Bimanual Coordination Dynamics in Poststroke Hemiparetics

Gwyn N. Lewis
Human Motor Control Laboratory
Department of Sport and Exercise Science
University of Auckland, New Zealand
and Sensory Motor Performance Program
Rehabilitation Institute of Chicago

Winston D. Byblow
Human Motor Control Laboratory
Department of Sport and Exercise Science
University of Auckland, New Zealand

ABSTRACT. Poststroke hemiparetic individuals (n = 9) and a control group (n = 9) completed a frequency-scaled circle-drawing task in unimanual and bimanual conditions. Measures of intralimb spatial and temporal task accuracy and interlimb coordination parameters were analyzed. Significant reductions in task performance were seen in both limbs of the patients and controls with the introduction of bimanual movement. Spatial performance parameters suggested that the 2 groups focused on different hands during bimanual conditions. In the controls, interlimb coordination variables indicated predictable hand dominance effects, whereas in the patient group, dominance was influenced by the side of impairment and prior handedness of the individual. Therefore, in this particular bimanual task, performance improvements in the hemiplegic side could not be elicited. Intrinsic coupling asymmetries between the hands can be altered by unilateral motor deficits.

Key words: bimanual coordination, hemiparesis, interlimb coupling, upper limb

Individuals who have suffered a monohemispheric cerebrovascular accident (CVA) are often left with varying degrees of hemiparesis, or partial paralysis on one side of the body. The deficit is commonly evident as reduced strength and speed of movement and impaired motor control and coordination of the affected limb. Until recently, therapy options available for chronic stroke patients were limited, and it was generally accepted that improvements in motor function are negligible more than 4–5 months poststroke (Jorgensen et al., 1995). Beyond that period, most patients tend to develop a reliance on compensatory methods, predominantly involving the unimpaired side, that act to work around the motor deficits, rather than focusing on enhancing motor performance on the paretic side.

In the last 10 years, constraint-induced therapies (CITs), which are based on the theory of learned non-use, have become more widespread and have demonstrated positive results for long-term stroke patients in terms of increased use of the impaired limb in everyday life (for a review, see Taub, Uswatte, & Pidikiti, 1999). CIT has proven successful in chronic patients many years poststroke; however, a drawback of the constraint approach is that its effectiveness is limited to those individuals with high levels of residual function in the impaired upper limb (Taub, Crago, & Uswatte, 1998; Taub et al., 1993). In further therapeutic interventions, investigators have examined the effect of bilateral activation techniques in hemiparetic populations (Cunningham, Phillips Stoykov, & Walter, 2002; Mudie & Matyas, 1996, 2000; Rice & Newell, 2001; Whitall, McCombe Waller, Silver, & Macko, 2000). In those studies, simultaneous bilateral activation and movement profiles of the two upper limbs, rather than constraints on the unimpaired side, have been encouraged. Bilateral isometric activation is a common technique used to facilitate muscle activation on the impaired side in the acute phase immediately poststroke (Tramby, 1995). Recently, researchers have investigated whether bilateral activation can also enhance trajectories and velocities of movement of the impaired limb. Cunningham et al. (2002) were able to demonstrate a tendency, although not statistically reliable, toward enhanced smoothness and improved velocity profiles of elbow extension movements when performed bilaterally in individuals poststroke. Improvements in certain spatiotemporal parameters of a circle-drawing task have also been noted during symmetric bimanual conditions in children with spastic hemiplegia (Volman, Wijnroks, & Vermeer, 2002). Similarly, Carson, Riek, Smethurst, Parraga, and Byblow (1997)
demonstrated improvements in performance of the nondominant limb of neurologically intact participants during a bimanual circle-drawing task. Conversely, other studies have shown that during bimanual performance, the impaired side of individuals with unilateral motor deficit appears to constrain the nonimpaired side, resulting in a degradation of the movement pattern of the noninvolved limb to match that of the impaired limb (Rice & Newell, 2001; Steenbergen, Hulstijn, de Vries, & Berger, 1996; Steenbergen, van Thiel, Hulstijn, & Meulenbroek, 2000).

Bimanual training therapies that involve concurrent activation of the noninvolved hemisphere, such as those just described, take advantage of the known interlimb influences that occur during bilateral movements. During bimanual tasks in neurologically intact individuals, there is a strong preference toward symmetry of the movement patterns, such that the limbs appear to be coupled together and controlled as a single functional unit (Haken, Kelso, & Bunz, 1985; Kelso, 1984). The preference is evidenced by the convergence of spatiotemporal movement parameters—for example, reaction times, movement times, and acceleration profiles—during bimanual performances, even when there are significant differences between the limbs under unimanual conditions (e.g., Kelso, Putnam, & Goodman, 1983; Kelso, Southard, & Goodman, 1979a, 1979b; Swinnen, Walter, & Shapiro, 1988). Interlimb coupling can be disadvantageous during tasks requiring disparate movements of the two limbs, such as buttoning a shirt, and needs to be suppressed so that the movements can be carried out effectively. However, interlimb coupling may be of potential benefit for the rehabilitation of movement control in individuals with unilateral motor deficits. Indeed, mirror movements, or involuntary motor output that accompanies activation in homologous muscles of the contralateral limb, are more prevalent in individuals with neuronal damage in the brain, suggesting a reduced ability to suppress those interlimb influences (Lazarus, 1982).

Because subtle handedness effects are evident in continuous bimanual coordination tasks in neurologically intact individuals, it is assumed that coupling influences between the hands predominate more in one direction than the other (e.g., Byblow, Carson, & Goodman, 1994; Carson, 1993; Treffner & Turvey, 1996). In bimanual coordination tasks, coupling asymmetries are manifest in lead-lag relationships between the limbs, the distribution of spontaneous pattern switching through kinematic alterations of the two hands, and the spatiotemporal stability of intralimb movements (Carson, Riek, Byblow, Abernethy, & Summers, 1999). The overwhelming consensus from previous investigations is that during bimanual movement, the nondominant limb is more strongly coupled to the dominant limb than vice versa. That is, movements of the dominant limb tend to be more stable, the dominant limb is likely to display a slight phase advancement in relation to the nondominant, and the dominant limb is less likely to contribute to involuntary transitions in movement pattern (Byblow et al., 1994; Byblow, Chua, Bysouth-Young, & Summers, 1999; Carson, Byblow, Abernethy, & Summers, 1996; Carson, Thomas, Summers, Walters, & Semjen, 1997; Semjen, Summers, & Cattaert, 1995). The intrinsic dynamics of individual performance can be altered under various task and environmental constraints, such as postural manipulations (Carson, Riek, Smehurst, Parraga, & Byblow, 2000), alterations in temporal cueing location (Byblow et al., 1994), and visual focal location constraints (Swinnen, Jardin, & Meulenbroek, 1996; Wuyts, Summers, Carson, Byblow, & Semjen, 1996).

There have also been suggestions that intrinsic asymmetries in coordination dynamics can be altered in healthy individuals who acquire multifrequency coordination patterns (Byblow, Bysouth-Young, Summers, & Carson, 1998; Peper, Beek, & van Wieringen, 1995; Summers, Todd, & Kim, 1993) as well as in those who develop unilateral motor deficits because of neurological impairment (Byblow, Summers, & Thomas, 2000).

Our aim in the current study was to examine intralimb coordination in a frequency-scaled, circle-drawing task completed in unimanual and bimanual conditions in individuals with hemiplegia caused by stroke. Specifically, we wished to determine if the involvement of the intact side in an identical movement pattern could enhance the spatiotemporal performance of the impaired limb. Interlimb coordination dynamics, measured in terms of pattern stability and coupling asymmetries, were also examined during the bimanual circling conditions (both symmetric and asymmetric patterns). Of particular interest was the effect of prior handedness and side of impairment on interlimb coupling asynchronies. We hypothesized that a CVA affecting the nondominant side would further enhance measures of dominance of the contralateral limb, whereas individuals with lesions affecting the dominant hemisphere might display coupling asynchronies in the opposite direction.

Method

Participants

Participants were 9 individuals (age range = 41–71 years, mean age = 56 ± 12 years) who had suffered a monohemispheric CVA (patient group), and 9 age-matched individuals (age range = 38–69 years, mean age = 54 ± 9 years) who served as controls. Details of patient characteristics are provided in Table 1. Inclusion criteria for the patient group were that the participant suffered a first-ever stroke within the last 2 years, presently displays a residual upper limb deficit but has the capacity to hold a pencil-style stylus in pinch grip, and can understand and follow instructions. We assessed functional ability of the affected upper limb of the stroke group by using the wrist and hand sections of the Fugl-Meyer, Jaasko, Leyman, Olsson, and Steglin (1975) rating scale. The inclusion criteria resulted in a patient group with minimal residual deficits in the upper limb. Patients were also questioned as to their hand dominance.

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before their stroke. Five of the patients had suffered a stroke affecting their previously dominant side, whereas the remaining 4 had nondominant-side impairments. All patients excluding Patient 6 were previously right-side dominant.

Control participants (Table 2) were required to have no known neurological impairments. We assessed the handedness of the control group by using the Edinburgh Handedness Inventory (Oldfield, 1971). Eight members of the control group were right-hand dominant and 1 was left-hand dominant. Informed consent was obtained from all participants before the initiation of data collection, and the University of Auckland Human Subjects Ethics Committee approved the procedures.

**Apparatus**

Participants were seated at a desk in front of two ACECAD digitizing tablets (30 cm square). A circle template 7-cm in diameter was located on each tablet at a distance of 25 cm from the desk edge and 16 cm apart. The participants' task was to trace around the circle templates with a pencil-style stylus in time with a computer-generated metronome (50-ms square wave, 800-Hz pitch). The position of each stylus on the tablets (in x- and y-axes) was monitored at 200 Hz and stored to disk.

**Procedure**

The participants drew around the circle templates in eight conditions: left hand, clockwise; left hand, anticlockwise; right hand, clockwise; right hand, anticlockwise; both hands, clockwise; both hands, anticlockwise; both hands, inward; both hands, outward. Those patterns are illustrated in Figure 1. The participants were instructed to trace around the circles in a continuous motion such that one circle was completed for each beat of the metronome. We stressed that they should make the circular movements as accurately as possible but keep in time with the pacing signal. Participants were given no specific instructions as to where to maintain focal location during the test trials.

Each trial consisted of six frequency plateaus of 7-s duration (total trial duration = 42 s). At the end of each plateau, metronome frequency was increased by 0.2 Hz, which resulted in a total movement frequency increment of 1.0 Hz from trial start to end. Before the test trials, participants completed two to three trials with the impaired (nondominant) hand to enable us to set the starting metronome frequency. Participants completed those trials by alternating between clockwise and anticlockwise directions. For each individual, metronome starting frequency was adjusted so that at the final frequency plateau, circle-drawing performance demonstrated signs of instability (any marked spatial inaccuracy or loss of temporal synchronization with the metronome). Three test trials were completed in each of the eight circling conditions in a random order. Participants were familiarized with each pattern of movement before initiation of the test session.
Data Processing and Analysis

We low-pass filtered two-dimensional displacement data from the tablets by using a dual-pass Butterworth filter with a cut-off frequency of 5 Hz. To provide measures of task performance, we assessed circling performance of each hand and, for bimanual trials, relative phasing between the limbs. At each frequency plateau, the best fitting ellipse was determined from all the closed trajectories (circles) completed during that plateau. We calculated circle size discrepancy by subtracting the area of the best fitting ellipse from the circle template area, such that positive discrepancies indicated enlarged trajectories. We analyzed ellipse circularity by determining the amplitude ratio between the major and minor axes of the best fitting ellipse, returning values from 0 (straight line) to 1 (perfectly circular). We used the cycle-to-cycle deviation of each circle trajectory from the best fitting ellipse to provide a measure of spatial stability of the circles.

We implemented a peak-picking algorithm to detect the frequency of movements in the x-axis, providing an indication of circling frequency. By subtracting the movement rate specified by the metronome from the frequency of circling movements, we calculated temporal deviation. The phase relationship between movements in the x-axis and the auditory pacing signal provided an indication of temporal stability. The variability (uniformity) of that relationship affords a measure of the temporal stability of circling (Mardia, 1972). Uniformity values ranged from 0 (highly variable) to 1 (no variability).

By computing the continuous tangential angle of each hand on the circle and subtracting the angle of the nonimpaired/dominant hand from that of the impaired/nondominant hand, we determined the relative tangential angle (RTA) between the hands (Carson et al., 1997). RTA provides a measure of asynchrony between the hands, such that a positive value reflects a nonimpaired/dominant hand
lead whereas negative values indicate an impaired/non-dominant hand lead. We derived continuous tangential angles for each hand from the displacement time series by using a two-point central difference algorithm. Where appropriate, we converted displacement trajectories to anticlockwise by changing the sign of the displacement along the x-axis before determining RTA. We determined uniformity of RTA, a measure of the dispersion of RTA, to obtain an index of pattern stability. The incidence of spontaneous pattern switching, obtained through direction reversals of one (or both) hands, was also examined in bimanual trials. For each disruption detected, we determined whether the pattern switch arose through a change in kinematics (reversal in direction) of the left, right, or both hands. That information provided a further index of interlimb asynchrony.

Statistical Analysis

Data from the six trials completed in each movement condition were averaged. Using a 2 (group: patient, control) × 2 (hand: nonimpaired/dominant vs. impaired/nondominant) × 3 (condition: unimanual, bimanual asymmetric, bimanual symmetric) × 6 (frequency) repeated measures analysis of variance (ANOVA), we analyzed the spatiotemporal performance of each hand. The preferred hand was defined as the nonimpaired limb of the patients and as the dominant limb of the control group. We implemented planned comparisons to investigate significant interactions of interest. We analyzed measures of RTA and uniformity of RTA by using a 2 (group: patient, control) × 2 (condition: asymmetric, symmetric) × 6 (frequency) repeated measures ANOVA. We used a Huynh-Feldt correction factor to adjust the results of the ANOVAs. Aspect ratio, temporal uniformity, and uniformity of RTA data, which are bound from 0–1, were log-transformed before statistical analysis (Mardia, 1972). Non-transformed values are provided in the text for clarity. Results are reported as mean ± standard deviation (SD).

Results

The starting frequency of movement ranged from 0.4–1.2 Hz for both groups (Tables 1 and 2). Overall, the average starting frequency for the patient group (0.64 ± 0.27 Hz) was lower than that of the control group (0.83 ± 0.32 Hz); however, the difference was not significant (p = .1). Because previous results have indicated an absence of direction effects on circle-drawing performance (Carson et al., 1997; Semjen et al., 1995), we averaged together circles drawn in anticlockwise and clockwise directions to form unimanual, asymmetric (both hands clockwise, anticlockwise) and symmetric (both hands inward, outward) conditions. To ensure that participants were well established in the correct movement pattern during the analysis period, we did not analyze data from the first frequency plateau. Any frequency plateaus in which the participant was not exhibiting the correct pattern of movement, such as after an uncorrected phase transition, were removed before data analysis. That procedure resulted in the removal of four frequency plateaus in the patient group and two in the control group. Example circle tracings from a control participant and a patient are shown in Figure 2.

Spatial Performance

To provide an indication of spatial performance of the circle-drawing task, we analyzed measures of amplitude deviation (circle size discrepancy), trajectory circularity (aspect ratio), and spatial variability (absolute error).

Amplitude Deviation

There were no main effects or interactions evident for amplitude deviation data (all ps > .08). Overall, participants underscaled circle size in relation to that specified on the tablet, although the underscaling did not differ between groups, hands, or circling conditions. Alterations in the amplitude of circling along a trial were generally consistent within a participant; however, the individual trends displayed varied somewhat between participants. Although some individuals progressively increased circle size as movement frequency increased, others displayed reductions in circle size, and some maintained a consistent amplitude. In a few individuals, differing effects of movement frequency were seen between the hands: One hand would increase movement amplitude, whereas the other reduced or maintained amplitude along the trial.

For those reasons, we decided to examine absolute deviation to obtain a measure of movement amplitude error regardless of direction (Figure 3). As expected, a significant effect of frequency was found, F(4, 64) = 11.2, p = .001, indicating a progressive increase in circle amplitude deviation as the frequency of movement increased. That effect confirmed that the absolute amplitude data were able to provide a sensitive indication of spatial performance. Significant effects of group, F(1, 16) = 15.9, p < .001, and condition, F(2, 32) = 14.8, p < .001, were also detected. Overall, the stroke patient group (13.7 ± 9.2 cm²) demonstrated larger amplitude error values than the control group (5.47 ± 4.06 cm²). Amplitude deviation was also greater in the bimanual asymmetric (9.94 ± 7.88 cm²) and symmetric (10.94 ± 9.16 cm²) patterns than in unimanual conditions (7.26 ± 6.25 cm²; both ps < .001). No other significant effects or interactions were detected (all ps > .05).

Aspect Ratio

Circle aspect ratio data indicated a steady reduction in the circularity of the trajectories drawn by participants as the speed of movement increased, which was confirmed by a significant effect of movement frequency, F(4, 64) = 15.8, p < .001. There were also main effects of group, F(1, 16) = 7.8, p = .01, hand, F(1, 16) = 17.8, p < .001, and condition, F(2, 32) = 19.1, p < .001, for those data. As predicted, trajectory aspect ratio was greater in the control group (0.87 ± 0.07) than in the patients (0.83 ± 0.07), and in the nonimpaired/dominant hand (0.87 ± 0.07) than in the
impaired/nondominant hand (0.83 ± 0.06). Most interesting, an interaction of group and hand, \( F(1, 16) = 7.7, p = .01 \), indicated that the performance superiority of the dominant hand was confined to only the control group.

Further analysis of the condition main effect indicated that circles drawn in unimanual conditions had a higher aspect ratio than did circles drawn in both bimanual conditions (both \( ps < .001 \)). There were no differences in trajectory circularity between the two bimanual conditions (\( p = .4 \)). Of substantial interest in the aspect ratio data was a significant interaction between group, hand, and condition, \( F(2, 32) = 6.6, p = .007 \). Inspection of Figure 4A reveals a marked drop in circularity from unimanual to bimanual conditions by the nondominant hand of the control participants. That drop was accompanied by a much smaller reduction in performance by the dominant hand in unicompared with bimanual circling conditions. In the stroke patient group, the opposite effect was evident. A considerable reduction in aspect ratio was seen in the nonimpaired hand of the patients from unimanual to bimanual conditions, paralleling the effect seen in the nondominant hand of the controls. A remarkably similar trend in performance was also noted between the impaired hand of the patient group and the dominant hand of the control group.

**FIGURE 2.** Circle tracings (A) from control participant C8 and (B) from patient participant P8, in unimanual (impaired, nondominant side) and bimanual conditions. Circles shown are from the second and last frequency plateaus. For both individuals, the starting frequency was 0.8 Hz. C8 was right-hand dominant, whereas P8 was right-side impaired and right-hand dominant. Arrows indicate the direction of circling. There are several features of note: a greater spatial accuracy and reduced trajectory variability of the control participant; a reduced performance of the impaired, nondominant hand in bimanual versus unimanual conditions; and the presence of spontaneous phase transitions (reversals in movement direction) in the bimanual asymmetric (anticlockwise) pattern.
tendency toward a result similar to that seen in the aspect ratio data is shown in Figure 4B; that is, the nonimpaired and nondominant hands of the patients and controls, respectively, demonstrated a more marked increase in spatial variability from unimanual to bimanual patterns than that seen in the opposite hands. The effect was not as strong in the spatial variability data as in the aspect ratio findings and appeared to be restricted to the asymmetric circling pattern.

**Temporal Performance**

We assessed temporal performance of the participants through measures of frequency deviation from the metronome and variability of movement frequency along each plateau (temporal stability).

**Temporal Deviation**

An effect of frequency indicated that temporal deviation progressively increased, in a negative direction, across the plateaus, $F(4, 64) = 32.8, p < .001$. At the initial frequency plateaus, participants cycled at a tempo slightly faster than that specified by the metronome; however, the gradual increase in temporal deviation meant that at the final plateaus, participants’ circling speed was underscaled. No further interactions with movement frequency were explored.

Although the effect of group was not significant for temporal deviation data, there were main effects of hand $F(1, 14) = 13.4, p = .002$, and condition, $F(2, 32) = 7.9, p = .002$, as well as their interaction, $F(2, 32) = 7.5, p = .002$ (Figure 5A). Temporal deviation of the nonimpaired/dominant hand was not significantly different from zero ($0.002 ± 0.13 Hz$, $p = .8$); that is, the movement frequency was equivalent to that specified by the metronome. However, the frequency of circling was significantly underscaled in the impaired/nondominant hand ($-0.06 ± 0.13 Hz$, $p < .001$). Analysis of the effect of condition revealed that although temporal deviation was not significant in unimanual conditions ($-0.001 ± 0.1 Hz$, $p = .9$), movement rate was underscaled in both bimanual asymmetric ($-0.05 ± 0.02 Hz$, $p < .001$), and symmetric ($-0.03 ± 0.01 Hz$, $p = .002$), conditions. The difference in the extent of frequency deviation between asymmetric and symmetric patterns was not significant, $p = .1$.

Further exploration of the hand and condition interaction revealed that a higher circling rate of the nonimpaired/dominant hand than the opposite limb, evidenced by a more positive frequency deviation, was seen only in unimanual and bimanual asymmetric conditions (both $p < .001$). During bimanual symmetric circling, the extent of temporal deviation did not differ between the two hands ($p = .4$). That finding indicates that during symmetric patterns the two hands were cycling at the same rate, whereas movement rates of the two hands differed during asymmetric circling patterns.

**Temporal Stability**

The temporal uniformity values displayed a main effect of frequency, indicating a progressive increase in the variability of movement frequency across the plateaus. The frequency deviated significantly more from the tempo specified by the metronome as the frequency increased, with the most significant underscaling occurring at the highest frequency (Figure 4B). The underscaling was most pronounced in the nonimpaired/dominant hand, where the movement frequency was underscaled by $-0.06 ± 0.13 Hz$, $p < .001$. In contrast, the movement frequency in the impaired/nondominant hand was not significantly different from zero ($0.002 ± 0.13 Hz$, $p = .8$). These findings indicate that the movement frequency was equivalent to that specified by the metronome for the nonimpaired/dominant hand but underscaled for the impaired/nondominant hand.

**Absolute Error**

Measures of absolute error, or trajectory variability, demonstrated an effect of movement frequency similar to that seen in the circularity data, $F(4, 64) = 51.5, p < .001$. As the frequency of circling increased along a trial, trajectory variability increased progressively, again demonstrating its suitability as a measure of spatial performance. No further interactions with movement frequency were investigated.

Significant effects of group, $F(1, 16) = 10.5, p = .005$, hand, $F(1, 16) = 22.1, p < .001$, and condition, $F(2, 32) = 35.2, p < .001$, were also found for the absolute error data. As in the analysis of aspect ratio, trajectory variability was greater in the stroke patients ($0.58 ± 0.22$ cm) than in the control participants ($0.42 ± 0.17$ cm), and in the impaired/nondominant hand ($0.57 ± 0.22$ cm) than in the nonimpaired/dominant hand ($0.43 ± 0.18$ cm). Further analysis of the effect of condition revealed that absolute error was higher in the two bimanual conditions than it was in unimanual circling (both $ps < .001$), and higher in asymmetric than in symmetric patterns ($p = .002$).

A group, hand, and condition interaction was also present for the trajectory variability data, $F(2, 32) = 4.0, p = .03$. A
of movement timing in relation to the metronome signal, $F(4, 64) = 4.9, p = .006$. An interaction between group and movement frequency, $F(4, 64) = 4.2, p = .01$ (Figure 5B) demonstrated that the reduction in the temporal stability of circling was more pronounced in the patient group. Further statistical investigations of interactions with movement frequency were not completed. The only remaining significant result found in temporal uniformity data was an interaction between hand and movement condition, $F(2, 32) = 4.5, p = .04$. In unimanual conditions, temporal variability was greater in the nonimpaired/dominant hand than in the impaired/nondominant one ($p = .01$), whereas uniformity values were equivalent between hands in the two bimanual conditions (both $ps > .1$).
Interlimb Measures

We analyzed measures of RTA, uniformity of RTA, and the contribution of each hand to pattern switching to obtain information on interlimb coupling during the bimanual circling conditions.

Relative Tangential Angle

RTA is an indication of temporal synchrony between the hands. Because measures of RTA become meaningless when the two limbs are uncoupled, we included RTA values for each plateau in the analysis only when uniformity was sufficiently high (> 0.8) to verify that there was a central tendency. Overall, the participants demonstrated an average RTA of 19.1°, representing a slight nonimpaired/dominant hand lead during circling. An effect of group was not found for RTA data, \( F(1, 16) < 0.1, p = 0.7 \); however, both the condition, \( F(1, 16) = 6.9, p = .02 \), and frequency, \( F(4, 64) = 3.6, p = .03 \), effects were significant. Supporting previous research, we found that RTA increased progressively as movement frequency was scaled upward, representing a greater asynchrony between the hands at higher circling rates, and was consistently greater in asymmetric (25.8° ± 30.8°) than in symmetric (17.5° ± 22.0°) patterns.

Of greater interest in the RTA data was the effect, if any, in the stroke patients of whether their previously dominant or nondominant side was impaired. Individuals in the stroke patient group were separated into individuals with previously dominant-side deficits and individuals with previously nondominant-side deficits, and RTA results were averaged across the two movement patterns (Figure 6). In comparison with control participants, individuals with deficits in the previously nondominant side showed a greater nonimpaired hand lead, whereas the opposite was true for those with impairments on the previously dominant side. Most interesting, individuals with dominant-side impairments did not demonstrate the gradual increase in interlimb asynchrony that was evident in the control group and in patients with deficits on the nondominant side. At the lower initial movement frequencies, those patients displayed a nonimpaired hand lead that shifted...
slightly to stabilize around a neutral RTA at the higher movement frequencies.

**Uniformity of Relative Tangential Angle**

Although the control group (0.90) demonstrated higher values of RTA uniformity overall than the stroke group did (0.87), the difference was not significant, F(1, 16) = 3.5, p = .08. Predictable effects of movement condition, F(1, 16) = 29.5, p < .001, and movement frequency, F(4, 64) = 29.5, p = .002, were evident for the uniformity values. Pattern stability was greater in symmetric patterns (0.95) than in asymmetric patterns (0.82) and also decreased uniformly with increasing movement frequency (Figure 7). No interactions with group were evident for those data, all ps > .6.

**Phase Transitions**

We investigated the incidence of spontaneous (involuntary) phase transitions during bimanual circling by detecting reversals of direction in one or both of the hands. Overall, 112 transitions were detected, 46 in the control group and 66 in the patient group (Figure 8). Phase transitions were seen during circling performance in all participants except P5, and the direction reversal was corrected and the original pattern of movement was regained in all but 3 of the total transitions. As expected, the majority of spontaneous transitions occurred during asymmetric circling (controls = 42, patients = 54), although transitions in the symmetric patterns were also evident (controls = 4, patients = 12). Across the two bimanual patterns, we investigated the number of transitions that were attributable to kinematic alterations in only one hand by using binomial distribution probabilities to compare the incidence of switching between the two hands. In the control group, 34 of the 41 transitions detected occurred through a reversal in direction of the nondominant side (p < .001). In contrast, the distribution of reversal directions in the stroke group was more evenly spread between the two hands, with 32 transitions occurring through alterations in direction of movement of the impaired hand and 25 through alterations in direction of the nonimpaired hand (p > .05). When the stroke patients were separated into those whose previously dominant side was affected and those whose nondominant side was affected, the distribution of hands contributing to spontaneous phase transitions remained even in both groups. In the dominant-side deficit group, 27 of 57 transitions occurred through the impaired hand, whereas 5 of the 10 transitions detected in the nondominant affected group were through the impaired hand (both ps > .05).

**Discussion**

In the present study, we investigated uni- and bimanual circle-drawing performance in a hemiplegic stroke patient population. One of our main objectives was to examine the influence of simultaneous bilateral movement in either...
symmetrical or asymmetrical patterns on the spatial and temporal task accuracy of the impaired side. Several inter-limb measures were also analyzed, and we hypothesized that intrinsic coupling asynchronies between the hands would be altered to reflect the unilateral motor impairments of the hemiplegic side. The findings in relation to those issues are discussed next.

**Spatiotemporal Performance**

As expected, the control group performed the circling tasks with greater spatiotemporal accuracy than the stroke patients did. The preferred hand also predictably displayed a higher task accuracy than the nonpreferred hand. It was somewhat surprising that the preferred-hand performance advantage for the spatial parameter of aspect ratio was evident only for the control group and was not significant at all for amplitude deviation results. It should be taken into account that for half the patient group, the impaired side was their previously dominant side. That feature may have served to reduce the performance differences between the two hands for those individuals.

Our primary aim in the study was to determine if the concurrent involvement of the intact side of hemiplegic stroke patients during a motor task could improve the performance of the impaired side. The results of the study did not provide any evidence that simultaneous bimanual movement improved spatial or temporal accuracy of the affected side. In fact, significant reductions in performance in both groups were evident in the bimanual conditions. That reduction was particularly true for the asymmetric movement patterns. The absence of motor enhancement during bimanual conditions follows the findings of similar studies in hemiplegic populations (Rice & Newell, 2001; Steenbergen et al., 1996; Steenbergen et al., 2000). In a circle-drawing task similar to that implemented in the present investigation, Carson et al. (1997) noted in a neurologically intact population an increase in the movement frequency of the non-dominant hand during bimanual conditions compared with that in unimanual conditions. It is noteworthy that the circling frequencies adopted in the current study were lower than those imposed by Carson et al. and that the control participants did not underscore movements of the nondominant hand to the same extent during unimanual performance. Those factors likely account for the absence of a comparable improvement in temporal performance of the nondominant hand, as reported in the earlier study.

It has been noted in individuals with a unilateral motor deficit that the performance of more complex bimanual movement tasks often results in a degradation of the movement pattern of the nonimpaired side, as opposed to enhanced movement patterns of the impaired side (Steenbergen et al., 2000; Utey & Sugden, 1998). In a recent review, Swinnen and Carson (2002) suggested that it might be easier for populations with movement disorders to compensate for motor deficits in simple than in more complex coordination tasks. The greater ease in compensating may be related to the general increase in the participation of distal musculature during more complex motor tasks. There is thought to be less involvement of bilaterally projecting pathways in the descending control of distal musculature than in those muscles located proximally (Kuypers & Brinkman, 1970), and it has been suggested that interlimb
coupling tendencies may arise through descending commands sent via those bilateral projections as a result of neural cross-talk at interhemispheric levels (Marteniuk & Mackenzie, 1980). It is possible that coupling strength between the two limbs is reduced in tasks that primarily involve muscleature with minimal input from bilateral projections, although evidence for that is yet to be provided (Byblow et al., 2000). The finding in the current study that task performance in the control group also deteriorated in bimanual conditions seems to indicate that the adopted task was relatively complex, and it is perhaps not surprising that the addition of intact limb movement negatively affected motor performance in the patient group. The absence of statistically significant group and condition interactions in any of the parameters analyzed indicates that the noted deficits in task accuracy in bimanual conditions were equivalent in both groups.

As well as the noted complexity of the adopted task, the well-recovered nature of the stroke group and the heterogeneity of lesion location may also have influenced the outcome of the study. Most of the patients who participated had little evident residual motor deficits, which was largely the result of the relatively high level of function required to grasp the stylus sufficiently to perform the circling task. Movement therapy approaches in which bilateral activation techniques are used to enhance force output generally target patients in initial stages of recovery, whose motor deficits are more pronounced (Trombly, 1995). In a long-term bilateral training study, Mudie and Matyas (1996) also reported greater beneficial effects in patients with more severe impairments of limb function. Certain motor control structures within the brain, such as the supplementary motor area and the cingulate motor area, have also been identified for their involvement in interlimb coordination, and individuals with lesions in those areas may display relatively greater performance decrements during bimanual tasks.

Previous investigators have implied that temporal constraints may influence the facilitatory or inhibitory effect of bilateral activation. Volman et al. (2002) suggested that motor tasks in which reaction or movement time variables, or both, are analyzed, and in which movements are required to be performed as fast as possible, may predispose a negative influence of the impaired limb because of coupling “detuning” at high movement rates. They suggested that the use of self-paced movements in which individuals are free to adopt their own velocity or frequency of movement may invoke the adaptation of the impaired limb to the nonimpaired more effectively. In contrast to that suggestion, others have proposed that enhanced interlimb coupling at high movement speeds (Uteley & Sugden, 1998) or loads (Cunningham et al., 2002) may reduce some of the inherent movement abnormalities of the hemiplegic limb.

The task implemented in the current study was somewhat of a mixture of preferred and high-speed movements. Participants started each trial at what was a comfortable circling speed for all, although the actual frequency of movement was guided by a pacing signal rather than self-generated. We adjusted the starting frequency for each individual to elicit spatial or temporal instability, or both, in the impaired nondominant hand at the final frequency plateau of unimanual circling. That meant that almost all participants were circling at near-maximum speed of the nonpreferred hand by the end of the trial, thereby enabling us to detect potential enhancements in movement rate during bimanual conditions. The temporal deviation data indicated that the participants were able to keep up with the pacing signal with the nonimpaired/dominant hand but that the circling speed of the impaired/nondominant hand was slower than that specified by the metronome. From that finding, it appears that the starting frequencies chosen were successful in challenging the movement velocity of the impaired/nondominant side. Most surprising, in unimanual conditions the nonimpaired/dominant hand demonstrated a greater temporal variability compared with that of the impaired/nondominant hand. It is possible that although the nonimpaired, dominant hand was able to keep up with the metronome pacing signal, the increased movement rate may have come at a cost of a reduction in the uniformity of circling speed.

What was most interesting was the movement frequencies adopted by the two hands in the bimanual circling conditions. During the symmetric patterns, both hands circled at same frequency but at a rate slower than that specified by the metronome; that is, the nonimpaired/dominant hand slowed down to match the circling rate of the impaired, nondominant hand. In the asymmetric patterns, the overall movement speed was again significantly less than that specified; however, the impaired/nondominant hand slowed even further and the two hands moved at different frequencies in that condition. That is a strong indication that in the asymmetric condition, the participants struggled to maintain the required patterns of movement at the frequencies specified.

An unexpected effect was present in the analysis of spatial performance data, which may point to a different focal strategy used by the control and patient groups. Circularity and spatial variability parameters deteriorated in bimanual conditions in both groups; however, that effect was more marked in one hand than the other. In the control group, the nondominant hand displayed a greater reduction in performance from unimanual to bimanual conditions, whereas in the patient group, the nonimpaired hand appeared more negatively affected in the bimanual conditions. One possible conclusion from that finding is that the control participants tended to focus on their dominant hand when both hands were circling, whereas the patients focused on their more impaired side. Certainly, there is much previous evidence to indicate that neurologically intact individuals given no particular instructions as to where to maintain focal location tend to concentrate on the performance of their dominant side (Peters, 1981, 1985). Wuys et al. (1996) and Swinnen et al. (1996) have demonstrated that
manipulating focal attention during a bimanual coordination task results in alterations in the spatial accuracy of the two hands, such that an augmentation of performance is noted in the hand to which attention is directed. Those findings are congruent with the hypothesis in the present study that during bimanual circling, the patient group attended to their impaired side to a greater extent than the control group did. A tendency for the stroke group to focus on the more impaired side may also account for the absence of performance differences between the two hands in terms of trajectory circularity measures.

Interlimb Coordination

The interlimb measures in the bimanual conditions demonstrated results that are consistent with those of other bimanual circle-drawing paradigms (Byblow et al., 1999; Carson et al., 1997; Semjen et al, 1995). That is, the asymmetric movement patterns were less stable than the symmetric; pattern stability decreased as the velocity of movement increased; the preferred hand displayed a slight phase advantage over the nonpreferred hand (positive lead-lag values); and, at least for the control participants, the nonpreferred hand contributed to spontaneous phase transitions significantly more than the preferred hand did. As well as the noted intralimb spatial accuracy effects, Swinnen et al. (1996) also reported that manipulating focal location during bimanual circling influenced the interlimb lead-lag relationship. They found that the extent of the dominant hand phase advance was increased and reduced when attention was directed to the dominant and nondominant hands, respectively. Although, overall, the control group in the current study demonstrated a larger phase lead of the preferred hand than the patients did (28° compared with 23°), supporting the idea of an attentional bias directed toward the impaired side in the stroke patients, the difference was not significant. It is likely that the large variance associated with the RTA data contributed to the absence of statistical effects. Indeed, when the stroke patients were divided into those with deficits on their previously dominant and nondominant sides, an interesting difference between the two groups became apparent. In accordance with the predictions outlined in the introductory comments, patients with nondominant-side impairments demonstrated a larger lead of the dominant side than did the control group, whereas the remaining group displayed no clear signs of phase advantage of one hand. Deficits in movement ability and stability in the impaired limb may strengthen the coupling asymmetry between the hands when the nondominant side is affected, reinforcing the natural dominance of the intact side. In the same light, reduced motor ability of the dominant limb would tend to normalize the intrinsic performance differences between the limbs. Evidence of that effect in the current study was shown by the absence of clear hand-dominance effects in the latter patient group.

Differences between the patient and control groups were also evident in the analysis of pattern switching data. A clear preference was seen in the control group for alterations in the kinematic performance of the nonpreferred hand to instigate spontaneous phase transitions, supporting earlier research (Byblow et al., 1994; Byblow et al., 1999; Carson et al., 1996; Carson et al., 1997; Semjen et al., 1995; Summers, Byblow, Bysouth-Young, & Semjen, 1998). That hand preference was less pronounced in the patient group. In fact, the detected incidence of impaired and nonimpaired-hand direction reversals was not significant based on binomial distribution probabilities. It is perhaps surprising that the equal division between the two hands was maintained when the patient group was separated into those with dominant- and those with nondominant-side deficits. Following the hypothesis outlined, we predicted that a more even distribution of direction reversals between the two hands would be seen in those patients whose previously dominant side was impaired; however, we expected that spontaneous transitions in those with nondominant-side deficits would almost exclusively occur via the impaired side. It should be taken into account that the incidence of phase transitions was very low in the latter group, making it difficult to formulate any strong conclusions on the basis of those results. As discussed previously, the spatiotemporal data suggest that the patient group tended to focus their attention on the impaired side during bimanual conditions, the opposite of that seen in the control group and that generally indicated by other studies. An enhanced concentration on the performance of the impaired side may have resulted in a reduction in the number of spontaneous transitions through that limb (cf. Wuyts et al., 1996).

Overall, the results of interlimb variables analyzed in this study suggest that intrinsic coupling dynamics can be altered in populations with hemiparesis. The unilateral motor impairments may induce a shift in the balance of dominance between the two limbs, either reinforcing or competing with inherent asymmetries, depending on the previous dominance of the affected limb. That finding is similar to that reported in an earlier study involving Parkinson’s disease patients with unilateral symptoms (Byblow, Summers, & Thomas, 2000). In the subgroup of patients with dominant-side deficits in the present study, it was evident in the RTA data that the preferred (nonimpaired) limb led the impaired limb at the lowest movement frequency but then tended toward neutral as the speed of circling increased. In this group of patients, the natural handedness asymmetry and the imposed stroke-related motor deficits provided competing hand-dominance tendencies. It is possible that at comfortable movement rates, the preferred (nonimpaired) hand may dominate; however, at higher movement rates, at which the motor system is under greater stress, the intrinsic preference of the previously dominant limb might prevail. It would be of interest to further examine that feature in a population with a range of residual motor deficits so that the influence of competing and cooperating handedness dynamics can be determined.
Conclusions

In summary, the bimanual paradigm implemented in the current study did not elicit any enhancements in motor performance of the affected side of hemiplegic stroke patients. In fact, deficits in the movement pattern were seen in both the patient and control groups in the bimanual circling patterns. Spatial measures provided indirect evidence that the patients focused more on the nonpreferred (impaired) side during bimanual conditions, whereas the control group tended to concentrate on their preferred (dominant) limb. We suggest that the intrinsic coupling asymmetries between the hands are altered by impairments in motor ability as a result of neurological impairment, either reinforcing or competing with inherent hand-dominance effects.

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