Fine Motor Control in Adults With and Without Chronic Hemiparesis: Baseline Comparison to Nondisabled Adults and Effects of Bilateral Arm Training

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ABSTRACT. McCombe Waller S, Whitall J. Fine motor control in adults with and without chronic hemiparesis: baseline comparison to nondisabled adults and effects of bilateral arm training. Arch Phys Med Rehabil 2004;85:1076-83.

Objectives: To characterize fine motor control through finger tapping in both arms of 10 patients with chronic stroke, to make baseline comparisons with matched controls, and to examine the responsiveness of deficits seen in stroke patients after 6 weeks of bilateral arm-based training.

Design: Nonrandomized controlled, cohort before-after trial.

Setting: Research institution.

Participants: Ten people from the community with chronic unilateral ischemic stroke and 10 age- and sex-matched healthy controls. Participants with hemiparesis had completed all conventional care and were more than 6 month poststroke. Inclusion criteria were at least 6 months since a unilateral stroke, ability to follow simple instructions and 2-step commands, volitional control of the nonparetic arm, and at least minimal antigravity movement in the shoulder of the paretic arm.

Interventions: Not applicable.

Main Outcome Measures: Measurements included rate and timing consistency of unilateral tapping at a preferred and a maximal rate and the accuracy and stability of interlimb coordination in bilateral simultaneous (inphase) and alternating (antiphase) tapping at a preferred rate.

Results: Nonparetic finger control was similar to that of the nondisabled participants except under bilateral conditions, where it was less consistent. A subgroup with residual paretic finger function, had slower and less consistent paretic finger tapping, as well as less accurate and more variable interlimb coordination; however, basic bilateral coupling relationships were preserved. Bilateral arm-based training improved bilateral nonparetic consistency but slowed unilateral preferred tapping. Training also improved paretic fine motor control in 2 of 4 participants with mild stroke severity. The 2 responders, with dominant hemisphere lesions, indicated a possible recovery advantage with bilateral training for such lesions.

Conclusions: In general, nonparetic finger control for tapping was preserved but paretic finger control was compromised. Disruption of nonparetic control of tapping, particularly consistency of tapping, occurred during bilateral tapping tasks but was responsive to 6 weeks of bilateral arm-based training. Despite the apparent lack of training specificity, the generalizable effects of bilateral arm training to fine motor interlimb coordination may reflect central motor control mechanisms for upper-extremity coordination, which may be accessed and may influence the recovery of arm function after stroke.

Key Words: Fingers; Hemiparesis; Motor skills; Rehabilitation.

UPPER-EXTREMITY HEMIPARESIS continues to be a major limiting factor in functional arm recovery in more than 80% of stroke survivors.[1] Novel training approaches to the rehabilitation of arm function in both human and animal studies have shown success in restoring partial functional capacity of the hemiparetic limb but have been primarily limited to participants with mild stroke severity.[2-5] The majority of contemporary training approaches focus on arm functional training and assessment with less emphasis on fine motor coordination and control. Although functional outcomes after therapeutic intervention are important, it is useful also to return to fundamental measures such as fine motor control and coordination to better understand the underlying impairments that may in turn have important implications for therapeutic approaches.

Evidence of paretic limb fine motor deficiency after stroke is limited, and it includes decreased rate of finger tapping after acute stroke[6] and impairment in voluntary control of finger extension from coactivation.[7,8] Fine motor deficits in the nonparetic limb include[9] decreased rate of tapping in acute stroke[6] and decreased gross and fine manual dexterity.[10] Even though many daily tasks require bilateral coordination, we found no reports of bilateral fine motor coordination. In fact, the nature of fine motor coordination and control in the nonparetic and paretic limbs has not been well characterized in stroke patients, particularly during bilateral movement, nor is it known if these ipsilateral or contralateral limb deficits would respond to current therapeutic approaches.

One such approach[11] included participants with mild and moderate chronic ischemic stroke and provided bilateral arm training with rhythmic auditory cueing (BATRAC), using principles of motor learning. After 6 weeks of training, there were significant improvements in paretic limb impairment, speed of arm movement, and functional use of the paretic limb during daily activities. Although fine motor coordination was not assessed, gains were seen in gross motor coordination (arm timing, interlimb phasing). Although the training was arm based, significant improvement in thumb opposition active range of motion (ROM) was also evident. Given the changes in timing and coordination in the arms, and a corresponding change in distal function, it is possible that a generalization effect to distal digit motor control may be induced because of central motor control mechanisms.

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We tested this hypothesis by measuring changes in fine motor control before and after 6 weeks of bilateral arm-based training. In addition, we extended our knowledge of fine motor control impairments in paretic, nonparetic, and bilateral limb tapping at baseline compared with the limbs of age- and sex-matched controls. Finger tapping tasks were selected for measuring fine motor performance because they are related to function, have well-defined unilateral characteristics, and can be used to assess interhemispheric and intrahemispheric motor control. Speed of finger tapping has long been used as a measure of central nervous system integrity.[12] This article focuses not only on speed but also on consistency and coordination of preferred speed conditions in both unilateral and bilateral tapping. We hypothesized that multiple deficits exist in paretic finger tapping and that nonparetic finger tapping shows deficits, particularly during the more complex tasks of rapid tapping and bilateral tapping tasks. Given that the arm-based BATRAC training uses repetition of stable coordination patterns that are also stable finger tapping patterns[13] and because of our earlier findings, we expected to see generalizable improvements in both interlimb and paretic and nonparetic intralimb timing and coordination after training.

METHODS

Participants

Ten participants (5 men, 5 women) with chronic hemiparetic arm dysfunction (4 mildly impaired, 5 moderately impaired, 1 severely impaired) were recruited from a rehabilitation center at the University of Maryland (UM) and Baltimore Veterans Affairs Medical Center. All participants had been discharged from conventional poststroke rehabilitation and were at least 12 months (median, 30mo) poststroke. Baseline evaluations included a medical history, the Folstein Mini-Mental State Examination (MMSE), and the Orpington Prognostic Scale.

Inclusion criteria were at least 6 months since a unilateral stroke, ability to follow simple instructions and 2-step commands, volitional control of the nonparetic arm, and at least minimal antigravity movement in the shoulder of the paretic arm. Paretic limb tapping was not an inclusion criterion, because this would have limited the participant pool to only those with mild stroke severity. Exclusion criteria were symptomatic cardiac failure or unstable angina, uncontrolled hypertension (>190/110), significant orthopedic or chronic pain conditions, major poststroke depression, active neoplastic disease, severe obstructive pulmonary disease, dementia (MMSE score, <22), aphasia with inability to follow 2-step commands, or severe elbow or finger contractures that would preclude passive ROM and positioning of the arm. Ten healthy, age- and sex-matched controls were recruited from the local community. No participant in either group had extensive musical training that might have influenced rhythmic finger performance. Written informed consent, approved by the UM institutional review board, was obtained from all participants before the study.

Testing

Tapping apparatus. Participants were seated in a quiet area at a table, facing 2 strain-gauged tapping keys interfaced with a personal computer via Datapac[a] analog-to-digital (A/D) hardware and software. Strain-gauge signals were amplified and low-pass filtered at 10Hz.[b] Trials were sampled before collection on the A/D hardware at 200Hz for 15-second intervals. Tapping key position and table heights were adjusted for individual comfort and consistency of hand-finger orientation. The arms were strapped at the forearm and the distal portion of the metacarpals to restrict motion to the metacarpophalangeal joints.

Procedures

Testing of finger coordination and timing. Participants were asked to maintain a consistent frequency for each of 3 trials in the following conditions: (1) nonparetic (hemiparetic participants) or dominant (nondisabled) index finger at a preferred, comfortable rate; (2) paretic or nondominant finger at a preferred, comfortable rate; (3) same as 1 at a maximal rate; (4) same as 2 at a maximal rate; (5) both index fingers simultaneously at a preferred rate (inphase coordination); and (6) both fingers alternately at a preferred rate (antiphase coordination). Conditions were administered in the above order to standardize order effect. No extrinsic timing cue was provided for this testing. A second rater recorded the patient's visual attention to the paretic or nonparetic fingers during the testing session.

Impairment and functional testing. Participants with hemiparesis also received the following baseline and posttraining testing: (1) Fugl-Meyer Assessment[14,15] (FMA) upper-extremity motor performance section test (a test of sensorimotor function), (2) the Wolf Motor Function Test[4,16] (WMFT), and (3) the University of Maryland Arm Questionnaire for Stroke[17] (UMAQS). Details about these tests can be found elsewhere.[11]

Training procedure. Training for the 10 participants with hemiparesis consisted of 20 minutes of bilateral arm training with rhythmic auditory cueing (BATRAC) 3 times a week for 6 weeks (18 sessions). Details of this training are published elsewhere.[11] Training sessions consisted of four 5-minute periods of BATRAC interspersed with 10-minute rest periods for 1 hour. Participants were seated, with the trunk stabilized to prevent trunk flexion substitution during arm movement, and they grasped 2 independent T-bar handles that moved nearly friction free in the transverse plane. A participant's hand was strapped if he/she could not grasp independently. Participants then pushed the handles away from them and then pulled the handles toward them. Periods 1 and 3 consisted of bilateral inphase training (arms moving together), and periods 2 and 4 consisted of bilateral antiphase training (arms moving alternately). Movements were timed to an auditory metronome set at each participant's preferred rate that was established at the first session and was provided at each training session. Frequency remained constant for the entire 6 weeks of training. At the completion of the training, all baseline-testing procedures were repeated.

Data Reduction

The digitized tapping data were exported as ASCII files, placed in an Excel spreadsheet,[c] and processed using a customized Matlab software program.[d] The output variables for each trial were mean intertap intervals (ITI), as a measure of tapping rate, and coefficient of variation (CV) of the ITI, as a measure of timing consistency, for each finger in all conditions. The interlimb coordination in the 2 bilateral conditions (interlimb phasing) was expressed as the average percentage of the nonparetic (dominant for controls) ITI when the paretic (nondominant for controls) finger contacted the key. Standard deviations (SDs) of mean interlimb phasing were calculated to measure variability (as a reflection of stability) of each coordination pattern. Data were averaged over the 3 trials for each condition.

Table 1: Comparison of Mean Rate (ITI in milliseconds) and Consistency (CV of the ITI) of Paretic Finger Tapping for the Subgroup of Hemiparetic Participants and Their Matched Controls

Subject	Paretic Preferred ITI	CV ITI Preferred	Paretic Maximal ITI	CV ITI Max	Inphase Paretic ITI	CV ITI Inphase	Antiphase Paretic ITI	CV ITI Antiphase
2	298	.111	311	.201	349	.205	560	.081
3	970	.143	929	.344	834	.406	1254	.373
4	537	.063	418	.139	487	.104	803	.058
Mean	602	.106	553	.228	557	.238	873	.171

Control	Nondom Preferred ITI	CV ITI Preferred	Nondom Maximal ITI	CV ITI Max	Inphase Nondom ITI	CV ITI Inphase	Antiphase Nondom ITI	CV ITI Antiphase
Match 2	654	.087	314	.109	462	.096	736	.092
Match 3	227	.090	214	.131	235	.202	334	.082
Match 4	331	.083	206	.108	227	.132	336	.112
Mean	404	.086	245	.116	308	.143	469	.095

Abbreviations: Max, maximum; Nondom, nondominant.

RESULTS

Comparison 1: Baseline Hemiparetic Participants Versus Nondisabled Controls

Baseline data collected for both groups were analyzed using 1-way analysis of variance with α set at .05. The dominant hand of the controls was compared with the nonparetic hand of hemiparetic participants, and the nondominant hand of the controls was compared with the paretic hand of hemiparetic participants. To ensure no bias of dominance in the controls, a generalized *t* test was performed and found no significant differences for any variable between dominant and nondominant hands. Because only 3 of the participants were initially able to produce tapping with the paretic hand, comparisons with matched controls for unimanual paretic finger tapping were not analyzed statistically.

Rate (mean ITI) and consistency of tapping (CV of ITI): paretic. Table 1 shows the mean ITI and CV of ITI for the subgroup of participants who could tap with their paretic hand and for matched controls. Subject 2 tapped at a faster rate than his matched control but with less consistency, except for the antiphase condition. Subject 3 tapped slower than his match and with less consistency across all conditions. Subject 4 tapped slower than his control but showed greater consistency in all conditions except for maximal rate tapping.

Rate (mean ITI) and consistency of tapping (CV of ITI): nonparetic. For the nonparetic hand in unimanual conditions, preferred and maximal tapping trials showed no significant difference in rate or consistency compared with controls. During bimanual tasks, these participants showed significant deficits in rate (inphase trials, $P<.01$; antiphase trials, $P<.004$) and consistency (inphase trials, $P<.02$; antiphase trials, $P<.006$) of tapping with the nonparetic finger (figs 1, 2).

Interlimb coordination (phasing and SD of phasing). Table 2 shows the relative phasing and SD of relative phasing results for the 3 hemiparetic participants who could complete bilateral (interlimb) tapping and for their matched controls. Inphase and antiphase tapping was preserved in all 3 hemiparetic participants; however, participants 2 and 3 were less accurate in fulfilling the required phasing and less consistent than the controls. Participant 4 outperformed his match, showing both accuracy and stability.

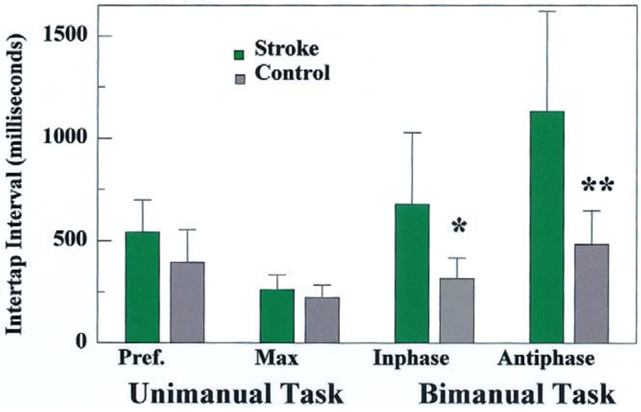

Fig 1. Baseline comparison for rate of nonparetic finger tapping in participants with stroke (n=10) and controls (n=10). Abbreviation: Pref, preferred. *$P<.01$; **$P<.005$.

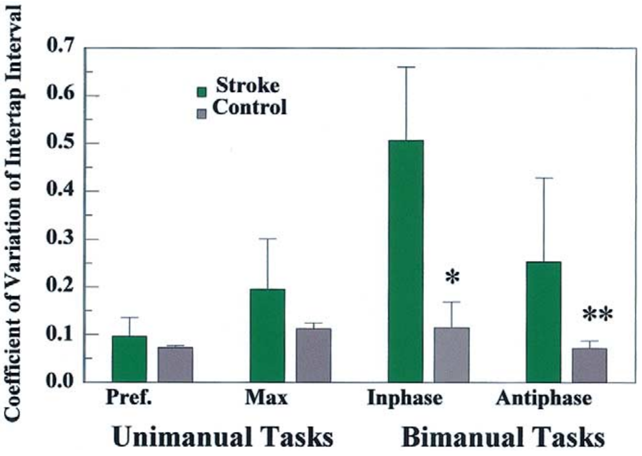

Fig 2. Baseline comparison for consistency of nonparetic finger tapping in participants with stroke (n=10) and controls (n=10). *$P<.05$; **$P<.01$.

Table 2: Mean Phasing (% Relative Phase) and SD (SD of Relative Phase) Representing Accuracy and Stability, Respectively, of Interlimb Tapping for Participants With Stroke and Controls

Subject	Inphase Phasing	Antiphase Phasing
Pretraining		
2	90.6±14.5	49.8±5.4
3	80.6±29.9	43.7±31.8
4	103.2±5.6	50.6±2.8
Mean	91.5±16.7	48.0±13.3
Control		
Match 2	106.7±6.4	50.3±5.1
Match 3	102.5±8.5	52.5±3.7
Match 4	97.7±8.8	47.1±7.4
Mean	102.3±7.9	50.3±5.4

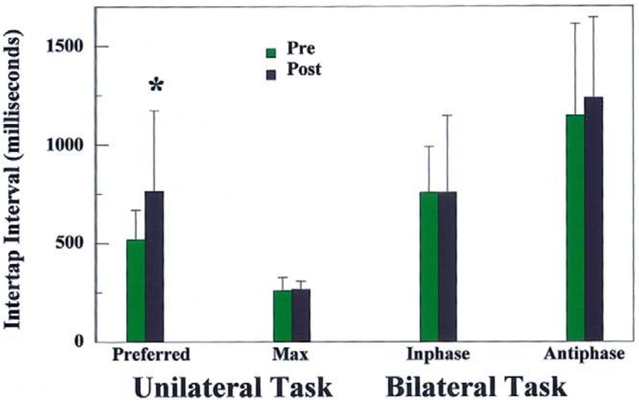

Fig 3. Pretraining and posttraining results for rate (ITI) of tapping of nonparetic finger in participants with stroke (n=9). **P*<.05.

Comparison 2: Hemiparetic Participants Before and After Training

Ten hemiparetic participants entered the training, and 9 completed the full 6 weeks. One subject dropped out because of transportation issues. Before and after training data were analyzed to determine a training effect, using a paired *t* test with α set at .05. In 4 of 54 instances (9 participants by 6 conditions each), data exceeded 3 SDs above or below the mean of the other scores, were considered to be outliers, and were removed from data analysis.

Rate and consistency of tapping: paretic. Data for rate and consistency of tapping are presented in table 3. Before the training, only 3 participants could tap with their paretic finger. After training, an additional participant (no. 1) could tap his paretic finger but only during the bimanual tasks. Participant 2 tapped slower in the preferred pace tapping trials but faster in the maximal and bilateral trials. Participant 3 tapped faster in all conditions except for bilateral inphase. Participant 4 tapped slower in all tapping trials with the exception of the bilateral inphase trials. Participant 2 was more consistent in tapping in all conditions with the exception of bilateral antiphase. Participant 3 was more consistent in maximal and bilateral inphase tapping and less consistent in preferred pace and bilateral antiphase trials. Participant 4 was less consistent in all trials, with the exception of the bilateral antiphase tapping.

Rate and consistency of tapping: nonparetic. After training, rate of tapping decreased significantly for the unimanual preferred rate trials (*P*<.05). During maximal rate tapping and the bilateral trials of inphase and antiphase tapping, the rate was essentially unchanged (fig 3). The consistency of the ITI for the nonparetic limb increased for all trials, significantly so for the bilateral trials of inphase (*P*<.05) and antiphase tapping (*P*<.03) (fig 4). Of note, the hemiparetic participants improved their consistency of tapping to a level that statistically did not differ from matched controls during inphase (*P*<.06) and antiphase (*P*<.07) tapping conditions.

Interlimb coordination (phasing and SD of phasing). Group and individual interlimb phasing results are presented in table 4 for the subgroup of participants who could tap with both their paretic and nonparetic fingers. One participant (no. 1), who was unable to demonstrate interlimb tapping abilities at baseline testing, was able to produce inphase and antiphase tapping after training, although with impaired accuracy and stability. Participant 2 improved in accuracy and stability for inphase tapping but changed very little in antiphase tapping, aside from a small decrease in stability. Participant 3 showed a decline in inphase stability and accuracy as well as antiphase accuracy but did improve in antiphase stability. Participant 4 improved his stability in both inphase and antiphase tapping, although he became less accurate. An overall group decrease was seen in relative phasing in the antiphase condition, but this was primarily due to the results of participant 3. Stability of

Table 3: Data for the Rate (ITI in milliseconds) and Consistency (CV of the ITI) of Tapping for Participants Who Could Tap With Paretic Finger

	Speed of Tapping							
	Preferred Rate		Maximal Rate		Inphase		Antiphase	
Subject	Pretraining	Posttraining	Pretraining	Posttraining	Pretraining	Posttraining	Pretraining	Posttraining
1	NA	NA	NA	NA	NA	1491	NA	1731
2	298	815	311	296	349	275	561	529
3	971	879	930	867	786	1312	1254	978
4	538	728	419	430	493	471	804	1027
	Consistency of Tapping							
	Pretraining	Posttraining	Pretraining	Posttraining	Pretraining	Posttraining	Pretraining	Posttraining
1	NA	NA	NA	NA	NA	.52	NA	.56
2	.11	.04	.20	.13	.21	.08	.08	.10
3	.14	.18	.35	.24	.41	.59	.37	.27
4	.06	.08	.14	.23	.11	.14	.06	.04

Abbreviation: NA, not applicable.

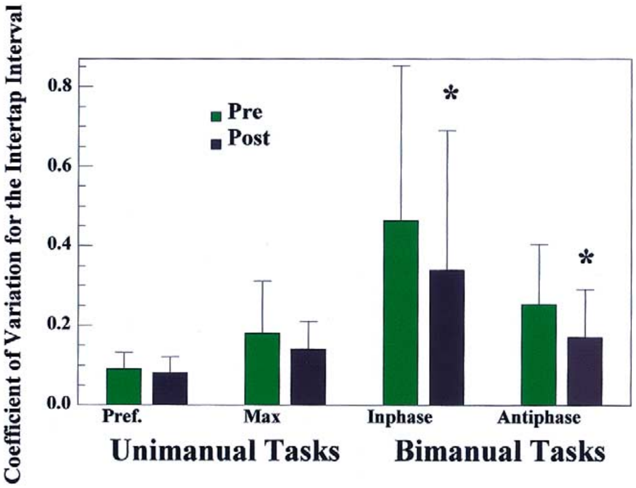

Fig 4. Pretraining and posttraining results for consistency (CV of ITI) of tapping of nonparetic finger in participants with stroke ($n=9$). *$P<.05$.

phasing in antiphase improved overall by 41% because of improvements in 3 of the 4 participants. These group results approached the value of the controls (post=10.3, control=5.5).

Functional outcomes. Significant gains were seen after training in all 3 functional measures (before FMA, 31.25; after FMA, 38.13; $P<.001$; before WMFT time, 51.50; after WMFT time, 44.85; $P<.01$; before UMAQS, 21.13; after UMAQS, 30.75; $P<.001$).

DISCUSSION

We characterized fine motor control in the paretic and nonparetic fingers of participants with chronic stroke, made comparisons with matched controls, and examined the responsiveness of deficits to arm-based rhythmic training. We found deficits in fine motor control in both paretic and nonparetic tapping. This is consistent with the findings of Prigatano and Wong[6] in an acute stroke population. Severe paretic fine motor deficits during unimanual tapping and nonparetic deficits in consistency during bilateral tapping were identified. In general, interlimb coordination was less accurate and stable than in the controls. Arm-based training improved paretic fine motor control in 2 of 4 participants with mild stroke severity. Regardless of stroke severity, nonparetic limb deficits improved after training. Despite the apparent lack of task specificity of arm-based training, generalizable effects of fine motor control were apparent, particularly for nonparetic limb function and interlimb coupling during bilateral movement tasks.

Fine Motor Control in Stroke Participants Versus Controls

Fine motor coordination deficits of the paretic limb were evident, with only 3 of the 10 participants able to move their paretic finger. Stroke severity in our participants (4 mild, 5 moderate, 1 severe) was such that one would not expect to find fine motor movements in 6 of our group. Distal musculature of the hand has primarily contralateral projections from the corticospinal tract,[18] although evidence now exists that there are ipsilateral projections from M1 to the hand.[19,20] Regardless of the pathway, preservation of motor input to the hand is necessary for the return of distal function. It is unlikely that preservation exists in our 6 participants with moderate or severe impairment, given the severe limitations in finger movement.

Of the 4 participants with mild stroke severity, 3 were substantially less coordinated than their matched controls. Participant 1 could not tap on initial testing. The tapping by the other 2, which was much slower than that of the controls, could be related to several factors, including the presence of tone in the flexors, decreased agonist recruitment of extensors, or difficulty in producing reciprocal movements. In contrast, participant 2 outperformed his nondisabled counterpart in most of the measures. Interestingly, he was in his late eighties and was unusually fit and active for his age—much more so than his age-matched control. Slowing of fine motor coordination in nondisabled elders is well documented,[21-24] but fine motor coordination can be preserved with continued activity and use.[25] It is encouraging that this decline in rate of movement may be preventable even after stroke if an active lifestyle is maintained.

Deficits were also found in nonparetic tapping consistency, but only during bilateral tapping tasks. In the nondisabled, timing consistency of finger tapping can be disrupted when a concurrent cognitive task is attempted that requires increased attention.[26] In the bilateral conditions for stroke participants, combining movement of the paretic with the nonparetic finger increases the neural complexity and attentional requirements of the task, similarly resulting in impaired performance. We tracked the visual attention of our participants and, in contrast to controls, who did not look at their fingers; the stroke participants did visually attend to both of their fingers, alternately, throughout the trial. We saw no pattern of increased attention specific to the paretic hand compared with the unilateral case, indicating that these participants were concentrating on the complete task and not focusing on the paretic finger.

A second contribution to nonparetic inconsistency in bimanual tapping is the tendency of the limbs to entrain or couple together.[27,28] For example, when 2 arms perform different tasks they do not perform entirely independently; rather, they either coordinate as a temporal, spatial unit[13,27,29] or, at the least, components of 1 arm's movement are seen in the movement of the other arm.[30-32] The hand performing the less difficult task typically couples to the hand completing the more difficult task. Similarly, the subdominant hand is more strongly coupled to the dominant hand.[33,34] What couplings occur in participants after stroke? In bilateral movements, Rice and Newell[35] reported that the nonparetic arm was limited by the paretic arm's

Table 4: Posttraining Results of Mean Phasing (% Relative Phase) and SD (SD of Relative Phase) Representing Accuracy and Stability, Respectively, for Interlimb Tapping in Stroke Participant

	Inphase	
Subject	Prephasing	Postphasing
1	Unable	90.00±21.32
2	90.66±14.55	101.00±11.37
3	80.67±29.92	76.45±40.00
4	103.20±5.65	115.80±4.75
Mean	91.51±16.71	95.81±19.36
	Antiphase	
1	Unable	39.43±17.31
2	49.87±5.48	49.55±7.72
3	43.73±31.85	29.83±13.42
4	50.63±2.85	44.56±2.50
Mean	48.08±13.39	40.84±7.88

ability to move, suggesting that the nonparetic hand is strongly coupled to the paretic hand. Therefore, inconsistencies of the nonparetic hand seen in bilateral tapping may be due to a coupling effect as a result of the deficits in the paretic limb.

Evidence for residual coupling of the fingers is seen in the interlimb coordination of the 3 participants who could actively tap with their paretic fingers at baseline. They retained the capability to tap simultaneously or in alternation, as demanded by the tasks. If the fingers were totally uncoupled, these task demands would not be met. The disruption of the nonparetic finger under bilateral conditions from coupling and attentional demands also translates into a less accurate and stable interlimb coordination than in the controls.

The neural basis for these findings may relate to cerebral control of unimanual and bimanual movements. In a positron emission tomography study of nondisabled participants, Goerres et al[36] showed that during distal unimanual finger movements, only the contralateral motor cortex was activated. During symmetrical bilateral tasks, the bilateral cortex was activated. There was additional bilateral mesial frontal cortex activation with increases of task complexity, including bilateral asymmetric finger movements. It can be reasoned that the task of tapping bilaterally would require activation of both motor cortices and in turn would present deficits even on the nonparetic side.

In the nonparetic unimanual tasks, we hypothesized that the nonparetic finger would have deficits in the maximal rate task; however, it did not. Our rationale was based on the fact that bilateral sensorimotor cortices are activated during more complex unimanual movement tasks in nondisabled[37,38] and chronic stroke participants.[9,39,40] For example, Winstein and Pohl[9] reported ipsilateral limb deficits in chronic stroke participants compared with age-matched controls during a rapid-reaching task using the nonparetic limb. The reaching task was at maximal rate and required aiming and greater control than did our task of rapid finger tapping. Possibly our maximal rate tapping task was not significantly challenging or was not of such complexity as to activate both cortices and thus disrupt performance.

Effects of Arm-Based Training on Fine Motor Control

We found mixed results in improving paretic finger function after bilateral arm-based training. In the 4 participants with preservation of distal hand function on the paretic side, 2 made substantive improvements, whereas 2 had more equivocal results. The 2 responders had lesions affecting their motor-dominant hemispheres, and the 2 nonresponders had lesions to the nondominant hemisphere. Although no conclusions can be made, given the small sample size, this suggests the possibility that a lesion to the dominant hemisphere may provide an advantage in recovery from stroke with bilateral training. Theoretically, there is support for this advantage based on the presence of interhemispheric inhibitory circuits between dominant and nondominant hemispheres. During unilateral movements there are transcallousal inhibitory projections to prevent mirror movement of the contralateral arm. In a nondisabled population, this inhibition becomes more refined with focused practice involving the dominant arm.[41,42] That is, the dominant hemisphere is better at inhibiting the nondominant hemisphere than vice versa. During bilateral activation, such as BATRAC, these pathways could be partially disinhibited, thus permitting overflow.[43] If the dominant hemisphere were lesioned, the potential benefit of overflow during bilateral training from 1 hemisphere to the other would be greater than if the lesion involved the nondominant hemisphere. This would explain why a participant with a lesioned dominant hemisphere showed a greater responsiveness of the paretic limb to bilateral training. Recent analysis of functional improvement after BATRAC training in right-handed chronic stroke patients supports this response advantage in 8 patients with dominant-hemisphere lesions versus 8 with nondominant lesions.[44]

The nonparetic limb was responsive to BATRAC training. Unexpectedly, preferred rate tapping actually slowed at posttraining. Again, we can explain this effect through the concept of coupling or entrainment. Entrainment is the tendency of 2 oscillator systems (or rhythmic limb movements), with different natural frequencies, to couple together such that they adopt the same frequency.[13,45] This entrainment also occurs between rhythmic movements and auditory beats in the nondisabled.[46] In the BATRAC protocol, the rate of the auditory cue and thus the rate of the training were determined by the participant's preferred rate of moving the 2 arms and were held constant during the training course. The slower-moving paretic arm limited this rate. As a result, participants were training their nonparetic arm at rates slower than the rate at which that arm would move naturally and independently. This entrainment effect of the 2 arms to each other and to the auditory cue may have had a long-term or priming effect on the adoption of a slower preferred frequency on unimanual tapping. Our data support this long-term entrainment effect. Preferred-rate unilateral tapping of the nonparetic finger was significantly faster than bilateral inphase tapping before training ($P<.03$), but after training no significant difference was found between tapping rates during these 2 conditions ($P<.94$) (see fig 3). This slowing of the nonparetic limb does not indicate a worsening of function, given that maximal effort (rate and consistency) was not altered. Entrainment may be a necessary first step in reestablishing coupled bilateral movements after stroke. Studies in which the training rate is progressively increased could determine if and when entrainment of the paretic limb to a faster rate is possible.

Timing consistency of nonparetic finger tapping in bilateral conditions was improved significantly after training without any change in tapping rate from baseline. The improvement was large enough that participants did not differ significantly from controls. Although we had no control group of stroke participants, we can speculate that the arm-training regimen of repeating inphase and antiphase patterns, coupled with auditory input, may have improved the ability to control the complex task and to manage the attentional demands of the bilateral finger conditions, which also consist of inphase and antiphase patterns. Certainly, participants practiced attending to and moving in time to a beat, and one might expect a task-specific improved neural efficiency in motor timing even without a beat. However, finger movements were not involved in the training practice, which suggests the presence and fine-tuning of a timing mechanism that is not effector specific but is more central in nature, such as an internal clock[47,48] or a central oscillatory system.[49]

CONCLUSIONS

We have shown the presence of fine motor timing and coordination deficits in the paretic and nonparetic arms of participants with chronic stroke. Both paretic and nonparetic limb coordination deficits can be explained by damage to known neural linkages that are associated with unilateral and bilateral movements. In participants where motor innervation exists to distal musculature, the interlimb coupling relationships are preserved, despite showing less accuracy and stability. A bilateral, arm-based, repetitive, rhythmic training program can have generalizable effects for some of these fine motor deficits, particularly nonparetic control during bilateral movement tasks. This finding adds to the work of Butefisch et al,[50] who found improved outcomes in paretic hand function after unilateral repetitive training. This responsiveness is suggestive of central control mechanisms for upper-extremity coordination that are accessed by repetitive rhythmic bilateral patterning of the arms. Although limited, preliminary data also indicate a possible advantage in recovery with bilateral training for participants with dominant hemisphere lesions. Further study of the central adaptations facilitated with bilateral repetitive rehabilitation approaches, such as BATRAC, are necessary to learn more about the mechanisms that underlie motor control and coordination and to guide the development of strategies that promote functional recovery.

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