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Kinematic Motion Analysis and Muscle Activation Patterns of Continuous Reaching in Survivors of Stroke

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ABSTRACT. Coordinated reaching requires continuous interaction between the efferent motor output and afferent feedback; this interaction may be significantly compromised following a stroke. The authors sought to characterize how survivors of stroke generate continuous, goal-directed reaching. Sixteen survivors of stroke completed functional testing of the stroke-affected side and a continuous reaching task between 2 targets with both sides. Motion analysis and electromyography data were collected to determine segmental contributions to reach (e.g., amount of compensatory trunk), spatiotemporal parameters (e.g., peak velocities), and muscle activation patterns (MAP). Repeated measures analyses of variance compared how survivors of stroke reach with the stroke-affected versus less affected sides. Correlations were determined between kinematic outcomes and functional ability. Participants used significantly more trunk movement and less shoulder flexion and elbow extension when reaching with the stroke-affected side. This corresponded with less muscle activity in the proximal musculature including the anterior, middle, and posterior deltoid on the stroke-affected side. There were significant correlations between the segmental contributions to reach (e.g., amount of compensatory trunk), spatiotemporal parameters (e.g., peak velocities), and muscle activation patterns (MAP). Cyclic reaching requires constant interaction between efferent motor output and afferent feedback (Hundza & Zehr, 2007), and should not be viewed as a concatenation of discrete reaching. Research in neurologically intact populations has demonstrated reciprocal movements reversing motion at target contacts rather than terminating motion on a target are likely regulated by distinct neural commands (Zehr, 2005; Zehr et al., 2004). Hogan and Sternad (2007) made significant contributions to formally defining reciprocal movements as “movements with recurring configurations” (p. 25) and discrete movements as movements bound by a period of no movement. These distinctions highlight differences not only in understanding but also in the experimental methodologies used to study motor control theories to explain aspects of motor performance. For example, concepts of generalized motor programs can explain discrete tasks, yet a dynamic-systems approach can explain cyclical tasks (Schmidt, 2005). Thus, rejecting one theory in favor of another is not yet justified (Schmidt, 2005).

The theoretical basis for cyclic reaching in neurologically intact populations continues to be updated (Ronsse, Sternad, & Lefevre, 2009; Smits-Engelsman, Swinnen, & Duysens, 2006; Sternad, 2008; Sternad & Dean, 2003; Zehr et al., 2004), and the unique properties of reciprocal reaching have been well documented in neurologically intact populations (Dounskaia, Wisleder, & Johnson, 2005; Smits-Engesman et al., 2006; Smits-Engelsman, Van Galen, & Duysens, 2002). Smits-Engelsman et al. (2006) demonstrated that cyclic movements resulted in superior movement speed and quality such that speed can be increased twice as much before a decrease in accuracy compared with discrete tasks (Smits-Engelsman et al., 2002). Dounskaia et al. (2005) demonstrated that movements are smoother when reaching continuously between two targets. Movement speed and smoothness are two characteristics of discrete reaching impacted by stroke, yet limited evidence exists to describe CR. Given the potential benefits of cyclic reaching in neurologically intact populations, an investigation of how survivors of stroke reach with the stroke-affected versus less affected sides is necessary to identify mechanisms that may facilitate rehabilitation efforts.

Keywords: EMG, hemiparesis, kinematic, motor control
Presently, there is limited understanding of how survivors of stroke perform CR (Prange, Jannink, et al., 2009). The neural damage caused by a stroke can result in a vast array of pathophysiological symptoms such as hemiparesis or altered muscle tone that may significantly impair motor control of the UE (Gracies, 2005a, 2005b). These impairments, along with nonneural, musculoskeletal changes such as muscle atrophy, likely influence the ability to incorporate the affected UE in functional tasks because movements can be difficult to generate, maintain, and control. During forward-reaching discrete tasks, survivors of stroke often use compensatory trunk movement and less elbow extension compared with neurologically intact controls (Cirstea et al., 2003). These segmental contributions coincide with altered spatiotemporal parameters including extended movement durations, decreased peak velocity, and more segmented movements. The neural damage caused by a stroke may interfere with the ability to continuously generate efferent motor output while incorporating afferent feedback such that performance is significantly impaired or unsuccessful. For example, the inability to generate CR may be evidenced by long dwell periods at target contact in contrast to the smooth accelerations and decelerations between target contacts with no dwell time seen in normal CR. Investigating CR in the stroke-affected UE is an important area for neurorehabilitation for two reasons: (a) it determines motor control impairments in the ability to generate CR and how that may influence functional ability and (b) it further develops the evidence base for interventions that incorporate CR.

In this study, we sought to characterize kinematics and muscle activation patterns (MAPs) of CR in survivors of stroke by comparing the less affected with the more affected side. We hypothesized that participants engaged in a CR task would demonstrate a less coordinated reach with a greater contribution of trunk movement and less use of the shoulder and elbow when using the stroke-affected side compared with the less affected side. Our goal is to provide a better understanding of how coordinated UE movement is executed in survivors of stroke to assist clinicians and researchers in the development and refinement of structured UE interventions to target specific motor impairments.

### Method

**Participants**

Sixteen survivors of stroke (9 men; 8 left cerebral vascular accident) with a mean age of 66.6 years (SD ± 11.6 years) participated and gave written consent in accordance with the policies of the local institutional review board. Table 1 summarizes participant demographics. Participants met the following inclusion criteria: at least 6 months post-stroke, and at least 10° of active wrist extension and approximately 30° of active shoulder flexion, both in the stroke-affected side. Exclusion criteria included other neurologic conditions (e.g., multiple sclerosis, Parkinson’s disease), injections treating spasticity within 3 months of participation, and a Mini-Mental State Exam score less than 24 (Folstein, 1975).

### TABLE 1. Participant Demographics

<table>
<thead>
<tr>
<th>Sex</th>
<th>Age (years)</th>
<th>Time since stroke (years)</th>
<th>Stroke type</th>
<th>Side of CVA</th>
<th>Lesion location</th>
<th>FM</th>
<th>BBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>63</td>
<td>13.8</td>
<td>I</td>
<td>L</td>
<td>MCA</td>
<td>28</td>
<td>4</td>
</tr>
<tr>
<td>F</td>
<td>64</td>
<td>3</td>
<td>I</td>
<td>R</td>
<td>basal ganglia</td>
<td>29</td>
<td>6</td>
</tr>
<tr>
<td>M</td>
<td>81</td>
<td>1.3</td>
<td>I</td>
<td>O</td>
<td>pons</td>
<td>39</td>
<td>20</td>
</tr>
<tr>
<td>M</td>
<td>86</td>
<td>4.1</td>
<td>I</td>
<td>O</td>
<td>anterior, central pontine</td>
<td>47</td>
<td>28</td>
</tr>
<tr>
<td>M</td>
<td>44</td>
<td>0.6</td>
<td>I</td>
<td>R</td>
<td>MCA</td>
<td>48</td>
<td>20</td>
</tr>
<tr>
<td>M</td>
<td>74</td>
<td>4</td>
<td>I</td>
<td>L</td>
<td>medulla</td>
<td>48</td>
<td>13</td>
</tr>
<tr>
<td>F</td>
<td>74</td>
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<td>I</td>
<td>R</td>
<td>Frontal</td>
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<tr>
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<td>65</td>
<td>1.8</td>
<td>H</td>
<td>L</td>
<td>cerebellar</td>
<td>56</td>
<td>18</td>
</tr>
<tr>
<td>F</td>
<td>66</td>
<td>6.8</td>
<td>H</td>
<td>L</td>
<td>MCA</td>
<td>57</td>
<td>28</td>
</tr>
<tr>
<td>M</td>
<td>75</td>
<td>3.1</td>
<td>I</td>
<td>R</td>
<td>parietal</td>
<td>57</td>
<td>25</td>
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<tr>
<td>M</td>
<td>61</td>
<td>1.3</td>
<td>I</td>
<td>O</td>
<td>pons, cerebellar</td>
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<td>18</td>
</tr>
<tr>
<td>M</td>
<td>68</td>
<td>1.6</td>
<td>I</td>
<td>L</td>
<td>MCA</td>
<td>60</td>
<td>22</td>
</tr>
<tr>
<td>F</td>
<td>41</td>
<td>0.5</td>
<td>I</td>
<td>R</td>
<td>MCA</td>
<td>60</td>
<td>19</td>
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<tr>
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<td>70</td>
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<td>I</td>
<td>L</td>
<td>posterior parietal</td>
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<td>30</td>
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<tr>
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<td>I</td>
<td>L</td>
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<td>41</td>
</tr>
<tr>
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<td>I</td>
<td>L</td>
<td>centrum semiovale</td>
<td>63</td>
<td>44</td>
</tr>
</tbody>
</table>

**Note.** M = male; F = female; I = ischemic; H = hemorrhagic; L = left; R = Right; O = other; CVA = cerebral vascular accident; FM = Fugl-Meyer; BBT = box and block test; MCA = middle cerebral artery.
Motion Capture Setup and Outcomes

See Figure 1 for experimental setup. Participants sat comfortably in a chair and were asked to reach back and forth between two targets located in a parasagittal plane at a height of 0.71 m. The initial starting position was approximately 0° of shoulder flexion, 90° of elbow flexion, and a neutral trunk position with the close target located approximately 25 cm anterior to the elbow. Participants were given 1–2 practice trials to become familiar with the task and were asked to have their hands in their lap while at rest. Participants were instructed before each trial to reach continuously between the two targets making contact with the fingertip. Participants were instructed to be as accurate to the center of the target and to perform the task as quickly as possible; no verbal encouragement was provided within the trial. Data were recorded for five consecutive reaching cycles after participants started reaching, and participants were not instructed to stop reaching until a short time period elapsed following the five complete cycles. The stroke-affected and less affected sides were collected, and that order was randomized.

Arm kinematics were recorded at 100 Hz with a seven-camera Vicon motion analysis system (Vicon, Centennial, CO, USA). Each target (0.10 m in diameter) was instrumented with a pressure sensor placed used to quantify target contact and were synchronized with the motion capture system. A custom UE marker set was utilized, including nine torso markers, radial and ulnar styloid, hand, fingertip, forearm, shoulder, elbow, and a cluster set (three markers) on each upper arm. Static calibration trials were collected for each side prior to the dynamic trials. Data were reconstructed and labeled in Nexus (Vicon), and processed in Visual3D (C-motion, Germantown, MD, USA). A low-pass fourth-order, zero-lag Butterworth filter was applied to kinematic data with a cutoff frequency of 7 Hz. All ranges of motion or excursion were calculated as the difference in joint angles between contact with the distal target and proximal target. UE joint angles were calculated as the following: shoulder flexion (rotation of the upper arm in relation to the thorax about the x-axis) and elbow extension (rotation of the lower arm in relation to the upper arm about the x-axis). Trunk contribution was calculated as anterior flexion, lateral flexion, and axial rotation. Trunk rotation was defined for each reaching side such that counterclockwise rotation of the trunk when using the right side and clockwise rotation when using the left side were considered positive. Lateral flexion was defined as positive when leaning away from the targets.

A number of spatiotemporal parameters were calculated. Reach and return movement times were determined as the time between consecutive target contacts. Movement velocities were calculated by determining the derivative of the wrist position marker in the sagittal plane. Peak velocities were determined as the peak reach and return velocity that occurred between consecutive target contacts. Velocity profiles of the wrist marker were plotted to determine smoothness of movement using zero-velocity crossings and were determined separately for the reach and return phases. The lowest number of velocity crossings possible was five, such that there was a bell shape velocity profile for each reaching cycle (one acceleration and deceleration phase). Variable error (a measure of accuracy at contact) was assessed from the spatial distribution of the fingertip marker as it made contact in relation to the mean of the target contacts (Dounskaia et al., 2005) using the following equation: \[ V = \frac{1}{n} \sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 + (y_i - \bar{y})^2}, \] where \( x_i \) and \( y_i \) are the coordinates of the fingertip marker as it made contact with the target, \( \bar{x} \) and \( \bar{y} \) are the averaged coordinates, and \( n \) is the number of reaching cycles.

Electromyography to Determine Muscle Activation Patterns

Electromyography (EMG) was recorded from a pair of electrodes (1 cm in diameter, 2 cm interelectrode distance; Noraxon, Inc., Scottsdale, AZ, USA) from the biceps brachii.
triceps brachii, posterior deltoid, anterior deltoid, middle deltoid, and upper trapezius muscles according to published guidelines (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). EMG data were collected through a Myosystem 1200 (Noraxon, Inc.) and synchronized with Vicon at a sampling rate of 2000 Hz. Data were band-pass filtered (16–400 Hz) and then full-wave rectified. A root mean square (RMS) value in a four-time domain analysis of EMG was calculated such that the RMS amplitude of EMG for each muscle was determined for the acceleration and deceleration phases of the reach and return. This has been demonstrated as a method to quantify EMG amplitude given that a maximum voluntary isometric contraction may not be accurate in survivors of stroke (Kisiel-Sajewicz et al., 2011). EMG data were checked for outliers and values were removed from the analysis that were below 0.001 mV or exceeded a value of 2 standard deviations above the mean.

Data Analysis

Descriptive statistics included mean and standard deviations were reported in the text (standard error of the mean in figures). The stroke-affected side was compared to the less affected side through one-way repeated measures analysis of variance (ANOVA) for the segmental contribution to reach (side as a factor), two-way repeated measures ANOVAs for the spatiotemporal outcomes (2 × 2; side-by-reach/return phase), and the MAP (2 × 4; side-by-acceleration/deceleration per phase). A one-way repeated measures ANOVA was utilized as a post hoc measure to investigate interaction effects for MAPs. Pearson product moment correlations were calculated for the kinematic range of motion (ROM) variables, functional ability scores (FM, BBT, and reaching time), and two MAPs (anterior deltoid and triceps). Statistical significance was set at \( p \leq .05 \).

Results

Segmental Contributions to Reach

Figure 2 illustrates the segmental contribution to reaching and Table 2 includes individual data. Participants used significantly more anterior trunk flexion (12.2 ± 6.0° vs. 3.2 ± 3.2°, respectively), \( F(1, 15) = 33.90, p < .001 \), and rotation (10.4 ± 2.5° vs. 7.5 ± 2.0°, respectively), \( F(1, 15) = .20.10, p < .001 \), when reaching with the stroke-affected side compared with the less affected side. Participants used significantly less shoulder flexion when reaching with their stroke-affected side compared with the less affected side (37.8 ± 13.2° vs. 57.1 ± 11.9°, respectively), \( F(1, 15) = 18.20, p = .001 \). Elbow extension, when reaching with the stroke-affected side, was approximately half compared with reaching with the less affected side, representing a significant difference (24.3 ± 16.8° vs. 54.3 ± 8.7°, respectively), \( F(1, 15) = 54.50, p < .001 \).

Spatiotemporal Outcomes

Figure 3 (panels A and B, two representative participants) depicts differences in velocity profiles when comparing the stroke-affected side to the less affected side. These differences include longer duration to achieve the five cycles of reaching in the stroke-affected side, \( F(1, 15) = 18.70, p = .001 \), but there was no difference between the forward reach versus return phase (reach vs. return), \( F(1, 15) = .19, p = .67 \). The average forward-reaching duration was 1.4 ± 0.7 s for the affected side compared with 0.8 ± 0.3 s with the less affected side. The return times were 1.4 ± 0.8 s for the more affected and 0.8 ± 0.4 s for the less affected side. Although there was no difference in peak velocities between sides (0.87 ± 0.3 m/s for the affected side compared with 0.97 ± 0.3 m/s), \( F(1, 15) = 3.60, p = .076 \), the peak velocities were significantly greater during the reaching phase compared with the return phase when simultaneously comparing both sides, \( F(1, 15) = 6.05, p = .026 \). The smoothness of the velocity profile was significantly different when comparing the number of zero-velocity crossings, with significantly more crossings when participants reached with their stroke-affected side (see panel C in Figure 3; at least five zero-velocity crossings required to complete the task). These zero-velocity crossings occurred when participants made contact with the targets and the additional crossings occurred when velocities fluctuated as participants reversed their reaching direction. The fluctuations at target contact were more prominent than the velocities remaining below a 5% peak velocity threshold, which would indicate a participant was resting or dwelling.
on the target. As illustrated in Figure 3, there was a negative correlation between degrees of elbow extension generated and zero-velocity crossings when reaching with the stroke-affected side (i.e., less joint motion, the greater number of zero-velocity crossings). This relationship is similar in magnitude to the association between zero-velocity crossings and the amount of trunk motion, such that movements were smoother if less trunk motion was used (see Table 3). All participants were able to make contact with the target with the fingertip and the variability in finger position at target contact was calculated as the variable error. Participants were more variable when reaching with the stroke-affected arm and hand (proximal target = 0.6 ± 0.4 cm; distal target = 0.5 ± 0.3 cm) compared with the less affected hand (proximal target = 0.4 ± 0.1 cm; distal target = 0.3 ± 0.2 cm), F(1, 15) = 15.80, p = .001.

**Muscle Activation Patterns**

Muscle activity was determined during four time domains and calculated as the RMS during the acceleration and deceleration phases of the reach and return. Figure 4 illustrates representative MAPs for the biceps, triceps, anterior deltoid, middle deltoid, posterior deltoid, and upper-trapezius. Figure 5 represents averages and upper-trapezius for the stroke-affected and less affected sides. Biceps muscle activity was significantly less in the stroke-affected side, F(1, 11) = 7.86, p = .017. Differences in muscle activity of the triceps depended on the phase of the reach (interaction), F(3, 42) = 3.80, p = .017, with significantly less activity in the stroke-affected side during the deceleration phase of the return movement, F(1, 14) = 6.88, p = .02. There was significantly less activity in the stroke-affected side in the posterior deltoid, F(1, 14) = 6.10, p = .027, which was most prominent during the return. There was a significant side-by-time interaction, F(3, 30) = 4.00, p = .017, in the MAP of the anterior deltoid with significantly less activity in the stroke-affected side during acceleration and deceleration of the reaching phase, F(1, 10) = 9.43, p = .012; F(1, 11) = 6.23, p = .03, respectively. There was significantly less middle deltoid amplitude in the stroke-affected side, F(1, 13) = 4.80, p = .048, in all phases of reach. Amplitude of contraction in the upper trapezius muscle did not differ significantly comparing sides, F(1, 11) = 3.30, p = .11.

Correlations between functional ability scores of the stroke-affected side, segmental contributions to reach, and MAPs of two muscles are presented in Table 3. The average FM score was 51.5 ± 11.1, with a range of 28–63. Participants did not exhibit any proprioception deficits in shoulder and elbow of the stroke-affected arm (data not included in FM score). The average number of blocks transported during the BBT was 21.9 ± 10.8, with a range of 4–44. The segmental contributions to reach (shoulder, elbow, and trunk ROM) were significantly correlated with the FM, BBT, and the overall reaching time during the kinematic task. Two muscles of interest (anterior deltoid and triceps) were significantly correlated with shoulder ROM and the BBT. Additionally, the anterior deltoid was significantly correlated with reaching time.

**Discussion**

This study established kinematic and spatiotemporal outcomes, and MAPs of CR in survivors of stroke in a task...
FIGURE 3. Spatiotemporal parameters of reach. Panels A and B illustrate wrist velocity profiles in two representative participants when reaching with the less affected stroke-affected sides. When comparing the stroke-affected side (right side of Panel A and B), the participant represented in Panel A had smoother accelerations and decelerations around target contact (which would occur at zero velocity). The positive velocities represent the forward-reaching phase and the negative represent the return phase. The stroke-affected side of Panel B represents a participant that was less able to reverse motion smoothly at target contact illustrated by the brief zero velocity between the peaks in positive and negative velocities. This participant also had lower peak velocities and required more time to complete the five reaching cycles. Panel C represents the relationship between the number of zero-velocity crossings (a metric of movement smoothness) with the amount of elbow extension. Elbow extension accounts for approximately 50% of the variance in movement smoothness such that participants with more elbow extension had smoother movements ($R^2 = .52$).

requiring continuous shoulder flexion and elbow extension without trunk restraint. This study extends the work of Prange, Jannink, et al. (2009) by investigating how survivors of stroke generate CR while determining the contribution of the trunk and characterizing a number of spatiotemporal parameters. We expected that movements would not be as smooth and coordinated when reaching with the stroke-affected side compared with the less affected side. Results indicated more trunk, and less shoulder flexion and elbow extension when reaching with the stroke-affected side. Participants with limited elbow extension on the stroke-affected side experienced the greatest degree of velocity profile irregularities. There was greater activation in the anterior deltoid during the reaching phase and posterior deltoid during the return phase when comparing less affected and stroke-affected MAPs. The triceps and anterior deltoid may have a distinct role in CR and functional ability evidenced by correlations with the kinematic and functional measures. These findings...
have direct clinical implications by fostering a better understanding among clinicians how interventions may target specific impairments through the therapeutic use of CR tasks. Our results highlight a number of interesting spatiotemporal characteristics of CR in stroke. Previous reports have suggested that survivors of stroke are unable to achieve similar peak velocities compared with neurologically intact controls when performing a discrete reaching task (Cirstea & Levin, 2000). Results from our study demonstrate that although movement durations were significantly longer in CR when reaching with the stroke-affected side compared with the less affected side, the peak velocities were not different. This suggests that survivors of stroke maintain some ability to accelerate but are not able to maintain faster movement speeds due to longer acceleration and deceleration phases. Alternatively, the longer reaching durations could have resulted from dwell times on the targets (partially observed in panel B of Figure 3). We do not feel target dwell times were a factor because the absolute velocities of participants with extended reaching durations fluctuated at the target contact rather than remaining below a threshold of 5% of the peak velocity for a period of time. More likely is that participants experienced greater difficulty in the reversal of the hand at target contact, which resulted in a greater number of zero-velocity crossings when using the stroke-affected side. Although there were more zero-velocity crossings when reaching with the stroke-affected side, approximately two-thirds of the sample fell within a similar range as the less affected side, suggesting that the majority of participants could more easily generate CR. Continuous reaching may be related to functional return of elbow extension and shoulder flexion as a greater ability to generate elbow extension was correlated with fewer irregularities in the velocity profile (see Figure 3), and both elbow range of motion and anterior deltoid MAP in acceleration for reach were correlated with a functional measure (BBT).

The consistency of spatiotemporal results with previous reports suggests that the cyclic nature of the task provided an adequate reaching structure for investigating how these movements are characterized in the stroke-affected side. Trunk contributions to reaching through anterior flexion and rotation reported here are consistent with previous literature describing discrete reaching tasks (Robertson & Roby-Brami, 2011), yet the present study extends the work of Prange, Jannink, et al. (2009) by precisely quantifying trunk motion during a cyclic task. Participants had more rotation when using the stroke-affected side (greater ROM), suggesting that is a compensatory trunk strategy during CR. In addition to the trunk contributions to reach, participants used less shoulder flexion and elbow extension when reaching with the stroke-affected side. One challenge is determining the specific impairment(s) causing these limitations. The traditional view of decreased ability to generate elbow extension was due to triceps weakness and possible impedance from antagonist hyperactivity of the biceps. We failed to detect hyperactivity of the antagonist muscle (biceps) during forward reach because the amount of biceps activity did not change over time and there was significantly less biceps activity on the stroke-affected side. Alternatively, triceps weakness or inability to generate triceps muscle activity may contribute to the altered segmental contributions. The only instance, however, of significantly less triceps activity in the stroke-affected side occurred during the deceleration phase of the return movement. Prange, Jannink, et al. suggested that triceps activity in the stroke-affected side had very low levels of activity throughout the reaching task compared with other MAPs including posterior deltoid. In reference to the leading joint hypothesis put forth by Dounskaia (2005), the low levels of triceps activity may result from the shoulder being the leading joint with relatively greater cyclic fluctuations for this type of task. Within this framework, triceps activity is an

### TABLE 3. Correlations Between Kinematic, Functional, and MAP Outcomes in the Stroke-Affected Side

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Reaching time</th>
<th>FM</th>
<th>BBT</th>
<th>Shoulder ROM</th>
<th>Elbow ROM</th>
<th>Trunk ROM</th>
<th>Ant delt (acc reach)</th>
<th>Triceps dec return</th>
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</thead>
<tbody>
<tr>
<td>Zero-velocity crossing</td>
<td>0.54* (16)</td>
<td>−0.60* (16)</td>
<td>−0.50* (16)</td>
<td>−0.50* (16)</td>
<td>−0.72* (16)</td>
<td>0.70* (16)</td>
<td>−0.30 (12)</td>
<td>−0.4 (15)</td>
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<tr>
<td>Reaching Time</td>
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<td>−0.53* (16)</td>
<td>−0.49* (16)</td>
<td>−0.61* (16)</td>
<td>−0.61* (16)</td>
<td>0.40 (16)</td>
<td>−0.58* (12)</td>
<td>−0.29 (15)</td>
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<tr>
<td>FM</td>
<td>−0.72* (16)</td>
<td>0.54* (16)</td>
<td>0.64* (16)</td>
<td>−0.70* (16)</td>
<td>0.54* (16)</td>
<td>0.25 (11)</td>
<td>0.43 (15)</td>
<td>−0.57 (15)</td>
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<td>BBT</td>
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<td>0.55* (16)</td>
<td>−0.48* (16)</td>
<td>0.55* (11)</td>
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<tr>
<td>Shoulder ROM</td>
<td>0.87* (16)</td>
<td>−0.81* (16)</td>
<td>0.46 (12)</td>
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<td>−0.29 (12)</td>
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<td>0.42 (11)</td>
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<tr>
<td>Elbow ROM</td>
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<td>0.46 (12)</td>
<td>0.55* (12)</td>
<td>−0.84* (16)</td>
<td>−0.63* (15)</td>
<td>0.42 (11)</td>
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<tr>
<td>Trunk ROM</td>
<td>−0.55* (12)</td>
<td>0.55* (12)</td>
<td>0.56* (15)</td>
<td>−0.63* (15)</td>
<td>0.42 (11)</td>
<td>0.63* (15)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note.* For each correlation, n is listed in parentheses. MAP = muscle activation patterns; FM = Fugl-Meyer; BBT = box and block test; ROM = range of motion. *p < .05.
important consideration for reaching tasks because it must incorporate interaction torques that result from the shoulder. We found that the ability to generate triceps activity in the return significantly correlated with performance on the BBT (see Table 3), which is intriguing because the BBT requires cyclic arm movements and the ability to activate the triceps muscle activity would benefit returning the arm to the retrieval side after the block had been released. The decreased ability to generate or utilize elbow extension also resulted in greater velocity profile irregularities. These findings support the concept that the ability to generate elbow extension is an important factor of motor control and function poststroke.

Although a single motor control theory or hypothesis has not prevailed, the relationships between kinematics and muscle activation are of interest for clinical researchers. As described previously, the leading joint hypothesis can add to the explanation of the differences in MAPs between the shoulder and elbow musculature. In comparison, the referent configuration hypothesis can be used to describe the interactions between central, biomechanical, and afferent components (St-Onge & Feldman, 2004). Muscle activation depends on the comparison of the actual configuration to the referent configuration, and the nervous system elicits movement by altering the referent configuration. In the context of the present study, the reversal in motion would occur because of a reversal in the referent configuration and muscle activation would result as a difference between the actual and referent configurations. The MAPs of the anterior deltoid and posterior deltoid did exhibit greater degrees of cyclic variations at the reversal of motion. This is consistent with previous studies (Prange, Kallenberg, et al., 2009; Prange, Jannink, et al., 2009). Of clinical interest, the anterior deltoid MAP significantly correlated with the amount of shoulder flexion, performance on the BBT, and reaching time during the kine- matic task (see Table 3). Functional ability and movement speed appear to be related to the ability to generate greater activity in the anterior deltoid. Future research should systematically investigate these relationships through carefully designed experiments or computer simulations. Potential experiments may include comparing MAPs generated in a computer simulation of forward reach compared with exper- imentally recorded values. Doing so may uncover potential

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**FIGURE 4.** Electromyography recordings from a representative participant for the stroke-affected and less affected sides. PD = posterior deltoid; AD = anterior deltoid; MD = middle deltoid; UT = upper trapezius.
Continuous Reaching in Stroke

FIGURE 5. Muscle activation patterns (MAPs) during cyclic reaching. (A) MAP for the biceps and triceps during cyclic reaching for the stroke-affected and less affected side. (B) The same characteristics for the anterior deltoid and posterior deltoid muscles. The MAP of the more proximal muscles illustrate the potential contributions of these muscles to cyclic reaching such that the anterior deltoid had greater activation during the reaching phase whereas the posterior deltoid had greater activation during the return phase. acc = acceleration phase; dec = deceleration phase; a = affected; l = less affected.

avenues for intervention to alter MAPs through training or augmentative approaches such as electrical stimulation.

Clinical Implications

The results of this study highlight two important clinical implications. First, the incorporation of CR tasks as screening measures may provide insight into the severity of the motor impairments following a stroke. The ability to generate CR requires constant and repetitive interaction between motor output, musculoskeletal system, and afferent feedback such that the demands are inherently different than a discrete reaching task. Better understanding the ability to generate continuous reach allows for more targeted interventions to improve the potential to incorporate the stroke-affected arm and hand in daily life. For example, slow performance on a CR task may suggest that MAPs are not sufficient to generate movement and could be targeted in an intervention. Second, the results emphasize reaching characteristics that should be considered within structured interventions that utilize CR tasks. Many of the traditional and newer movement therapies tend not to include CR tasks, which reduces the likelihood of integrating motor output with afferent feedback required for smooth coordinated movement. For example, traditional approaches like neurodevelopmental treatment (NDT) emphasize stability and tone reduction through stretching and weight bearing, whereas constraint-induced therapy often utilizes discrete movement tasks. A number of interventions, however, have incorporated cyclic reaching for survivors of stroke (Malcolm, Massie, & Thaut, 2009; Senesac, Davis, & Richards, 2010; Whitall, McCombe Waller, Silver, & Macko, 2000). Our results provide evidence that participants with mild to moderate impairments can accomplish CR without long dwelling periods at target contacts, yet used altered strategies when compared with the less affected side. Interventions, therefore, may need to consider and target these specific motor impairments within interventions that incorporate CR.

Limitations

This study is not without limitations. Participants presented with a level of motor function common in approximately 20% of the stroke population (Hakkennes & Keating, 2005), limiting the potential to generalize findings to survivors with severe motor deficits. One challenge in the field of stroke rehabilitation is the limited ability to characterize scapular movement with motion analysis. We minimized this limitation by characterizing the trunk contributions with greater specificity in relation to rotation, lateral flexion, and anterior flexion and by incorporating MAP of the shoulder region.

Conclusions

Mild to moderate motor control impairments in survivors of stroke did not limit the ability to generate CR, yet there were distinct strategy differences between the stroke-affected and less affected sides. Participants used more trunk rotation and had diminished MAP amplitudes in the proximal musculature (anterior and posterior deltoid) when comparing the stroke-affected to the less affected side, yet these reductions were less prominent in the biceps and triceps. The significant and moderately strong correlations linking functional to kinematic and MAP outcomes suggest that a CR task may be of benefit as a poststroke screening measure to determine the ability to generate continuous movement of the stroke-affected UE. These findings suggest that additional research investigating cyclic versus discrete reaching in survivors of stroke is warranted to aid in the refinement of UE interventions and updating the theoretical approaches to UE interventions.
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