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Coupled bilateral movements and active neuromuscular stimulation: Intralimb transfer evidence during bimanual aiming

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Abstract

Motor improvements in chronic stroke recovery accrue from coupled protocols of bilateral movements and active neuromuscular stimulation. This experiment investigated coupled protocols and within-limb transfer between distal and proximal joint combinations. The leading question focused on within-limb transfer of coupled protocols on distal joints to a bimanual aiming task that involved proximal joints. Twenty-six volunteers completed one of three motor recovery protocols according to group assignments: (1) coupled bilateral involved concurrent wrist/finger movements on the unimpaired limb coupled with active stimulation on the impaired limb; (2) unilateral/active stimulation involved neuromuscular electromyogram-triggered stimulation on the impaired wrist/fingers; and (3) no protocol (control group). During the pretest and posttest, subjects performed transverse plane target aiming movements (29 cm) with vision available. The coupled bilateral group showed positive intralimb transfer post-treatment when both arms moved simultaneously. During the posttest, the coupled bilateral group displayed improved movement time, higher peak limb velocity, less variability in peak velocity, and less percentage of total movement time in the deceleration phase than during the pretest. The evidence confirms that within-limb transfer from distal joint training to proximal joint combinations is viable and generalizable in chronic stroke rehabilitation. Moreover, these intralimb transfer findings extend the evidence favoring motor improvements for coupled bilateral protocols during chronic stroke.

Keywords: Stroke; Rehabilitation; Protocols; Intralimb transfer; Bimanual aiming

Focal neurological attacks severely constrain voluntary motor control and drastically diminish a persons' capacity to execute even simple movements. Over 60% of the individuals with stroke in the chronic phase of recovery are constrained by motor disabilities in their upper extremity [24,26,28]. Indeed, moving an impaired arm to a target is demanding.

Researchers have proposed various treatment protocols to assist the impaired arm in regaining voluntary control (e.g., active stimulation, passive stimulation, active bilateral movements, passive bilateral movements, constraint-induced movement therapy). However, disagreement reigns concerning the efficacy and effectiveness of stroke motor interventions. Recognizing the conflicting evidence and the limited advances in stroke motor recovery, Abbot urged researchers to investigate novel combinations of rehabilitation treatment protocols [1]. Thus, one solution to the conflicting findings for a particular intervention is to administer two protocols simultaneously to determine if the interaction effect of the two is stronger than the individual main effects. Consistent with this recommendation, the current study administered two effective intervention strategies (i.e., bilateral movement training and active neuromuscular stimulation) for chronic stroke hemiparesis.

Moreover, strong treatment intervention evidence indicates improved motor capabilities when two protocols are simultaneously coupled during training. Coupled protocols refer to bilateral movement training combined with active EMG-triggered neuromuscular stimulation [4–7]. The intact limb assists the impaired limb during simultaneous movement execution while EMG-triggered neuromuscular stimulation is applied directly to the hemiparetic limb. Evidence supporting chronic stroke recovery improvements with cou-

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pled bilateral movements and active stimulation include a higher number of blocks moved, decreased reaction time, and stable sustained muscle contractions [4–7].

An additional critical rehabilitation issue that has not been addressed concerns transferring the improved motor capabilities within-limb. Are chronic stroke patients able to transfer the motor benefits of coupled bilateral training from the distal wrist/finger joints to the proximal shoulder and elbow joints? Is within-limb distal joint training generalizable to proximal joint combinations or is effector training specific to the involved joints [27]? To investigate within-limb transfer of rehabilitation training on distal joints to proximal joint combinations, the present study implemented training on efficacious motor recovery protocols for the distal wrist/finger extension while evaluating pretest/posttest performances on a non-practiced target-aiming task. Executing the aiming task required proximal shoulder and elbow joint combinations.

The distal treatment interventions involved wrist and finger extension movements according to group assignments. The three groups were: (1) coupled bilateral (bilateral movements on the intact limb in combination with active stimulation on the impaired arm); (2) unilateral/active stimulation (only active stimulation on the impaired limb); and (3) a healthy control group. Consistent with earlier coupled bilateral movement and active stimulation findings, we hypothesized that the coupled bilateral group would perform better on the movement trajectory analyses (e.g., movement time, peak velocity, time to peak velocity) of the target-aiming task than the unilateral/active stimulation group. Specifically, we expected the coupled bilateral group distal training to transfer to the proximal joints (shoulder and elbow) target-aiming task with both arms performing better than the unilateral/active stimulation group across the tests sessions.

Twenty-six participants volunteered and 21 of the subjects were in the chronic stroke phase of recovery. Demographic characteristics for participants are found in Table 1. Admission criteria for the rehabilitation protocol groups included: (1) diagnosis of no more than three strokes; (2) a lower limit of 10° of voluntary wrist/finger extension from a 80° wrist flexed position; (3) no more than 80% upper limit of motor recovery; (4) absence of other neurological deficits; and (5) currently not participating in another upper extremity recovery program. This experiment received ethical approval from the University of Florida's Institutional Review Board prior to being conducted.

Subjects performed sets of seven aiming movements in three randomly ordered experimental conditions that varied on hand combinations: left or right single-hand and two-handed movements [17]. Participants sat at a desk in front of four medium-size switches (diameter: 6.35 cm) located 25.4 cm from the near edge of the desk. The home and target switches were placed so that medial flexion adduction movements (29 cm) by each arm could be readily performed. Subjects started on the distal target switches (44 cm to each side of the body's midline) and moved medially to target switches located 15 cm left and right of the midline of the body. Subjects were instructed to depress the center of each switch (activation level: 0.93 N) with their index and middle fingers, and to execute the transverse plane movement between switches as quickly and accurately as possible. The medial movements involved flexion/adduction in the transverse plane of the shoulder–elbow–wrist–finger linkage [17]. Initiation of a trial began with the command "Ready" and following a variable foreperiod interval (500, 1000, or 1500 ms), a 1 kHz 75 dB (A) SPL tone signaled movement initiation. According to Fitts' index of difficulty equation, $\mathrm{ID} = \log_2(2 \times \text{amplitude/target width})$, the distance and precision of the current medial movements equaled 3.17 [13]. All subjects performed 21 aiming trials during the pretest and posttest sessions.

An electromagnetic data acquisition system recorded the movement kinematics of each hand (Skill Technologies, Phoenix). The magnetic field was sensitive to perturbations of the sensors attached to the back of each hand (proximal to the second finger's knuckle). The sensors (X, Y, and Z coordinates) were sampled at a rate of 120 Hz, digitized, and saved for subsequent off-line analyses.

The beginning and end of movements were defined by velocity profiles. Based on the central difference method, the criterion for initiating movement was when the velocity profile exceeded 5 cm/s based on sample duration of 200 ms (i.e., 24 samples). For the end of movement, the velocity profile went from positive to zero; less than 5 cm/s for 24 data points.

Group assignment followed a randomization schedule in that allocation to either the unilateral/active stimulation group ($n = 10$) or the coupled bilateral group ($n = 11$) was completed once subjects qualified on the pretest [2]. The control group ($n = 5$) did not have any stroke history and they were recruited for similar age and group gender composition.

For the active neuromuscular stimulation assistance (i.e., unilateral/active stimulation group and coupled bilateral

Table 1
Demographic characteristics of participants with mean years (standard deviation)

Group	Gender	Age (years)	Post-stroke time (years)	Stroke location
Unilateral/active stimulation	4 females; 6 males	63.29 (10.81)	3.57 (2.42)	4 left hemisphere 6 right hemisphere
Coupled bilateral	6 females; 5 males	69.37 (10.14)	4.73 (3.52)	2 left hemisphere 9 right hemisphere
Control	3 females; 2 males	54.48 (14.29)	No stroke history	No stroke history

group), surface electrodes were attached to the extensor communis digitorum and extensor carpi ulnaris of the impaired arm. For each wrist/finger extension movement, subjects voluntarily generated a criterion threshold level of EMG activity. On achieving the threshold, a Neuromove microprocessor immediately provided an electrical stimulation that assisted the wrist/finger extension muscles. Settings for the electrical stimulation included: an initial threshold level of 50 μV, 1 s ramp up, 5 s of biphasic stimulation at 50 Hz, 15 to 29 mA range, pulse width of 200 μs, and 1 s ramp down. When the EMG activity reached the target threshold, the device automatically increased the threshold for the next trial. If participants could not generate enough muscle activity to reach the criterion, then the device lowered the activation level slightly. Twenty-five seconds of rest separated consecutive trials. The two stroke motor recovery groups completed 4 days of 90-min training/week over 2 weeks.

The only assistance given to the voluntary wrist/finger extension in the unilateral/active stimulation group was EMG-triggered neuromuscular stimulation. In contrast, the coupled bilateral group executed bilateral movements in the intact wrist/fingers simultaneously with active stimulation on the impaired limb. The control group followed the same testing procedures as the unilateral/active stimulation and coupled bilateral groups. However, the control group did not complete any wrist/finger training sessions. Additionally, no group practiced the aiming task between the pretest and posttest.

Off-line calculations included median reaction time, movement time, peak velocity, time-to-peak velocity, as well as acceleration and deceleration phases. Shapiro-Wilk's normality test indicated skewness violations in peak velocity and time-to-peak velocity necessitating data transformations. A square root transformation stabilized the data and achieved normality [31]. The other dependent variables met the assumption of normality.

Separate mixed design three-way ANOVAs, Group (unilateral/active stimulation, coupled bilateral, and control) × Test Session (pretest and posttest) × Impaired Limb (alone or with the intact limb) analyzed the data. Group was a between-subjects factor and the other two factors were within-subjects: 3 × 2 × 2. The critical alpha level was set at 0.05 for all statistical tests, and Tukey-Kramer's multiple comparison procedure served as a follow-up test.

The reaction time analysis revealed a significant Group × Impaired Limb interaction [$F_{2,23} = 8.32$, $P < 0.001$]. The intact limb displayed faster reaction times for both the unilateral/active stimulation (*Med* = 314 ms, S.D. = 59) and coupled bilateral (*Med* = 296 ms, S.D. = 50) protocols groups than the impaired limb (unilateral: *Med* = 390, S.D. = 84; coupled bilateral: *Med* = 375 ms, S.D. = 58). Stroke individuals were slower at initiating aiming movements with their impaired limb than their intact limb. The analysis failed to identify a reliable reaction time test session (training) effect.

Four primary findings provide clear evidence favoring the coupled bilateral movement and active stimulation treatment effect in aiming movements. First, the movement time analysis indicated a reliable Group × Test Session interaction, [$F_{2,23} = 5.98$, $P < 0.01$]. As shown in Table 2, the coupled bilateral group improved movement time pretest to posttest by 88 ms when collapsed across the testing situation conditions. On the contrary, neither the unilateral group nor control group revealed any significant decreased movement times.

Additional analysis of the single limb alone testing condition identified a Group × Impaired Limb interaction, [$F_{2,23} = 5.65$, $P < 0.02$]. The intact limb executed the 29 cm movement faster than the impaired limb for both rehabilitation groups (*unilateral*: intact = 398 ms, S.D. = 102, impaired = 672 ms, S.D. = 200; *bilateral*: intact = 355 ms, S.D. = 47, impaired = 641 ms, S.D. = 191). In comparison, the control group performed left and right hand movements with equivalent movement times (242 and 264 ms). Further, this two-way interaction failed significance when both limbs moved together.

Second, peak limb velocity revealed a significant Group × Test Session × Impaired Limb interaction, [$F_{2,23} = 3.83$, $P < 0.038$] (see Table 2). The coupled bilateral group from pretest to posttest improved their peak velocity when both the impaired and intact limbs moved together. On the contrary, peak velocity remained the same when the impaired limb moved alone. The unilateral/active stimulation group performed with higher peak velocity during the posttest in the impaired limb moved alone condition. Further, the control group increased peak velocities across the test sessions when moving their non-dominant limb alone.

Third, the variability in the peak velocity findings further differentiated the treatment group by test session by impaired limb interaction, [$F_{2,23} = 4.16$, $P < 0.029$]. As seen in Table 2, the coupled bilateral group displayed no change in the variability (standard deviation) results across the test sessions or impaired limb conditions. There were consistent peak velocity movements to the targets with one arm or both arms. On the other hand, the unilateral/active stimulation group increased peak velocity variability in the single limb testing condition. Further, the control group increased variability significantly in the one hand testing condition and decreased variability in the two hand testing condition.

Fourth, analysis of the deceleration time (i.e., movement phase 2 from peak velocity to target switch touch) differentiated the coupled bilateral movement and active stimulation group across the test sessions when concurrently moving the intact arm with the impaired limb, [$F_{2,23} = 4.35$, $P < 0.026$]. For both arms moving together, the coupled bilateral group shortened deceleration time considerably from the pretest to posttest. Moving the impaired limb alone did not improve deceleration times. The changes in deceleration times were contrary for the unilateral/active stimulation group. Specifically, the unilateral/active stimulation group demonstrated longer deceleration times when both arms approached the targets in the posttest than in the pretest. The control group showed equivalent deceleration times across limb combinations and test sessions.

Table 2
Median performances (±S.D.) for the three groups as a function of test session (pre and post) and testing condition (impaired limb alone and impaired limb with intact limb)

Dependent measure	Impaired limb alone						Impaired limb with intact limb					
	Pretest			Posttest			Pretest			Posttest		
	Uni group	Bil group	Con group	Uni group	Bil group	Con group	Uni group	Bil group	Con group	Uni group	Bil group	Con group
RT (ms)	399 ± 91	366 ± 55	276 ± 57	381 ± 77	384 ± 64	281 ± 23	413 ± 79	382 ± 70	294 ± 50	376 ± 75	386 ± 78	293 ± 34
MT (ms)	681 ± 214	663 ± 199	268 ± 45	662 ± 191	619 ± 185	259 ± 33	798 ± 285	751 ± 234	271 ± 33	767 ± 263	619 ± 189	268 ± 25
Peak velocity (cm/s)	8.81 ± 1.32	9.31 ± 1.37	13.68 ± 0.55	9.13 ± 1.33	9.32 ± 1.43	14.17 ± 1.12	8.47 ± 1.84	8.83 ± 1.56	14.14 ± 0.46	8.72 ± 1.77	9.10 ± 1.56	13.79 ± 0.71
S.D. peak velocity	3.05 ± 0.82	3.80 ± 0.93	4.19 ± 1.2	3.51 ± 1.4	3.51 ± 1.3	5.18 ± 1.1	3.23 ± 0.88	3.31 ± 0.91	4.81 ± 1.5	3.59 ± 0.92	3.47 ± 0.71	4.39 ± 1.0
Deceleration time (ms)	457 ± 199	438 ± 211	143 ± 27	452 ± 174	428 ± 186	135 ± 24	550 ± 256	598 ± 239	135 ± 21	519 ± 222	501 ± 244	137 ± 20

Note. RT: reaction time; MT: movement time; Uni: unilateral/active stimulation; Bil: coupled bilateral; Con: control.

This study determined that within-limb transfer from distal joints to a combination of proximal joints was feasible. Coupled protocols (i.e., simultaneous onset of bilateral movements in the wrist/fingers of both hands along with onset of active stimulation on the impaired limb) training improved bimanual aiming that required shoulder and elbow joints movements. Peak velocity, variability in peak velocity, and deceleration time (adjustment phase) findings revealed a target aiming task advantage for the coupled bilateral group, especially when both arms moved together.

The positive transfer identified from the practiced (trained) distal coupled bilateral protocols (wrist/finger: extension) to the proximal joint combinations of the upper extremity (shoulder/elbow joints: flexion and adduction). These results are consistent with recent findings by Vangheluwe et al. [27]. They reported positive transfer in star/line drawing within-limb distal to proximal, and the active neurophysiological mechanisms involved in within-limb transfer appear to be the intrahemispheric supplementary motor areas [18,19,21].

In addition, the current within-limb transfer findings contribute to the bimanual aiming literature. Previous target aiming studies on individuals with chronic stroke investigated the limitations and adaptations used in executing movements. Levin and colleagues reported that upper extremity movements to targets in the frontal plane typically involved the upper trunk [8,20]. Further, a set of experiments by Winstein et al. indicated that for reciprocal aiming movements, limb transport and targeting activated population encoded cortical–subcortical loops [32,33]. Nevertheless, the present study was the first stroke rehabilitation investigation that focused on within-limb transfer from distal joint training to proximal joint benefits in bimanual aiming.

Moreover, additional target aiming explanations discussed Woodworth's two-component model and biomechanical modeling [11,22]. Woodworth's two-component model postulates an initial impulse phase and an adjustment or "homing" phase. Based on discontinuities in movement trajectories, as the hand approaches the target, there appears to be an inhibition of movements reflected in shorter second phase (homing) times [11]. The current study identified faster deceleration times in the coupled bimanual group after training when both limbs moved simultaneously. Perhaps stroke patients in the coupled bilateral group were better able to turn on the antagonist muscles for adjustments near the targets when they moved both limbs together after training.

The distinct coupled bilateral group advantage findings extend the coupled protocols benefits reported earlier [4–6]. For individuals with chronic hemiparesis, combining active neuromuscular stimulation on the impaired limb with identical bilateral movements on the intact limb improves transverse plane bimanual aiming movements as well as other motor capabilities. Extending the evidence favoring, these coupled treatment protocols shows that unique combinations of rehabilitation treatments assist chronic stroke individuals with upper extremity recovery of voluntary control. This is consistent with the postulate that neural plasticity can readily go beyond only trying to establish compensatory movements in stroke rehabilitation [23,29]. Further, these findings are consistent with the hypotheses and provide new information.

In addition, the coupled bilateral findings are consistent with propositions of bimanual coordination theory. Cohen stated that concurrent bilateral movement evidence suggests a single central regulatory mechanism controlling both limbs [9]. Bilateral neural networks may govern upper extremity motor control as a central regulatory mechanism [30]. Indeed, symmetrical bilateral movements trigger similar patterns in both hemispheres when homologous muscle groups are simultaneously activated in each limb [9,10,12,14,25,30]. This supports the proposition that training movements on both limbs directly stimulates both hemispheres [12,14]. Further, recent evidence indicates that extensive bilateral projections of corticospinal axons from a single hemisphere contribute to bilateral motor control more than previously reported [12]. Bilateral projections of the corticospinal axons originating from a single motor cortex may assist in bilateral motor control [12,14].

Moreover, the coupled bilateral findings are consistent with a classic *Science* article on interlimb coordination. Kelso, Southard, and Goodman reported that people execute two-handed lateral movements to targets of different difficulty, either different distances or precision, at the same time [17]. The two-handed movements appear to be constrained to the same timing mechanism. Even though the results are contrary to Fitts' law (i.e., different spatial demands should produce different movement times), the evidence is convincing that concurrent bilateral hand aiming movements are simultaneously completed [17]. The current movement time findings suggest that a similar neurophysiological mechanism controls both the impaired and unimpaired limbs. Performing the bimanual aiming task with a constrained upper extremity over constant spatial demands produced equivalent movement times across the experimental conditions. In addition, the distal joint training coupled bilateral group demonstrated an increased capability on the impaired proximal joints for three kinematic measures across the test sessions even though equivalent movement times persisted.

Granted, rehabilitation issues abound on making progress toward motor recovery [3,15,16]. As researchers continue to ask questions about treatment onset, intensity/frequency, and duration, we encourage them to examine potential benefits of within-limb transfer. The current coupled protocols produced intralimb transfer evidence for distal practice and proximal joint combination benefits. When the rehabilitation strategy activated two interventions simultaneously for distal wrist/finger extension, benefits accrued in a transfer task that required proximal shoulder and elbow joints movements. Identifying unique combinations of rehabilitation strategies and positive transfer conditions may significantly decrease the severity of motor disabilities that challenge many stroke survivors.

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