7-2012

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Stacey L. DeJong
Washington University School of Medicine in St. Louis

Rebecca L. Birkenmeier
Washington University School of Medicine in St. Louis

Catherine E. Lang
Washington University School of Medicine in St. Louis

Recommended Citation
DeJong, Stacey L.; Birkenmeier, Rebecca L.; and Lang, Catherine E., "Person-specific changes in motor performance accompany upper extremity functional gains after stroke" (2012). *Physical Therapy Faculty Publications*. Paper 25.
http://digitalcommons.wustl.edu/pt_facpubs/25

Person-specific changes in motor performance accompany upper extremity functional gains after stroke

Stacey L. DeJong, PT, MS[1], Rebecca L. Birkenmeier, OTD, OTR/L[2], Catherine E. Lang, PT, PhD[1,2,3] [1]Program in Physical Therapy, [2]Program in Occupational Therapy, [3]Department of Neurology, Washington University School of Medicine, St. Louis, MO

sldejong@wustl.edu
birkenmeierr@wustl.edu
langc@wustl.edu

Corresponding author: Catherine Lang, PT, PhD
Program in Physical Therapy
Washington University School of Medicine
4444 Forest Park Avenue, Campus Box 8502
St. Louis, MO 63108
Phone: 314-286-1945
Email: langc@wustl.edu

Word count: Text: 5387
Abstract: 194

Abbreviated title: Changes in motor performance that accompany functional gains
Keywords: reach, grasp, kinematic, force

ABSTRACT

In animal models, hundreds of repetitions of upper extremity (UE) task practice promote neural adaptation and functional gain. Recently, we demonstrated improved UE function following a similar intervention for people after stroke. In this secondary analysis, computerized measures of UE task performance were used to identify movement parameters that changed as function improved. Ten people with chronic post-stroke hemiparesis participated in high-repetition UE task-specific training 3 times per week for 6 weeks. Before and after training, we assessed UE function with the Action Research Arm Test (ARAT), and evaluated motor performance using computerized motion capture during a reach-grasp-transport-release task. Movement parameters included the duration of each movement phase, trunk excursion, peak aperture, aperture path ratio, and peak grip force. Group results showed an improvement in ARAT scores ($p = 0.003$). Although each individual changed significantly on at least one movement parameter, across the group there were no changes in any movement parameter that reached or approached significance. Changes on the ARAT were not closely related to changes in movement parameters. Since aspects of motor performance that contribute to functional change vary across individuals, an individualized approach to upper extremity motion analysis appears warranted.

INTRODUCTION

Reduced upper extremity function is a devastating consequence of stroke. Of the nearly 800,000 people who experience stroke each year in the United States, 50% have persistent hemiparesis (Lloyd-Jones et al., 2010; Mayo et al., 1999), and hand function often remains limited, even in those with good overall recovery (Lai et al., 2002). Typically, within the first six months post-stroke, partial functional improvement occurs and is accompanied by compensatory movement strategies that develop either spontaneously or through rehabilitation that focuses on restoring function. Neuroscientific discoveries over the past several decades have shown that the brain undergoes a continual process of reorganization, strongly influenced by behavioral experience, in healthy individuals and particularly in those with recent neural injury (Kleim & Jones, 2008; Nudo et al., 2007). These discoveries have renewed interest in the idea that greater motor recovery may be possible after stroke, and that it may be possible to restore function through return of normal movement patterns instead of through compensatory strategies (Cramer, 2008; Krakauer, 2005; Kwakkel et al., 2004; Levin et al., 2009).

Repetitive training is a powerful behavioral stimulus for driving use-dependent neural adaptation in animals (Butefisch et al., 2000; Kleim et al., 2004; Monfils et al., 2005; Nudo et al., 1996), and in humans (Askim et al., 2009; Jang et al., 2003; Liepert et al., 2000; Schaechter et al., 2002). Rehabilitation protocols that include repetitive task-specific training can produce gains in upper extremity function early after stroke (Harris et al., 2009; Winstein et al., 2004; Wolf et al., 2006), and at later time points as well (Pang et al., 2006; Page et al., 2008; Platz et al., 2001; Taub et al., 2006). Important features of training include acquisition of skills that are salient for the individual, and repetition of the newly learned skills at an adequate intensity (Kleim & Jones, 2008).

Investigators have begun to explore changes in specific movement parameters that may result from task-specific training, and that may contribute to changes in function. For example, in a series of three cases, measures of grasp force and functional task performance both improved after six weeks of distributed repetitive practice (Conti & Schepens, 2009). In studies of constraint-induced movement therapy, four of five participants showed improved grasp force generation in a key-turning task (Alberts et al., 2004), and a group of eight participants showed faster, more coordinated arm movement (Caimmi et al., 2008). In four individuals, positive changes in kinematic variables and measures of muscle activity were reported following task-specific training designed to remedy each person's key movement impairments (Lum et al., 2009). Several research groups have shown improved shoulder and elbow movement and decreased compensatory trunk movement, after repetitive reaching practice with trunk restraint (Michaelsen et al., 2006; Thielman et al., 2008; Woodbury et al., 2009). These findings support the idea that functional gains after stroke can occur at least partially through recovery of normal movement patterns rather than compensation, and that evaluation of specific movement parameters may provide insights that are useful when selecting and progressing training tasks, and when describing how movement changes after intervention.

In attempts to better understand the movement problems that underlie loss of upper extremity function, numerous motor impairments have been studied in people with post-stroke hemiparesis. These include diminished muscle activation (Canning et al., 2000; McCrea et al., 2005; Wagner et al., 2007), reduced movement speed (Beer et al., 2000; Cirstea et al., 2003; Dewald & Beer, 2001; Lang et al., 2005; Levin et al., 1996; Reisman & Scholz, 2003; Wagner et al., 2007), synergistic movement patterns that constrain multijoint movements proximally and distally (Cirstea et al., 2003; Ellis et al., 2005; Lang & Beebe, 2007; Lang & Schieber, 2004; Li et al., 2003; Schieber et al., 2009), and related compensatory movements of the trunk (Cirstea & Levin, 2000; Levin et al., 2002; Roby-Brami et al., 2003). Moderate correlations have been demonstrated between several of these movement parameters and deficits in upper extremity function (Celik et al., 2010; Depietro et al., 2007; Ellis et al., 2008; Lang et al., 2006a; McCrea et al., 2002). It remains unclear, however, to what extent changes in specific movement parameters underlie the changes in function observed after task-specific training.

Recently, we studied the feasibility of implementing high-repetition doses of upper extremity task-specific training in people post-stroke, and questioned whether the high-repetition protocol would lead to gains in upper extremity function (Birkenmeier et al., 2010). Primary results demonstrated feasibility and functional improvement. The current investigation is a secondary analysis of outcome data collected during that study, in which we measured motor performance of a reach-grasp-transport-release task using computerized motion analysis methods. The purposes of this secondary analysis were to identify movement parameters that improved after training, and to determine whether improvements in upper extremity function were associated with improvements in specific movement parameters. Based on previous descriptions of stroke-related motor impairments and their relationships to function, we hypothesized that functional gains would be associated with decreases in movement time, trunk excursion, and inefficient finger movement, and with increases in thumb-finger separation (aperture) and grip force.

METHODS

Participants

People with hemiparesis due to stroke were recruited from the St. Louis metropolitan area via the Cognitive Rehabilitation Research Group Stroke Registry at Washington University and from local outpatient rehabilitation clinics. Potential participants were included if they had been diagnosed with stroke at least six months prior and had unilateral upper extremity hemiparesis, indicated by a score of 1, 2, or 3 on the Motor Arm item of the National Institutes of Health Stroke Scale (NIHSS). Potential participants were excluded if 1) they had ever been diagnosed with any other neurological or psychiatric condition, 2) they were participating in any other upper extremity stroke intervention (e.g. Botox), 3) they had NIHSS scores indicating insufficient cognitive ability or severe hemineglect (a score of 2 on the Questions item, 1 or 2 on the Commands item, or 2 on the Extinction and Inattention item), or 4) they did not anticipate being able to attend all study related appointments. During the 1-year period of the study, 27 people were screened, 15 were enrolled, and 13 completed the intervention and functional assessments. Ten of the 15 participants were assessed using the motion analysis procedures described in this report. All ten completed the training program, with 97 % attendance. The five enrolled participants who were not assessed using motion analysis included four who began training before motion analysis was added to the study protocol, and one who was unable to complete the initial phase of the assessment task. This study was approved by the Washington University Human Research Protection Office, and all participants provided informed consent before participation.

Intervention

The intervention consisted of supervised massed practice of upper extremity tasks, for three one-hour sessions per week for six weeks (Birkenmeier et al., 2010). During each session, participants were encouraged to perform at least 300 repetitions of task practice (3 tasks per session, ≥100 repetitions each). Each task included four movement components that are essential for most upper extremity functional tasks: reaching for, grasping, moving or manipulating, and releasing an object. In order to identify tasks that were relevant and motivating for each participant, the Canadian Occupational Performance Measure was administered by an occupational therapist during the first baseline assessment session (Dedding et al., 2004; Law et al., 1990). For each participant, three tasks were selected, adjusted for difficulty, and progressed throughout the study, in order to provide a training stimulus that was continually challenging but not overwhelming. Additional detail regarding the selection and progression of training tasks is provided elsewhere (Birkenmeier et al., 2010).

Assessments

The primary outcome measure, used to assess the benefit of the intervention was the Action Research Arm Test (ARAT). This criterion-rated test quantifies the ability to reach, grasp, manipulate, and release a variety of everyday objects. The ARAT consists of 19 items, with each item scaled on a 0-3 point scale (total score = 57). The ARAT is strongly correlated with timed tests of upper extremity function at multiple time points post stroke with absolute r values ranging from 0.87 – 0.95 (Lang & Beebe 2007; Beebe & Lang 2009). It is clinically useful because of its low testing burden and strong psychometric properties (Beebe & Lang 2009; Lang et al., 2006a; Lyle, 1981; Van der Lee et al., 2001; Yozbatiran et al., 2008). The ARAT was administered on the affected side during three baseline assessment sessions one week apart, and at the end of the six-week intervention. For descriptive purposes, spasticity of the elbow flexors was assessed on the affected side during the first baseline session, using the modified Ashworth scale (Bohannon & Smith, 1987). We also measured maximal grip force bilaterally, using a Jamar grip dynamometer and the method described by Fess (1992).

Motor performance of the affected upper extremity was assessed using computerized motion analysis of a reach-grasp-transport-release task, during the last baseline session and at the end of the intervention. All participants performed the same task, which involved reaching for an object on a table, grasping it with a palmar grip, lifting it onto a shelf, and releasing it, with the goal of completing the task *as quickly as possible* (Figure 1A). None of the participants practiced the assessment task during the intervention. In choosing the assessment task, we tried to accommodate a wide range of motor abilities and to minimize floor and ceiling effects. We considered the chosen task relatively easy, and thought that potential participants who met our study criteria and could participate in the intervention would also be able to complete ten trials of the assessment task. At the same time, we believed that the task would be responsive to change, since improved motor performance could be reflected in measures of movement time, excursion, efficiency, and grip force, each of which has a continuous scale.

The object to be grasped (seen in Figure 1A) consisted of a custom-fabricated vertical cylinder (3.4 cm diameter, 11.3 cm height) attached to a rectangular base (13.5 cm by 6 cm) that was designed to hold a Tekscan I-scan electronic interface (Tekscan, Inc., South Boston, MA). The cylindrical portion of the object was covered with a Tekscan pressure sensor (I-scan model 5101/3414TI/10, 111.8 x 111.8mm, 1936 sensels, spatial resolution of 15.5 sensels/cm^2). Combined weight of the object, sensor and electronics was 420 grams (4.12 N). Pressure data were collected at 100 Hz.

Measurement of grip force is a novel use of pressure sensor technology. This method was chosen instead of a more typical strain gauge system because it does not require that participants place their hand or fingers on specific locations, and instead allows for more natural grasping performance. A disadvantage of the pressure sensor system is that it only measures grip forces (normal forces) and is unable to measure load forces (shear forces). For use in this study, we believed that the advantage of capturing natural movements outweighed the disadvantage of limiting our force analysis to grip (i.e. normal) forces. Psychometric properties of this grip force measurement method have not been reported.

Three dimensional movement of the affected upper extremity was captured at 50 Hz using an electromagnetic tracking system (MotionMonitor, Innovative Sports Training, Chicago, IL). Seven sensors were attached to the trunk and the affected upper extremity, as follows: 1) trunk: midline below the sternal notch, 2) upper arm: proximal to the lateral epicondyle, bisecting the upper arm mass, 3) forearm: midpoint between the radial and ulnar styloids on the dorsum of the forearm, 4) hand: midpoint of the third metacarpal on the dorsum of the hand, and 5 through 7) thumb, index and middle fingers: on the nail of each digit.

Participants were seated in a chair with back support, and a table was placed with its closest edge across the participant's mid-thighs. Table height was adjusted so the surface was approximately 10 cm above the thighs. For each participant, equal table height for the pre- and post-training assessments was ensured. A 25 cm high shelf was placed on the table, at a distance from the participant equal to 90% of the length of the arm from shoulder to wrist, and the center of the shelf was aligned with the mid-clavicle in the frontal plane. The object to be grasped was placed on the table, near its closest edge, also aligned with the mid-clavicle.

Prior to each trial, the participant was instructed to rest both hands in their lap with thumb and fingers together, wait for the word 'go', then use their affected limb to reach and grasp the object with a palmar grip, lift it and place it on the shelf, then release and return their hand to their lap (Figure 1A). They were asked to perform the movement as quickly as possible while still successfully completing the task. Verbal instructions and demonstration were provided. Ten trials were recorded, with approximately ten seconds of rest between trials. We limited each trial to ten seconds, since preliminary testing had shown that healthy adults consistently performed the task in less than two seconds. Onset of data collection was electronically triggered, ensuring synchronization of the Tekscan and MotionMonitor systems. Video was also recorded during each testing session.

Analysis

Pressure data were converted to grams of force, using Tekscan software to multiply recorded pressure by the sensor's spatial area. After low-pass filtering of kinematic data at 6 Hz using a second-order Butterworth filter, sensor position data were extracted using MotionMonitor software (Innovative Sports Training, Chicago, IL). Video recordings were used to verify whether each movement phase was successfully completed during each trial. Subsequent analysis was then completed using custom software written in MATLAB (The MathWorks, Inc., Natick, MA).

Durations of the reach, grasp, transport, and release phases were determined based on hand velocity, force on the object, and object position, as follows (Figure 1B). The reach phase began when velocity of the hand sensor first exceeded 5 mm/s, and ended when force on the object first exceeded 5 grams. The grasp phase began at the end of the reach, and ended when the vertical position of the object increased by 3 mm from its initial value. The transport phase began at the end of the grasp, and ended when the vertical position of the object was first within 3 mm of its final stable value. Duration of the release phase was calculated as the difference in time between the end of transport, and the time when force on the object returned to within 5 grams of its baseline value. In some cases, force returned to baseline prior to the object reaching a final stable position. In these cases, the calculated duration of the release phase was negative, indicating release of the object before it was placed securely on the shelf. In other cases, the object reached a stable position before force returned to baseline, yielding a positive release phase duration.

Other variables of interest included trunk excursion, peak aperture, aperture path ratio, and peak grip force. Trunk excursion was determined separately for the reach phase and for the transport phase, and was defined as the difference between the maximum and minimum resultant trunk sensor positions. Trunk excursion values close to zero represented normal performance, and higher values indicated compensatory trunk movement. Peak aperture was the maximum three-dimensional distance between sensors on the thumbnail and the index fingernail during the reach phase. Aperture path ratio quantified the smoothness/efficiency of thumb and index finger movement during the reach phase, and was calculated as follows (modified from Lang et al., 2005 and Lang et al., 2006b):

$$\frac{\text{(Sum of the absolute values of all changes in aperture during the reach phase)}}{\text{(Peak aperture – aperture at beginning of reach) + (Peak aperture – aperture at end of reach)}}$$

An aperture path ratio equal to one indicates smooth and direct separation of the thumb and index finger to the maximum aperture value, followed by smooth and direct closing onto the object. Higher values indicate abnormal, inefficient opening and closing of the thumb and index fingers, typically seen when participants make multiple attempts to open their hand and then close it on the object. Peak grip force was defined as the maximum force applied to the object during the transport phase.

Variables were calculated separately for each trial. Kolmogorov-Smirnov tests were used to test whether data was normally distributed within and across participants. Since all data met the normality assumption ($p > 0.05$), parametric statistics were used. Statistically significant pre-post changes for each participant were identified individually using paired t-tests to compare the ten pre-training trials to the ten post-training trials. For analysis of group results, each participant's performance was represented by the mean value for each variable across the ten trials within each assessment session. Pre-post changes for the group were identified using paired t-tests. Statistica software was used for all statistical analyses (Version 6.1 Statsoft Inc., Tulsa, OK), and the criterion for significance was set at $p < 0.05$. Given the numerous comparisons required for individual and group analysis of movement parameters, we also noted pre-post differences that were statistically significant using a more stringent Bonferroni-adjusted p value of 0.0005. Effect sizes and estimated sample sizes that would have been needed to detect significant pre-post differences for each movement parameter were derived from change scores (mean change/SD of change) using a paired t test design and assumptions that power = 0.80 and 2-tailed alpha = 0.05. Pearson product moment correlation coefficients were used to examine relationships between changes in UE function (post-training ARAT score minus the mean of the three baseline ARAT scores) and changes in each movement parameter (post-training mean minus pre-training mean). Correlation coefficients were considered low when $r < 0.50$, moderate when r was between 0.50 and 0.80, and high when $r > 0.80$.

In order to facilitate interpretation of the movement parameter data, values are reported for a group of twelve healthy controls (6 males, 6 females, 10 right handed, 2 left handed) who performed a similar task in our laboratory. The controls had an average age of 52.4 years (std. dev. 15.7), had no current or prior neurological diagnosis, and had no history of musculoskeletal disorders involving either upper extremity. Using one randomly selected side (7 dominant, 5 non-dominant; 7 right, 5 left), they performed a reach-grasp-lift task that was identical to the task used in the current study, except that instead of placing the object on a shelf and releasing it, they lifted it and held it approximately 10 cm above the table for 5 seconds. As a result, normative data are available for most of the movement parameters included in the current study, but are not available for transport duration, release duration, and trunk excursion during transport. Methods for collecting and analyzing the control data were identical to the procedures used in the current study, including the instruction to perform the task as quickly as possible.

Reliability of upper extremity kinematic measures has been investigated recently in healthy individuals and people with post-stroke hemiparesis. Excellent test-retest reliability has been reported for reach duration (Pearson $r > 0.90$) in healthy controls reaching at their self-selected speed (Caimmi et al., 2008). In a study of people with post-stroke hemiparesis performing reaching movements, reliability estimates for reach duration ranged from poor to excellent, depending on the speed of movement and the height of the reaching target (Wagner, et al, 2008). In a recent evaluation of a reach-to-grasp task that resembled the task used in the current study, Patterson et al. (In press) reported excellent reliability for reach duration, peak aperture, and trunk excursion ($r > 0.75$) in a group of people with hemiparesis after stroke. The smallest amount of change that exceeds measurement error and can be considered real change (minimal detectable change, 90% confidence), was estimated to be 280 milliseconds for reach duration, 5 millimeters for peak aperture, and 36 millimeters for trunk excursion. Reliability and minimal detectable change have not been investigated for the other movement parameters used in this study.

Results

Characteristics of the participants are shown in Table 1. For the six females and four males included in this study, time since stroke varied widely from six months to ten years. Five participants had right hemiparesis and five had left hemiparesis. In six participants, the affected side was their dominant side. All except one were right handed.

Individual and group results are reported for the ARAT and movement phase durations in Table 2, and for all other movement parameters in Table 3. In Tables 2 and 3, each of the 10 participants (R005 through R015) is represented by two rows, one for the pre-training data (upper row) and one for the post-training data (lower row). Pre- and post-training group means are presented in the bottom rows of tables 2 and 3, along with the number of participants included in each mean.

Pre-training ARAT scores ranged from 9 to 43 (mean 25.4 ± 11.3 SD). Changes on the ARAT ranged from 0 to 19 points. For the group of 10 participants included in this analysis, upper extremity function increased significantly after training, as indicated by an average ARAT score increase of 8 points ($p = 0.003$). The average improvement of 8 points exceeded the 4-point minimal detectable change for this measure (Lin et al., 2009), and exceeded the 6-point estimate of minimal clinically important difference for people with chronic post-stroke hemiparesis (van der Lee et al., 1999).

In Tables 2 and 3, each participant's mean pre-training and post-training values are reported for each movement parameter, averaged across all trials for which the movement parameter could be determined. The number of trials included in each mean is also reported. Although 10 trials were attempted during each assessment session, in some cases the participant did not complete all phases of the task, resulting in $n < 10$ for certain movement parameters. For example, when the reach phase was not completed, no movement parameters could be calculated (e.g. 2 of the 10 pre-training trials for R007), and when the transport phase was not completed, trunk excursion during transport could not be calculated (e.g. 3 of the 10 pre-training trials for R007).

Pre-training data showed impaired motor performance. In all participants, mean values for reach duration, grasp duration, and trunk excursion during the reach phase exceeded mean control values. Aperture path ratio exceeded the control mean for all except one participant (R010). Most participants also showed diminished peak aperture and diminished peak grip force. Exceptions included R005 and R011, whose peak apertures exceeded the control mean, and R008 and R012, whose peak grip force exceeded the control mean.

After training, eight of the ten participants showed an improvement in at least one movement parameter, indicated by a change toward the mean value for healthy controls when available, or by a decrease in transport phase duration, a decrease in trunk excursion during transport, or release duration closer to zero. Examples of improvements are illustrated in Figure 2, including a decrease in trunk excursion during the reach phase for R010 and a decrease in aperture path ratio for R014. In six of the ten participants, at least one movement parameter changed in the opposite direction, away from the control mean, possibly representing compensatory movement strategies. Examples include increased reach duration for R005, R010, and R011, and increased trunk excursion during the reach phase for R007, R011, and R012. Of the eight participants who gained at least four points on the ARAT, two showed only improvements in movement parameters (R014, R015), four showed a combination of improvements and compensatory changes (R005, R007, R008, R010), and two showed only compensatory changes (R011, R012).

In some cases, changes in movement parameters were consistent with changes in upper extremity function. For example, participant R014 improved by 9 points on the ARAT, with faster completion of the reach, grasp, and transport phases, lower aperture path ratios during the reach, increased peak grip force, and decreased trunk excursion during the transport phase. R009 showed little change on the ARAT, and also showed no advantageous changes in movement parameters other than a 5 mm increase in peak aperture. In participant R015, however, large improvements in the reach, grasp, and transport phase durations occurred despite a modest functional gain. The participant with the largest functional improvement (R005) showed small improvements in trunk excursion during reaching and in the timing of object release. Reach duration, however, increased slightly and grip force was further diminished after training. These examples suggest that functional gains are not necessarily reflected in movement parameter changes, and vice versa.

Despite the improvement in upper extremity function, group results revealed no significant changes in any of the movement parameters ($p > 0.20$). Highly variable performance across participants kept the mean pre-post differences from reaching statistical significance. Effect sizes were calculated as the mean change score divided by the standard deviation of change scores (bottom row of Tables 2 and 3). While the effect size was very large for the ARAT, effect sizes for the movement parameters were small to moderate. Accordingly, much larger sample sizes would be required in order to detect statistically significant changes in the movement parameters.

Across individuals, no consistent pattern emerged linking specific movement parameters to changes in function. Changes in ARAT scores and ARAT subscores were not highly correlated with changes in movement parameters (Table 4). The only statistically significant correlation was between the grasp subscale and the aperture path ratio ($r = -0.67$, $p < 0.05$).

Discussion

It is logical to think that improvements in upper extremity function after task-specific training would be produced by changes in certain measurable aspects of motor performance. Our data support this idea at the level of the individual participant, but not at the group level. Each participant's motor performance changed as they achieved greater function, and such changes were identified using a set of movement parameters that quantified different aspects of motor performance. Numerous significant changes were observed within individuals, including improvements toward more normal motor performance, as well as changes in the opposite direction, possibly representing compensation. Several participants demonstrated improvement in some movement parameters and compensatory changes in others.

The appreciation of change, however, was lost in the group analysis. Reasons for the lack of significant group findings include the low effect sizes for most movement parameters, and the small number of participants. Post-hoc power analyses showed that effect sizes were much lower for all movement parameters than for the ARAT score, and that a large sample size would be required for most of the observed movement parameter effects to reach statistical significance. Exceptions include the transport and release phase duration effects, which would have reached significance with a sample size of 21. Since effect size is diminished by high variability between-participants, it is likely that the heterogeneity of participants in this study contributed to the lack of significant group findings. Severity of motor deficits, in particular, is known to be strongly negatively correlated with motor recovery after stroke, and likely limited the effect sizes observed in this study. Additional factors may have also contributed, including other participant characteristics such as time since stroke and/or lesion location, measurement error, and individual differences in terms of which movement parameters changed and in which direction. Statistical power in this study was not sufficient to conclude that any movement parameters fail to change with intervention or with functional improvement. Our findings do show, however, that changes in specific movement parameters may not be large enough and consistent enough to show change across a small group, even when functional gains are significant across the group.

An important finding in this study is the lack of strong relationships between upper extremity functional gains and changes in specific movement parameters. Correlation analysis illustrates that none of the movement parameters included in this study is a suitable substitute for the measurement of upper extremity function as an outcome of intervention. Rather, motion analysis is a useful tool for studying how function improves, through restoration of normal movement patterns, development of compensatory strategies, or through a combination of the two. As discussed by Lum et al. (2009), principle components analysis, confirmatory factor analysis, and structural equation modeling hold promise as alternative methods to analyze motor performance, but their application to upper extremity rehabilitation studies is currently limited because of the large sample sizes required and the need for further theoretical understanding about upper extremity kinematic analysis.

The lack of strong relationships between functional gains and changes in movement parameters suggest that, to some extent, the two assessments measure different constructs. This highlights the importance of matching assessment tools to the purpose of research studies. For example, in clinical trials where the goal is to assess effectiveness of intervention aimed at improving upper extremity function, we suggest that measures of function should serve as the primary outcome. Motion analysis is clearly useful, however, in studies that seek to distinguish between restoration of normal movement and development of compensatory movement strategies, and in studies of intervention aimed at improving specific movement problems. Given the numerous changes within individuals and the lack of significant group changes in this study, we further suggest that an individualized approach to upper extremity motion analysis may be optimal in studies that explore changes in motor performance. For example, baseline motion analysis could be used to identify each person's most limiting movement problems and then to develop an individualized task-specific training program to address those specific deficits. Post-training motion analysis could then be used to evaluate outcomes. Group analysis is clearly useful when all group members share a common movement problem that is the target of intervention.

Several limitations should be considered when interpreting our data. First, this study included a small, heterogeneous sample of people with hemiparesis that varied in terms of severity and time since stroke. Further, the intervention was individualized and was aimed at improving function rather than improving specific movement parameters. While more stringent recruiting criteria and a more focused intervention may have yielded more significant group results, our study closely paralleled the circumstances encountered in clinical settings and in many other studies of upper extremity rehabilitation. Given the small sample size in this study, we were unable to explore the effects of participant characteristics on responsiveness to intervention. Larger studies are needed to investigate whether initial movement problems, lesion location, and time since stroke affect the magnitude or type of changes seen in movement parameters after training.

For certain variables, interpretation of our results is limited by a lack of control data and reliability estimates. It is not clear how long the transport and release phases last in healthy individuals, and the amount of trunk excursion that typically occurs during the transport phase is unknown. Nevertheless, it is reasonable to assume that in people with hemiparesis, a faster transport phase with less trunk excursion represents better upper extremity performance, so the desirable direction of change is fairly clear. Similarly, release durations that approach zero can be considered advantageous, indicating that release of grip force closely coincides with placement of the object securely on the shelf. Although the minimal detectable change is unknown for several of the movement parameters we studied, statistically significant pre-post changes in those variables were quite large, exceeding a 50% change in 17 of 24 instances, and exceeding a 20% change in all instances.

In summary, our results suggest that changes in motor performance after training vary across individuals, and that group analysis of movement parameters can obscure significant changes within individuals, particularly in small samples. After high-repetition task specific training, upper extremity function improved, and each participant changed significantly on at least one variable that quantified timing, movement or grip force. None of the movement parameters, however, changed significantly across the group, and improvements in upper extremity function were not closely related to changes in any of the movement parameters. Since functional assessments and measures of motor performance can produce different results, outcome measures used in research studies should be carefully selected depending on the purpose of the study. Our findings further suggest that an individualized approach to upper extremity motion analysis may be more informative than group designs when exploring changes in motor performance.

Acknowledgements: This work was supported in part by HealthSouth Corporation, the Missouri Physical Therapy Association, the Foundation for Physical Therapy (SLD), NIH K01HD047669 (CEL), NIH R01HD055964 (CEL), and NIH T32HD007434 (SLD).

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Figure Captions

Figure 1: Assessment of motor performance. A) Illustration of the experimental set-up and a participant performing the reach-grasp-transport-release task. B) Example data from one trial. Vertical dashed lines demonstrate division of the task into movement phases. The reach phase began when hand velocity exceeded 5 mm/sec, the grasp phase began when grip force exceeded 5 grams, the transport phase began when the vertical position of the object increased by 3 mm, and the transport phase ended when the vertical position of the object returned to within 3 mm of its final resting position. Duration of the release phase was calculated as the difference in time between the end of transport, and the time when force on the object returned to within 5 grams of its baseline value.

Figure 2: Examples of improvements in movement parameters in individual participants. A) After training, R010 showed decreased trunk excursion during the reach phase. Ten pre-training trials and ten post-training trials are shown. B) After training, R014 showed improved efficiency of finger movement, seen as a smoother aperture trace and quantified by a decrease in the aperture path ratio (see Methods). Reach duration also decreased. One representative trial is shown for each time point.

Tables

Table 1 Characteristics of participants

Participant	Age (years)	Months post-stroke	Spasticity §	Grip Strength §§	
				Affected side (kg)	Affected side as % of less affected side
R005	44	6	1	14	47
R007	55	120	3	15	61
R008	28	48	0	11	43
R009	57	18	3	10	25
R010	50	48	0	22	65
R011	65	36	2	6	22
R012	56	57	4	12	25
R013	57	36	1	10	43
R014	90	48	4	15	58
R015	33	22	1	17	34
Mean ± SD	54 ± 17	44 ± 31	1.9 ± 1.5	13.2 ± 4.4	42.3 ± 13.9

§ Elbow flexors were assessed on the affected side using the Modified Ashworth Scale.

§§ Maximum isometric grip strength assessed with a Jamar grip dynamometer

Table 2 Changes in ARAT scores and movement phase durations

		ARAT	Reach Duration (msec)		Grasp Duration (msec)		Transport Duration (msec)		Release Duration (msec)	
Healthy Controls mean ± 1 SE		57 ± 0	425 ± 17		236 ± 14		not available		not available	
Participant			mean	n	mean	n	mean	n	mean	n
R005	Pre	38	**442**	10	314	10	964	10	**186**	10
	Post	57	**548 ‡**	10	263	10	935	10	**-122 ‡**	10
R007	Pre	20.3	1050	8	**365**	8	2196	7	590	7
	Post	28	1060	10	**281 ‡**	10	2762	10	1153	10
R008	Pre	43	**558**	10	**327**	10	**2630**	10	**-1647**	10
	Post	56	**379 †**	10	**157 †**	10	**740 †**	10	**-15 †**	10
R009	Pre	9.3	3870	10	2127	9	2550	2		0
	Post	11	2646	7	1483	7		0		0
R010	Pre	40	**593**	10	325	10	**2334**	10	**-1455**	10
	Post	53	**963 †**	10	302	10	**1412 ‡**	10	**-11 †**	10
R011	Pre	26.7	**1692**	10	447	10	4011	7	-641	7
	Post	31	**2466 †**	10	666	10	2477	7	63	7
R012	Pre	20	2004	10	1359	10	**2910**	9	909	8
	Post	24	1794	10	1754	10	**3764 ‡**	9	400	9
R013	Pre	15	1491	10	**497**	10	3990	1	-220	1
	Post	15	1516	10	**827 †**	10		0		0
R014	Pre	22	**2022**	10	**1435**	10	**3811**	7		0
	Post	31	**1367 †**	10	**681 ‡**	10	**1893 ‡**	10	1485	10
R015	Pre	20	**3664**	10	**2194**	5	**2114**	5	-550	1
	Post	24	**1803 ‡**	9	**356 ‡**	9	**1427 ‡**	9	-312	9
Group	Pre	**25**	1739	10	939	10	2751	10	-354	8
	Post	**33 ***	1454	10	677	10	1926	8	330	8
	Effect size (Est. N)	1.61 (6)	0.37 (60)		0.39 (54)		0.65 (21)		0.66 (21)	

* Post > Pre, p = 0.003

Bold type indicates individual or group pre-post differences that were statistically significant at the p < 0.05 level (‡) or at the p < 0.0005 level (†). Note that some significant changes were in the unexpected direction (e.g. increased reach phase duration for R005, R010, R011). For R005 through R015, n represents the number of trials included in the individual's mean. Where n < 10, the participant was unable to complete the movement phase during every trial. For Group results, n represents the number of participants for whom data were available. The pre-training ARAT score is the mean of three baseline tests each separated by one week. The post-training ARAT score is from one test administered at the end of the training program. The effect sizes and estimated sample sizes (Est. N) are from post-hoc power analyses for each parameter (see Methods).

Table 3 Changes in movement parameters

		Reach Phase						Transport Phase			
		Trunk Excursion (mm)		Peak Aperture (mm)		Aperture Path Ratio		Trunk Excursion (mm)		Peak Grip Force (g)	
Healthy Controls mean ± 1 SE		4 ± 2		125 ± 3		1.13 ± 0.04		not available		5659 ± 1629	
Participant		mean	n	mean	n	mean	n	mean	n	mean	n
R005	Pre	**16**	10	145	10	1.29	10	9	10	**3745**	10
	Post	**4** ‡	10	124	10	1.11	10	18	10	**1464** ‡	10
R007	Pre	**11**	8	82	8	1.55	8	20	7	3075	8
	Post	**33** ‡	10	77	10	1.35	10	18	10	3739	10
R008	Pre	**10**	10	101	10	**3.60**	10	**45**	10	**6930**	10
	Post	**1** ‡	10	103	10	**1.08** †	10	**5** †	10	**3321** ‡	10
R009	Pre	31	10	**100**	10	2.24	10	29	2	797	10
	Post	20	7	**105** ‡	7	2.02	7		0	610	7
R010	Pre	**64**	10	102	10	1.13	10	**109**	10	**2084**	10
	Post	**13** †	10	93	10	1.40	10	**38** †	10	**3620** ‡	10
R011	Pre	**23**	10	162	10	1.76	10	53	7	4643	10
	Post	**64** †	10	171	10	2.09	10	62	7	4347	10
R012	Pre	**105**	10	99	10	**1.39**	10	42	9	7323	10
	Post	**124** ‡	10	105	10	**2.02** ‡	10	103	9	7169	10
R013	Pre	**67**	10	**92**	10	1.70	10	68	1	**1176**	10
	Post	**27** ‡	10	**62** ‡	9	2.00	10		0	**751** †	10
R014	Pre	15	10	119	10	**2.12**	10	**37**	7	**2091**	10
	Post	12	10	121	9	**1.56** ‡	10	**17** ‡	10	**3466** ‡	10
R015	Pre	105	10	**45**	10	3.67	10	82	5	2566	10
	Post	97	9	**59** ‡	9	3.72	9	77	9	1276	9
Group	Pre	45	10	105	10	2.04	10	49	10	3443	10
	Post	39	10	102	10	1.84	10	42	8	2976	10
	Effect Size (Est. N)	0.19 (220)		0.20 (199)		0.24 (139)		0.19 (220)		0.29 (96)	

Bold type indicates individual or group pre-post differences that were statistically significant at the $p < 0.05$ level (‡) or at the $p < 0.0005$ level (†). Note that some significant changes were in the unexpected direction (e.g. increased trunk excursion during reach for R007, R011, R012). For R005 through R015, n represents the number of trials included in the individual's mean. Where $n < 10$, the participant was unable to complete the movement phase during every trial. For Group results, n represents the number of participants for whom data were available. The effect sizes and estimated sample sizes (Est. N) are from post-hoc power analyses for each parameter (see Methods).

Table 4 Correlations between changes on the ARAT and changes in movement parameters

	Total Score	Grip Subscale	Grasp Subscale	Pinch Subscale	Gross Movement Subscale
Reach Duration	0.32	0.22	0.12	0.43	0.31
Grasp Duration	0.08	-0.12	-0.14	0.30	0.27
Transport Duration	-0.11	-0.16	-0.37	0.03	0.15
Release Duration	0.19	0.21	0.31	0.14	-0.05
Trunk Excursion during Reach	-0.19	-0.25	-0.06	-0.10	-0.29
Peak Aperture	-0.10	<0.01	0.10	-0.17	-0.35
Aperture Path Ratio	-0.41	-0.17	-0.67 *	-0.36	-0.28
Trunk Excursion during Transport	-0.45	-0.60	-0.46	-0.24	-0.16
Peak Grip Force	-0.29	0.05	-0.39	-0.36	-0.42

* The only correlation that reached statistical significance was between the Grasp Subscale and the Aperture Path Ratio. For transport duration, trunk excursion during transport, and release duration, $n = 8$ and $p < 0.05$ when $r > 0.62$. For all other movement parameters, $n = 10$ and $p < 0.05$ when $r > 0.55$ (one-tailed).

Figures

Figure 1

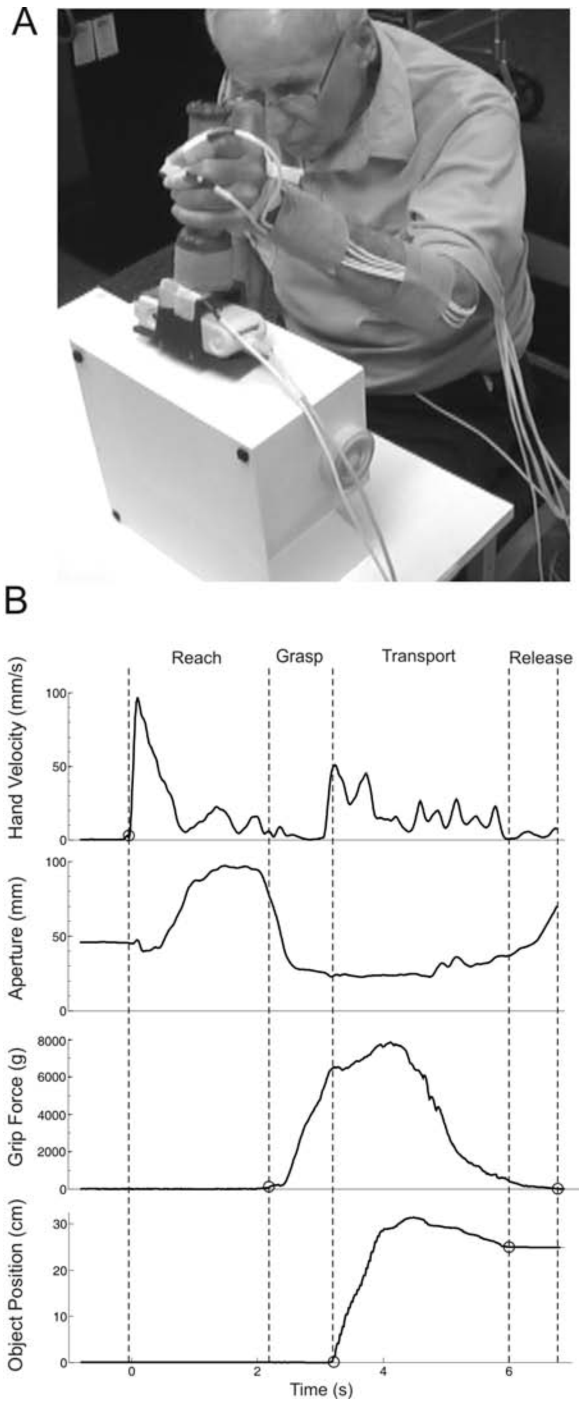

Figure 1: Assessment of motor performance. A) Illustration of the experimental set-up and a participant performing the reach-grasp-transport-release task. B) Example data from one trial. Vertical dashed lines demonstrate division of the task into movement phases. The reach phase began when hand velocity exceeded 5 mm/sec, the grasp phase began when grip force exceeded 5 grams, the transport phase began when the vertical position of the object increased by 3 mm, and the transport phase ended when the vertical position of the object returned to within 3 mm of its final resting position. Duration of the release phase was calculated as the difference in time between the end of transport, and the time when force on the object returned to within 5 grams of its baseline value.

Figure 2

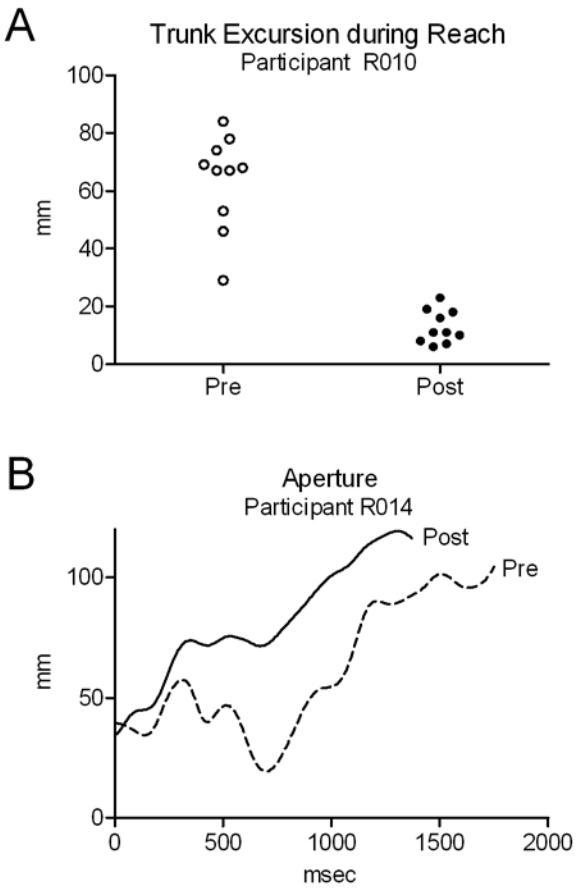

Figure 2: Examples of improvements in movement parameters in individual participants. A) After training, R010 showed decreased trunk excursion during the reach phase. Ten pre-training trials and ten post-training trials are shown. B) After training, R014 showed improved efficiency of finger movement, seen as a smoother aperture trace and quantified by a decrease in the aperture path ratio (see Methods). Reach duration also decreased. One representative trial is shown for each time point.