Alterations in Reaching After Stroke and Their Relation to Movement Direction and Impairment Severity

Derek G. Kamper, PhD, Alicia N. McKenna-Cole, MS, PT, Leonard E. Kahn, MS, David J. Reinkensmeyer, PhD


Objectives: To examine the effects of stroke severity and target location on reaching (1) to identify regions in space that are difficult to reach, (2) to determine whether specific alterations in reaching are associated with particular clinical impairment levels, and (3) to characterize relationships between reaching alterations.

Design: Participants reached toward a screen of 75 targets spanning an approximate range from ±90° side to side and from waist to head.

Setting: Rehabilitation research center.

Participants: Sixteen chronic stroke patients with a wide range in residual arm function and 4 control subjects.

Interventions: Not applicable.

Main Outcome Measures: Chedoke-McMaster Stroke Arm Assessment, distance, velocity, smoothness, straightness, and direction of the hand path during each reach. Hand position trajectories were recorded with an electromagnetic sensor.

Results: Reaches performed with the impaired arms showed significant degradation in all performance measures. Although only modestly dependent on the target location, these features correlated strongly with impairment level, as well as with each other. Reaching distance showed the strongest correlations with the other parameters.

Conclusions: Stroke alters a broad array of features of reaching, yet largely the same degree of movement control is preserved across a range of target locations. The only consistently problematic task is to reach far out from the torso, independent of the movement direction. Thus, active range of motion (AROM), rather than control over a specific subset of movement directions, is a logical focus for therapy. In addition, measuring AROM is a simple clinical measure that yields much information.

Key Words: Arm; Cerebrovascular accident; Kinematics; Motor activity; Outcome assessment (health care); Rehabilitation.

© 2002 by the American Congress of Rehabilitation Medicine and the American Academy of Physical Medicine and Rehabilitation

Arm movement is commonly impaired after stroke, with approximately 80% of patients experiencing acute hemiparesis and approximately 40% experiencing chronic hemiparesis.1-3 This impairment limits manipulation of the surrounding environment and thus the functional use of the paretic arm.

Characterizing the features of reaching with the hemiparetic arm is important for rehabilitation practice and research. Quantification of specific parameters provides a way to measure natural recovery and treatment efficacy. Careful analysis also enables therapists to treat specific deficits, as well as furthering the mechanisms of impairment.

To this end, several studies have examined reaching in stroke subjects. Most studies have analyzed reaching with the arm supported and found that stroke subjects have decreased elbow velocity,4 decreased hand velocity,5 initial movement direction error,6 increased off-axis forces against the support surface,7,8 segmentation,5,9 and decreased movement distance and increased trajectory curvature.10 Other researchers have examined unsupported, free reaching toward a limited number of targets. Under these conditions, decreased velocity11-13 and increased segmentation11-13 were again evident, along with an increased path length of the hand trajectory.11

These studies left unanswered several fundamental questions. First, the effect of workplace location on reaching was largely unexplored because the studies limited reaching targets to a small fraction of the horizontal plane. It is conceivable that reaching performance could vary significantly over different portions of the reaching workspace. Thus, a key objective of our study was to determine if certain workspace regions are especially difficult to reach or are associated with degraded reaching quality, thereby indicating a need for special therapeutic considerations. Second, the effect of the level of clinical impairment on the different features of reaching has not been well described. It is conceivable that some of the features of reaching are associated with distinct levels of impairment. This would suggest a need for different treatment strategies for different impairment levels. Although Levin10 found significant correlations between motor impairment and several reaching indices, Archambault et al11 did not. However, both studies examined subjects with a limited range of motor impairments.

Finally, the possible relationships between the parameters used to describe reaching have not been well characterized. Previous studies have looked at movement speed,5,11-13 smoothness,9,11,13 distance,10 path length,14 and direction,6 but no one study has examined all of these parameters and their interrelationships. A better understanding of those relationships will give insight into underlying mechanisms of impairment.
In this study, we examined free reaching over many targets encompassing a large portion of the seated workspace. Twenty participants reached toward an array of 75 targets spanning an approximate range from $\pm 90^\circ$ side to side and from the waist to head high. Position and orientation of the hand during reaching were measured with an electromagnetic motion tracking system. Reaching performance was analyzed by examining an array of features of the hand movement, including range, speed, smoothness, and direction.

METHODS

Participants

Twenty subjects, 16 with chronic hemiparetic stroke and 4 nonimpaired persons, participated in the study. Stroke subjects were recruited from the outpatient clinics of the Rehabilitation Institute of Chicago, Chicago, IL, and had computed tomography or magnetic resonance imaging evidence of single-hemisphere involvement. The stroke subjects ranged in age from 30 to 85 years, in time postincident from 9 months to 6 years, and in arm impairment level from severe to mild. Criteria that excluded participation were cognitive dysfunction sufficient to limit comprehension of the experimental task, apraxia, and severe concurrent medical problems (including shoulder pain) sufficient to preclude repetitive reaching to targets across the workspace. Subjects gave informed consent in accord with the Helsinki Declaration, and the institutional review board of Northwestern University approved all procedures.

Experimental Protocol

Each subject’s upper-extremity impairment was rated by an experienced therapist by using the Stage of Arm section of the Chedoke-McMaster (CM) Stroke Assessment Scale, an evaluation tool that has high inter- and intrarater repeatability, as well as strong correlation with the Fugl-Meyer score.\textsuperscript{14-16} The 4 control subjects, aged 24 to 39 years, were unimpaired and thus were classified as Chedoke stage 7. The therapist also measured passive range of motion (PROM) for the shoulder, elbow, and wrist with a goniometer.

Subjects were asked to perform 150 reaching movements, 75 with the paretic arm and 75 with the contralateral arm. Although some studies have suggested varying degrees of involvement of both limbs after a left-sided cerebrovascular accident,\textsuperscript{17} all of our subjects used their contralateral arm regularly for functional tasks; thus, this arm served as a within-subject basis for comparison with the paretic arm. Each reach was directed at a target chosen at random from a set of 75 targets evenly spaced along 5 latitudinal meridians (rows) and 15 longitudinal meridians (columns) separated by $12^\circ$ in both directions, for spans of $48^\circ$ in latitude and $168^\circ$ in longitude (fig 1). The subject was positioned so that the sternoclavicular notch was aligned with the middle of the target area. The subject’s trunk was restrained with a 4-point harness,\textsuperscript{a} which allowed full scapular mobility. The subject’s wrist was splinted to prevent wrist flexion.

From an initial posture with the thumb against the umbilicus and the palm resting against the body, each subject was instructed to reach at a comfortable pace to a point as close as possible to the target without displacing the trunk, to maintain that position for 1 second, and to return to the starting position. Subjects were given periodic rest breaks to minimize fatigue. A Flock of Birds® sensor\textsuperscript{b} was attached to the dorsum of the hand to measure the position and orientation of the hand (fig 1). Care was taken to remove ferrous metals from the workspace of the sensor\textsuperscript{18}; the Flock of Birds readings were tested to be accurate to at least 1 cm.

Analysis

During each reach, hand position data were gathered at a sampling rate of 100 Hz and stored on a computer. These data were then digitally low-pass filtered forward and backward in time at 5 Hz with a 30th-order finite-impulse response filter to attenuate high-frequency noise without altering signal phase. Subsequent analyses used this filtered data. Multiple features of the hand paths were extracted to examine the range and quality of movement (summarized in table 1).

To estimate the attainable workspace, the smallest distance between the hand and the intended target was found for each reach trial. The trials involving the nonparetic arm (or dominant arm, in the case of a control subject) were examined first to locate the position for which the reach came closest to the target. By using the symmetry of the deployment of the targets, these positions could be reflected across the sagittal plane to serve as the putative desired positions (D) for corresponding reaches with the paretic arm. Data from a given trial with the paretic arm were searched to find the actual point ($A_p$) closest to the desired point ($D_p$). The distance from point $A_p$ to $D_p$ was divided by the distance from the starting position ($S_p$) to $D_p$. Subtraction of this fraction from 1 yielded the fraction-of-reach (FOR) measure, a measure of active range of motion (AROM) that is normalized to each subject’s arm length. Use of the FOR measure also helped to normalize reaching ability across all targets because certain targets were closer to the starting hand position than others. Theoretically, the FOR measure should approach 1 as the impairment diminishes.

$$\text{FOR} = 1 - \frac{\sqrt{(x_D - x_A)^2 + (y_D - y_A)^2 + (z_D - z_A)^2}}{\sqrt{(x_S - x_A)^2 + (y_S - y_A)^2 + (z_S - z_A)^2}}$$

Movement quality was assessed by computing linearity of movement, movement direction, peak speed, and the number of speed peaks. Linearity of hand motion was assessed by comparing the hand path traversed from the starting position to the location closest to the target with the straight-line distance between these 2 points. The distance actually traversed by the hand, calculated by finding the arc length of the hand path, was divided by the straight-line distance to obtain the path length ratio (PLR). Thus, a hand trajectory that followed a straight-line path to the target would have a PLR equal to 1, whereas a hand trajectory that traveled twice as far as needed would have a PLR of 2.

Control over movement direction was assessed by comparing the direction of hand movement of the paretic hand to the
Defined as the target location. The yaw angles for the paretic arm were used to describe the target yaw angle, with the endpoint hand when it had traveled 5 more centimeters. A yaw angle of the path length. The endpoint was defined as the position of the hand in the horizontal plane. The starting point for calculating the yaw angle was defined as the hand location at half the total path length. The endpoint was defined as the position of the hand when it had traveled 5 more centimeters. A yaw angle of 0 denoted a straight-ahead movement. The same starting point was used to describe the target yaw angle, with the endpoint defined as the target location. The yaw angles for the paretic arm and for the target were regressed to determine whether the hand was headed in the proper direction for the different targets. The root mean square value of the residuals of this regression was used to quantify movement direction variability (MDV).

Subjects were instructed to move at a comfortable speed. To determine how this speed differed between the paretic and nonparetic arms, the ratio of the peak speed for the paretic arm to that of the nonparetic arm for symmetrical arm and for the target were regressed to determine whether the impairment severity increased (table 2, fig 3). ANOVA results revealed that FOR increased with Chedoke stage with a linear contrast \( P=0.001 \). For Chedoke stages 4 and above, the achievable ROM approached that for the unimpaired arms, with FOR within 15% of that for the controls (stage 7).

AROM deficits, averaged across subjects, were fairly uniform across the space tested (fig 3, lower right). It was not typical for the AROM to be near normal for certain regions of the space, yet severely limited for others (for an exception, see subject F, fig 3). However, AROM did vary to some extent with location of the target in the workspace. Both the horizontal position of the target (ie, column, \( P<0.001 \)) and the interaction term between Chedoke stage and vertical position of the target (Chedoke stage \( \times \) row, \( P=0.021 \)) were significant in the ANOVA, with FOR increasing linearly with these terms. Thus, statistical trends existed for subjects to reach slightly further to ipsilateral targets, and for subjects in lower Chedoke stages to have more difficulty reaching to higher targets. Reaching up and across the body was the motion associated with the greatest reduction in active range. The mean FOR corresponding to reaches toward targets in the first 5 target columns and first 2 target rows (ie, up and across the body) was 20% less than that for reaches toward targets in the last 5 columns and last 2 rows (ie, down and outward from the body).

To determine how this speed differed between the paretic and contralateral arms (fig 2) revealed alterations in reaching with respect to hand movement distance, speed, smoothness, straightness, and direction. The impact of clinical impairment level and target location on each of these parameters follows.

Movement Distance

The FOR parameter indicated that AROM decreased as impairment severity increased (table 2, fig 3). ANOVA results revealed that FOR increased with Chedoke stage with a linear contrast \( P=0.001 \). For Chedoke stages 4 and above, the achievable ROM approached that for the unimpaired arms, with FOR within 15% of that for the controls (stage 7).

AROM deficits, averaged across subjects, were fairly uniform across the space tested (fig 3, lower right). It was not typical for the AROM to be near normal for certain regions of the space, yet severely limited for others (for an exception, see subject F, fig 3). However, AROM did vary to some extent with location of the target in the workspace. Both the horizontal position of the target (ie, column, \( P<0.001 \)) and the interaction term between Chedoke stage and vertical position of the target (Chedoke stage \( \times \) row, \( P=0.021 \)) were significant in the ANOVA, with FOR increasing linearly with these terms. Thus, statistical trends existed for subjects to reach slightly further to ipsilateral targets, and for subjects in lower Chedoke stages to have more difficulty reaching to higher targets. Reaching up and across the body was the motion associated with the greatest reduction in active range. The mean FOR corresponding to reaches toward targets in the first 5 target columns and first 2 target rows (ie, up and across the body) was 20% less than that for reaches toward targets in the last 5 columns and last 2 rows (ie, down and outward from the body).

Deficits in AROM were much greater than those measured in PROM for the stroke subjects. All had ostensibly normal

**Table 1: Description of Reaching Parameters**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Name</th>
<th>Quantification</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOR</td>
<td>Fraction of reach</td>
<td>AROM</td>
</tr>
<tr>
<td>PLR</td>
<td>Path length ratio</td>
<td>Straightness</td>
</tr>
<tr>
<td>PSD</td>
<td>Peak speed difference</td>
<td>Speed</td>
</tr>
<tr>
<td>NSP</td>
<td>Number of speed peaks</td>
<td>Smoothness</td>
</tr>
<tr>
<td>MDV</td>
<td>Movement direction variability</td>
<td>Directional control</td>
</tr>
</tbody>
</table>

**Fig 2.** Example of measured reaching trajectories. Data are from subject G (Chedoke 3) for the highest row of targets. Legend: thick lines, paretic arm; dashed, contralateral arm. Left arm data are flipped about the midline for comparison. Diagram of subject’s body is left out of back view for clarity, but X marks acromion and O the sternal notch.
passive elbow flexion and extension, and all but one had normal passive forearm pronation. Most of the loss of PROM involved the shoulder, especially external rotation of the shoulder. The mean deficit in passive external rotation, given a normal range of 90°, was $52° \pm 30°$. In comparison, the deficit for internal rotation was only $9° \pm 8°$. Mean passive shoulder flexion across the stroke subjects was $130° \pm 25°$ (out of 180°) and mean shoulder abduction was $93° \pm 24°$ (out of 120°).

**Movement Speed**

Although subjects were told to move at a comfortable speed rather than as quickly as possible, the self-selected speed of the paretic arm was typically slower than that of the contralateral arm.
limb. PSR increased with increasing Chedoke stage with a significant linear contrast ($P<.001$, table 2). For stages 2 to 4, mean peak speed of hand trajectory for the paretic limb was less than 70% of that for the nonparetic arm. This rose to more than 95% for the higher Chedoke stages.

Vertical target location did have a small but statistically significant influence on normalized reaching speed ($P<.03$). With the impaired arm, subjects reached fastest toward the lower targets and slowest toward the highest targets (linear contrast significant, $P<.02$). The magnitude of the effect, however, was relatively small; across all stroke subjects, the mean PSR was .61 for the highest row of targets and .69 for the lowest row, a difference of only 12%.

Movement Smoothness

Movements made by stroke subjects were less smooth. Typically, several peaks were present in the speed trajectory of the paretic limb, as opposed to the smooth bell-shaped velocity profiles of the nonparetic limb (fig 4). A linear contrast for NSP in Chedoke stage was significant ($P=.001$). Subjects at Chedoke stage 2 displayed an average total of 9.74 peaks in the velocity profile during the outward reaching and return movement, whereas subjects at Chedoke stages 5 and 6 had only 3.35 peaks. The NSP did not depend significantly on target location ($P>.36$).

Movement Straightness

The path length of the reaching trajectory was increased for stroke subjects, with their mean PLR being 32% greater than that of the controls (table 2). For the paretic limb, Chedoke stage had a statistically significant impact on PLR ($P=.023$), with mean PLR following the order of the Chedoke stage in accord with a significant linear contrast ($P=.005$). Target location did not have a significant impact on PLR ($P>.46$).

Movement Direction

All subjects showed significant linear regressions ($P<.05$) between the hand movement directions and the target directions, and the slopes of the regressions were not statistically different between Chedoke stages. Thus, the stroke subjects showed at least a degree of control of movement direction across the space described by the targets. Subjects at lower Chedoke stages did, however, show increased variability in movement direction. In particular, the root mean square of the residuals for the regressions increased with decreasing Chedoke stage with a significant linear contrast (ANOVA, $P<.05$; table 2).

Parameter Variances

Variances across the different Chedoke stages were not equal (table 2). Variance generally increased as the degree of clinical impairment increased. The effect on the statistical inferences, however, did not appear to be significant. For example, reduction of the disparity in variance by a reciprocal transformation of the data for PLR actually led to a slight reduction in the $P$ value for the effect of Chedoke stage ($\Delta P=.01$).

Relationships Between Kinematic Features

Although a given stroke subject typically performed better in some reaching features over others, there were general trends in performance across features. Correlation analyses performed across all possible pairs of reaching features across all stroke subjects revealed significant relationships between the features (table 3). The strongest correlations were seen with the AROM measure FOR.

### DISCUSSION

The 3 objectives of this study were to identify workspace regions that are problematic for reaching after stroke, to deter-
mine whether specific alterations in reaching are associated with particular clinical impairment levels, and to characterize interrelationships between reaching parameters across a range of impairment levels.

Regarding objective 1, our findings indicate that target location has a relatively minor effect on reaching deficits. The only significant dependencies on target location were for FOR and speed of motion, with reaching up and across the body being slightly more impaired than down and to the side. A likely explanation for this moderate decrease in AROM is restricted scapular motion, with the scapula often adducted and downwardly rotated after stroke as a result of hypertonus or hypotonus in muscles surrounding the shoulder. However, in agreement with the observations of Beer et al6 for smaller supported movements in the horizontal plane, overall our subjects preserved largely the same degree of control across a wide range of movement directions, and no one movement direction was particularly problematic. The only positions that were difficult to reach were those far away from the torso independent of the intended direction of the movement. Thus, AROM, rather than control over a specific subset of movement directions, is a logical focus for arm therapy.

Concerning objective 2, highly significant linear trends existed between the reaching parameters and stage of the arm portion of the CM Stroke Assessment Scale. Thus, specific altered features were generally not associated with particular clinical impairment levels but rather were continuously related. This finding suggests that the different alterations of reaching, such as reduced range, speed, smoothness, and increased movement direction noise, all typically require redress at all impairment levels after chronic hemiparesis.

As for the interrelationships between reaching parameters, significant correlations existed between the majority of the reaching parameters despite their diverse natures. The strongest correlations were with the FOR measure, which was used to quantify AROM. Because the CM Stroke Assessment Scale indirectly addresses AROM, its correlation with the reaching parameters is understandable. From a mechanistic viewpoint, the strong correlations between these diverse parameters suggest that these may share a common origin. For example, loss of descending motor drive may act to concomitantly cause decreased AROM, slowing, decreased smoothness, indirect hand paths, and initial errors in movement direction.

CONCLUSION

This study provides 3 important insights into poststroke arm assessment. First, the strong correlations between the CM Scale and the reaching parameters reinforce the mutual validity of these different assessment approaches. Second, the strong correlations also indicate that detailed quantification of hand-path features during reaching can provide a continuous measurement of reaching performance and thus should be useful in tracking natural recovery and therapeutic interventions. Third, the fact that the FOR parameter showed the strongest correlations with both Chedoke stage and the other parameters suggests that AROM is the single best summary assessor of reaching impairment. Thus, the measurement of AROM during reaching is a powerful clinical measure, rich with information, yet simple and quick to administer.

References

Suppliers
a. Dynaform™; Adaptive Engineering Lab Inc, PO Box 12930, Mill Creek, WA 98092.
b. Ascension Technology Corp, PO Box 527, Burlington, VT 05402.