident _ electromyography _ fingers _ motor activity _ muscle, skeletal _ transcutaneous electric nerve stimulation _ wrist

Cerebrovascular accidents (CVAs) are currently the leading cause of motor disabilities; a flexor synergy typically develops in an upper extremity during recovery.¹ This pathological synergy may persist for years as a motor paralysis on 1 side of the body (hemiparesis), and many people experience difficulty in isolating movements out of synergy.² Frequently, people develop compensatory strategies involving both the impaired and unimpaired upper extremities; however, voluntary control of the impaired limb is difficult.³ Indeed, there is a paucity of information about the most effective way to rehabilitate the motor system to maximize improvements in neurological function.^{2,4}

Testing rehabilitation protocols on the basis of sound motor control theoretical propositions would advance understanding.

For example, sensorimotor integration theory is a viable theoretical basis given the accumulating evidence regarding the method by which alternate motor pathways can

be recruited and activated to assist the CVA-damaged efferent pathways.^{3,5-7} Reacquiring movement capabilities involves relearning to initiate motor actions on voluntary command as well as knowing that the impaired limb is moving. Indeed, a coherent perception-action relationship must be reestablished in stroke patients so that they will be able to expand their limited motor repertoire.⁸

One protocol that is consistent with the propositions of sensorimotor integration theory is electromyography (EMG)-triggered neuromuscular stimulation. This protocol requires CVA patients to voluntarily contract a group of muscles for a movement. The EMG activity level generated by patients is supplemented by an electric stimulation on the skin above the involved muscles, and the limb goes through a particular motion.^{4,9} According to Ghez and colleagues,¹⁰ movement-generated proprioceptive feedback serves a critical role in motor planning by updating an internal model of the state and properties of the limb. Specifically, proprioceptive feedback that returns to the cerebellum and the somatosensory area can be used to establish and reinforce voluntary movement control associations with the adjacent primary motor cortex.^{11,12}

Two previous sensorimotor integration theory studies examined the effect of EMG-triggered neuromuscular stimulation on movements in the upper extremity. Bowman et al¹³ investigated positional feedback and neuromuscular stimulation in hemiplegic patients as they attempted to complete

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wrist extension movements. They reported benefits for the positional feedback group with neuromuscular stimulation in comparison to a control group who received typical physical therapy. A more recent study involving the wrist and finger extensors was conducted by Cauraugh et al.⁴ The experimental group received 6 hours of EMG-triggered neuromuscular stimulation on the extensor communis digitorum and extensor carpi ulnaris muscles as a facilitative treatment for voluntary control. The EMG-triggered stimulation group improved in terms of the number of blocks moved in a motor capability test as well as sustained force contractions more than the randomized control group.

Dynamic Systems Theory: Interlimb Coordination

Motor recovery rehabilitation protocols traditionally focus on single-limb (unilateral) tasks for the affected upper extremity.

^{14,15} However, dynamic systems theory (bimanual coordination) and interlimb coupling should not be neglected. The phenomenon of 2 arms working together bilaterally in coordination situations has generated considerable interest in motor control researchers.¹⁶⁻¹⁹ As Bernstein suggested, evidence clearly indicates that both arms are centrally linked as a coordinative structure unit: hands and fingers function in a homologous coupling of muscle groups on both sides of the body.^{12,14,20-22} Coordinated movement patterns emerge spontaneously from the constraints on the system as a function of

dynamics.²³ This approach emphasizes the inherent characteristics of muscles as important for motor control. When 2 limbs execute the same type of movement (eg, wrist extension) at the same time, the complex system is referred to as stable and in-phase.

Moreover, Mudie and Matyas²⁴ postulated that bilateral actions trigger interhemispheric disinhibition that may allow alternative recruitment pathways to be activated. Three alternative recruitment pathways were proposed to supplement actions originally controlled by the damaged hemisphere: (1) spared ipsilateral corticomotoneuron pool in the damaged hemisphere, (2) ipsilateral corticospinal pathways from the undamaged hemisphere, and (3) indirect ipsilateral corticospinal pathways.

Executing movements with both arms simultaneously presents a distinct advantage for CVA patients with chronic hemiparesis as they attempt to overcome the neuromuscular constraints imposed on the system.^{15,21} Indeed, 2 studies reported improved movement capabilities in impaired limbs after subjects completed bimanual coordination rehabilitation programs. Mudie and Matyas²⁴ found decreased acute hemiparesis with bilateral training assistance on specific upper limb movements. In addition, Whittall et al¹⁵ reported an advantage in upper extremity auditory-cued bimanual rhythmic timing during elbow extension and flexion. Again, decreased hemiparesis was identified in the bilateral training group in comparison to the unilateral training group.¹⁵

Coupled Motor Recovery Protocols

In separate protocols, studies of EMG-triggered neuromuscular stimulation and bilateral coordination training produced convincing evidence of motor improvements in subjects with hemiparesis. Moreover, both sets of findings are based on accepted motor control theories: sensorimotor integration and dynamic systems. Furthermore, these theories complement each other in that the body is viewed as an active dynamic system that executes movements through an interaction of sensory input and motor actions given imposed neuromuscular constraints on the system. Indeed, the 2 theories essentially activate the same central and peripheral neural mechanisms associated with the pyramidal tract.^{11,12}

Combining these 2 innovative rehabilitation protocols could expedite the progress of motor recovery. Thus, the purpose of this study was to determine the effect of EMG-triggered neuromuscular stimulation in conjunction with bilateral movement training on motor improvements of the upper extremity in subjects who had experienced CVA at least 1 year previously and had chronic hemiparesis. It was hypothesized that the coupled EMG-triggered stimulation and bilateral movement protocol would demonstrate evidence of motor progress in subjects with chronic hemiparesis in comparison to the unilateral movement/stimulation and control protocols.

Subjects and Methods

Subjects

Volunteer participants (n=25 [4 women and 21 men]) had a CVA (left hemisphere_13; right hemisphere_12) at least 1 year ago. The mean length of time since CVA onset was 39.1 months, and the mean age of the sample was 63.7 years. All subjects displayed mild to moderate upper extremity chronic hemiparesis. Participants were

randomly assigned with the restriction that 20 subjects were tested in the 2 treatment groups (10 each in the unilateral and bilateral wrist/finger movement groups with EMG-triggered neuromuscular stimulation), and 5 subjects served as the control group with no movement assistance.

All subjects met 6 admission criteria: (1) diagnosis of at least 1 CVA and no more than 2 CVAs on the same side of the brain; (2) an upper limit cutoff point of 80% motor recovery, as assessed by rectified EMG activation patterns and sustained force contractions during direct comparison of the impaired and unimpaired limbs^{25,26}; (3) a lower limit cutoff point of 10° of voluntary wrist or finger extension against gravity from a 90° flexed position; (4) absence of other neurological deficits, including a pacemaker; (5) no use of drugs for spasticity; and (6) no enrollment in another motor recovery rehabilitation protocol. Before testing began, subjects read and signed an informed consent form approved by the institutional review board.

Pretest-Posttest Instruments and Procedures

Motor functions of the upper extremity were evaluated with 3 categories of measurement. The first category was a functional manual dexterity test termed the Box and Block timed manipulation test. For 1 minute, subjects attempted to reach and grasp a 2.54-cm cube, transport it over a short barrier, release the block, and return to the original side for another block. Figure 1 shows a subject performing the task.

The other 2 categories of measurements were laboratory-based chronometric and force generation tasks: (1) simple reaction time for speed of information processing and rapid muscle onset and (2) sustained muscle contractions and force modulation (stability control). The hands and arms were inserted into separate devices so that isometric wrist/finger extension movements were executed against 11.4-kg load cells. For both arms, force and EMG signals were recorded online. EMG activity of the wrist/finger extensor muscles was recorded with surface electrodes (silver–silver chloride electrodes with an epoxy-mounted preamplifier).

In the chronometric simple reaction time task, subjects were instructed to respond as quickly as possible to the onset of an

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auditory stimulus by initiating the wrist/finger extensors against the cushioned platforms holding the load cells. Ten reaction time trials were administered to each arm separately, and 10 trials were given to both limbs doing the same isometric bilateral movement. In the sustained muscle contraction task, subjects were instructed to gradually increase their wrist/finger extension force to a maximal isometric contraction and hold that level for at least 6.5 seconds, an interval signaled by the experimenter. Three trials were completed for each arm/wrist separately and together. The 2 force-generation tasks were tested in a random order with 5 minutes of rest between tasks.

Motor Recovery Protocols: Training Procedures

The unilateral training group only received EMG-triggered stimulation to assist with wrist and finger extension. However, the bilateral training subjects received both EMG-triggered stimulation and assistance from their unimpaired limb as wrist/finger extension was executed simultaneously on both limbs.

A treatment session started with stretching, and surface electrodes were attached to the extensor communis digitorum and extensor carpi ulnaris muscles of the impaired limb. The electrodes were connected to an Automove (AM 800) EMG Facilitation Stimulator microprocessor, and when a target threshold level of EMG activity was voluntarily achieved, the unit immediately provided a surface neuromuscular electric stimulation (ie, 1-second ramp up, 5 seconds of biphasic stimulation at 50 Hz, pulse width of 200 μ s, 1-second ramp down, and mA range of 16 to 29) that assisted the muscles to execute a full range of motion. The initial threshold was set at 50 μ V,

and as participants successfully achieved the target threshold level, the microprocessor unit automatically increased the target level slightly higher. If the threshold level was not met, then the unit decreased the threshold level closer to the amount of voluntary activity that the individual could produce. Trials were separated by 25 seconds of rest.

During each day of training, subjects completed 3 sets of 30 successful EMG-triggered neuromuscular stimulation trials (approximately 1 hour and 30 minutes) according to the motor recovery protocol group assignments (ie, bilateral or unilateral movements). The 6 hours of training (4 days) were completed during 2 weeks. The control group followed the same procedure as the 2 experimental groups except they did not receive the neuromuscular electric stimulation or bilateral assistance for the wrist/fingers extensors. After the impaired limb was stretched, subjects tried to voluntarily extend their wrist/fingers for 5 seconds, followed by 25 seconds of rest. These repeated movement attempts and rest periods continued for approximately 90 minutes.

Data Reduction

Once the chronometric simple reaction time EMG data were rectified and smoothed at 100, fractionated components (premotor and motor) were determined. Premotor reaction time, a central component, was operationally defined as the time from stimulus onset until the EMG activity of the extensor muscles reached 30% of peak activity. Motor reaction time, a peripheral component, began directly after premotor reaction time and ended with movement initiation, operationally defined as 30% of peak force amplitude.^{4,27,28}

For the sustained contraction task, the ability to maintain the level of force generated was determined. Root mean square error was the response variable, and it was an overall measure of bias and variability in peak force amplitude across the sustained contraction interval. To allow for the gradual increase to peak force, root mean square error was calculated for 5 seconds 1.5 seconds after stimulus onset.

Data Analysis

Separate analyses were conducted on the dependent measures. The number of blocks moved in the Box and Block test was analyzed in a mixed design Motor Recovery Protocol (3: bilateral, unilateral, and control)_ Test Session (2: pretest and posttest) ANOVA with repeated measures on the second factor. Analysis of the simple reaction time and sustained contraction data included a second within-subject factor; a limb factor was introduced with 2 levels (impaired alone and both arms together). Thus, both the reaction time and sustained muscle contraction data were analyzed in separate mixed design 3_2_2 (Motor Recovery Protocol_Test Session_Limb) ANOVAs with repeated measures on the last 2 factors. All statistical tests were conducted with α set at 0.05; when appropriate, the Tukey-Kramer procedure was used as the multiple comparison follow-up test.

Results

Box and Block Test

The mixed design analysis of the impaired limb revealed 2 significant findings: (1) test session main effect ($F_{1,22} = 23.96$, $P < 0.001$) and (2) Motor Recovery Protocol_Test Session interaction ($F_{2,22} = 3.86$, $P < 0.04$). As shown in Figure 2, at the pretest, the motor capabilities of the 3 treatment groups were equivalent. However, at the posttest, the number of blocks moved by the bilateral training group, coupled with EMG-triggered stimulation, increased in comparison to the unilateral and control groups. Additionally, the unilateral training/stimulation group moved more blocks than the control subjects across the test sessions. Even when it is acknowledged that the number of blocks moved by the bilateral

movement/stimulation protocol (27) is less than the normalized block scores for an unimpaired elderly population (71), **Figure 1.** Subject performing the Box and Block test with his impaired right hand.

Figure 2. Mean number of blocks moved for the motor recovery protocols as a function of test sessions.

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the improvement in the present study is 7 times better than that of the control group.²⁹

Simple Reaction Time and Fractionated Components

Tests of normality on distributions of the motor recovery protocol groups indicated that the mean reaction times were heavily skewed. Therefore, median reaction times were calculated, and normality was reexamined. The median times approached normality, although 2 subjects displayed extreme simple reaction times. Thus, consistent with recommendations by Ratcliff,³⁰ 2 subjects were excluded from the analyses, and all subsequent median reaction time analyses were conducted on 23 subjects.

The initial 3-way analysis of simple (total) reaction time revealed 2 important significant interactions. The reaction times decreased significantly (53 ms) across the test sessions for the bilateral training/stimulation group. However, the groups were not equivalent at the pretest: the unilateral group was faster than the bilateral and control groups. Thus, the critical assumption of equivalent groups at the pretest session was violated. A solution to this violation is an ANCOVA with the pretest data used as the covariate for the posttest.^{31,32} Therefore, the chronometric reaction time data were reanalyzed with a 2-way covariate analysis (Motor Recovery Protocol_Limb: 3_2). This new analysis revealed that the pretest covariate was significant ($F_{1,39} = 77.84, P < 0.001$), and the additional assumption for equality of slopes was not violated. Furthermore, the 2-way interaction reached significance ($F_{2,39} = 3.81, P < 0.03$). Post hoc analysis on the adjusted medians in the Motor Recovery Protocol_Limb interaction (Figure 3) indicated a distinct advantage for the bilateral training/stimulation group's impaired limb in both testing situations (alone and with the unimpaired limb) in comparison to the control group.

ANCOVA of the central component of simple reaction, premotor reaction time, revealed a significant covariate ($F_{1,39} = 71.41, P < 0.001$) with equal slopes. In addition, the analysis found a reliable motor recovery protocol main effect ($F_{2,39} = 5.59, P < 0.01$). The Tukey-Kramer multiple comparison test on the adjusted group medians indicated that the bilateral training/stimulation group (median_227 ms, SD_34) was faster than the unilateral/stimulation group (median_255 ms, SD_35) as well as the control group (median_269 ms, SD_35.2).

Analysis of the chronometric measure motor reaction time, the peripheral component of simple reaction time, indicated a significant pretest covariate ($F_{1,39} = 21.66, P < 0.001$) as well as a reliable motor recovery protocol main effect ($F_{2,39} = 7.13, P < 0.003$). Median comparisons revealed faster motor reaction times for both training groups (bilateral/stimulation: median_57 ms, SD_25.9; unilateral/stimulation: median_63 ms, SD_25.8) than the control group (median_95 ms, SD_26).

Sustained Muscle Contraction and Force Modulation

To be consistent with the reaction time analyses, median values were calculated and analyzed. Preliminary analysis of normality on the median root mean square error data for each treatment group revealed an extensive amount of skewness as well as heterogeneity. Therefore, the data were transformed by a square root function, and the normality tests were run a second time. Transforming and removing an outlier subject stabilized the data set, normality was approached, and homogeneity was achieved. All subsequent analyses were computed on the transformed data of 24 subjects.

Analysis of the sustained muscle contraction indicated a reliable Motor Recovery Protocol_Test Session_Limb interaction ($F_{6,63} = 2.35, P < 0.05$) (Figure 4). Follow-up analysis revealed that in the single-arm testing condition, the impaired limb of the bilateral movement/stimulation group improved considerably from the pretest to the posttest. For the unilateral/stimulation group, the impaired limb of the single-arm and 2-arm testing conditions decreased root mean square error approximately the same amount across the test sessions. These pretest-posttest patterns contrasted with the patterns of the control group.

Discussion

The overall conclusion is that the 2 coupled motor recovery protocols increase movement capabilities in stroke patients with chronic hemiparesis. Three lines of evidence clearly

Figure 3. Median simple reaction time for the impaired limb testing situation as a function of motor recovery protocol. Bim Impaired indicates that both limbs are tested together, and the impaired limb's performance is displayed.

Figure 4. Median root mean square error (RMSE) for the motor recovery protocols and the impaired limb condition as a function of test session (pretest and posttest). Bim Impaired indicates that both limbs are tested together, and the impaired limb's performance is displayed.

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support the hypothesis that coupled EMG-triggered neuromuscular stimulation and bilateral movements improved motor functions more than did 1 protocol or no protocol. The number of blocks moved in the functional task, the rapid muscle onset times to initiate movements, and the sustained muscle contraction capabilities all favor the coupled bilateral training/neuromuscular stimulation protocol. This new evidence is convincing in that subjects in the coupled motor recovery protocols were able to demonstrate an enhanced motor capability across the 3 categories of tasks.

Coupled Protocols Evidence

The reliable interaction effect for the Box and Block task extends previous findings on stroke patients with chronic hemiparesis.⁴ Specifically, the higher number of blocks moved by subjects in the coupled motor recovery protocol group after training extends earlier results. Cauraugh et al⁴ reported better functional motor capabilities for EMG-triggered neuromuscular stimulation while subjects performed unilateral movements. The present findings confirm a higher motor capability in the impaired limb after bilateral training/stimulation.

Additional evidence favoring the increased motor function advantage in the impaired limb for the coupled bilateral movement/neuromuscular stimulation protocol was found in

faster simple reaction times. Bilateral training subjects decreased rapid onset contraction time by voluntarily activating the impaired wrist/finger extensors to the target level for electric stimulation onset while simultaneously moving the unimpaired limb. This evidence clearly suggests that the 2 protocols complemented each other.

Moreover, analyses on the fractionated central and peripheral reaction time components confirm and extend the simple reaction time results. The central component findings identified a distinct premotor reaction time advantage for the bilateral movement/neuromuscular stimulation protocol in comparison to the 2 other protocols. In addition, the reliable faster motor reaction times (peripheral component) for the bilateral movement/stimulation protocol as well as the unilateral movement/stimulation group indicate a contribution to the simple reaction improvements. These findings extend the rapid muscle onset times to both the bilateral and unilateral/stimulation protocols. Furthermore, the present results are consistent with the characteristics of the motor reaction time component and traditional fractionated reaction time observed by researchers, in that once the neuron signal arrives at the wrist and finger muscles, there is a shorter delay in response of the impaired limb after the 2 coupled rehabilitation protocols.^{4,27,28} Moreover, the improved simple, premotor, and motor reaction times for individuals with chronic residual hemiparesis are new findings.

Discussion of the sustained muscle contraction force modulation task results focuses on the minimal root mean square error identified in the impaired limb. The displayed advantage for the impaired limb during the 2-handed test situation for the coupled bilateral training/neuromuscular stimulation group is consistent with motor control theories.^{4,15,24,33} Subjects were able to maintain a sustained contraction in the wrist and finger extensors better at the posttest than the pretest. Additionally, these subjects accumulated less variability by maintaining the generated force level over an extended period of time. In contrast, CVA patients with chronic hemiparesis typically show increased variability (eg, muscle activity continually being turned on and off) across the contraction interval.^{4,34}

The combined evidence is interpreted as support for both the sensorimotor integration theory and dynamic systems theory (interlimb coordination). The theoretically based coupled protocols are viewed as activating mechanisms in the corticomotoneuron pool for the wrist and finger muscles by requiring that subjects generate a voluntary response in the impaired limb. This voluntary action is supplemented by the EMG-triggered neuromuscular stimulation as well as the identical movement in the unimpaired limb. Afferent input from the wrist and finger movements returns to the somatosensory area and most likely influences subsequent actions (movements) generated by the adjacent primary motor cortex.³⁵

Mudie and Matyas²⁴ directly applied dynamic systems theory to stroke rehabilitation research when they found an advantage for bilateral movements. They argued that bilateral actions trigger interhemispheric disinhibition that may allow alternative recruitment pathways to be activated. As stated in the introduction of this article, 3 alternative recruitment

pathways were proposed to supplement actions originally controlled by the damaged hemisphere. In addition, Fischbach³⁶ argued that learning is a function of new neural ensembles; the author noted the tendency of synapses and neuronal circuits to change as a result of activity (ie, voluntary muscle contractions and neuromuscular stimulation). The identified recruitment pathways and new neural ensembles are viable explanations for the coupled motor improvements found in the present study.^{37,38}

EMG-Triggered Neuromuscular Stimulation Evidence

The EMG-triggered neuromuscular stimulation and the unilateral movement comparisons with the control group provide additional evidence supporting motor progress in patients with chronic hemiparesis after CVA. Indeed, consistent with the findings of Cauraugh et al,⁴ the present study found that the unilateral training/EMG-triggered neuromuscular stimulation group was better than the control group on 2 dependent measures: (1) Box and Block test and (2) motor reaction time. The number of blocks moved by the unilateral movement/stimulation group at the posttest was 6 more than that for the control group. Additionally, an advantage for the unilateral/stimulation group was found in the impaired limb during the 2-handed testing situation in that median motor reaction times decreased in comparison to the same condition in the control group. These findings lend support to the sensorimotor integration theory explanation for improving motor capabilities constrained by chronic hemiparesis after a CVA in that motor actions are known to dynamically alter the somatosensory cortex as well as the primary cortex.^{11,12,35,39}

In conclusion, both bilateral and unilateral training of the wrist/finger extensors in combination with EMG-triggered neuromuscular stimulation improved motor capabilities in CVA patients with chronic hemiparesis. However, hand **Cauraugh and Kim Coupled Motor Recovery Protocols 1593** function improvements were more prevalent for subjects in the coupled protocols of bilateral movement and EMG-triggered neuromuscular stimulation. These findings are consistent with predictions for 2 motor control theories: (1) sensorimotor integration and (2) dynamic systems. Moreover, evidence continues to accumulate supporting the proposition that specific rehabilitation protocols assist voluntary control and an expanded motor repertoire in CVA patients with chronic hemiparesis.

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