Research Report

Reproducibility and Minimal Detectable Change of Three-Dimensional Kinematic Analysis of Reaching Tasks in People With Hemiparesis After Stroke

Joanne M Wagner, Jennifer A Rhodes, Carolynn Patten

JM Wagner, PT, PhD, is Research Health Scientist, Rehabilitation Research and Development Center, VA Palo Alto Health Care System, Palo Alto, Calif.

JA Rhodes, PT, MSPT, is a DPT student, University of California, San Francisco, and San Francisco State University, San Francisco, Calif.

C Patten, PT, PhD, was Research Scientist, Rehabilitation Research and Development Center, VA Palo Alto Health Care System, and Clinical Associate Professor, Department of Orthopaedic Surgery, Stanford University, Stanford, Calif, at the time of this study. Dr Patten is now Research Scientist, Brain Rehabilitation Research Center, Malcom Randall VA Medical Center, and Associate Professor, Department of Physical Therapy, University of Florida, 1601 SW Archer Rd (151A), Gainesville, FL 32608 (USA). Address all correspondence to Dr Patten at: patten@phhp.ufl.edu.

[Wagner JM, Rhodes JA, Patten C. Reproducibility and minimal detectable change of three-dimensional kinematic analysis of reaching tasks in people with hemiparesis after stroke. *Phys Ther*. 2008;88:652–663.]

Background and Purpose. Three-dimensional kinematic analysis of reaching has emerged as an evaluative measure of upper-extremity motor performance in people after stroke. However, the psychometric properties supporting the use of kinematic data for evaluating longitudinal change in motor performance have not been established. The objective of this study was to determine, in a test-retest reliability manner, the reproducibility and minimal detectable change for reaching kinematics in people after stroke.

Subjects and Methods. Fourteen participants with hemiparesis after stroke performed forward reaching tasks on 2 occasions 37.3 (SD=9.8) days apart. At each session, participants performed 4 forward reaching tasks produced by the combination of 2 target heights (low and high [109 and 153 cm from the floor, respectively]) and 2 instructed movement speeds (self-selected and as fast as possible). Two analytical methods were used to calculate kinematic parameters.

Results. Relative reliability (intraclass correlation coefficient) ranged from .04 to .99, and absolute reliability (standard error of measurement) ranged from 2.7% to 76.8%, depending on the kinematic variable, the demands of the motor task (target height and movement speed), and the analytical method. Bland-Altman analysis, a statistical method used to assess the repeatability of a method, revealed few systematic errors between sessions. The minimal detectable change ranged from 7.4% to 98.9%.

Discussion and Conclusion. Depending on the demands of the motor task and the analytical method, most kinematic outcome measures (such as peak hand velocity, endpoint error, reach extent, maximum shoulder flexion range of motion, and minimum elbow extension range of motion) are reliable measures of motor performance in people after stroke. However, because of the magnitude of within-subject measurement error, some variables (such as peak hand velocity, time to peak hand velocity, and movement time) must change considerably (>50%) to indicate a real change in individual participants. The results of our reliability analysis, which are based on our cohort of participants with hemiparesis after stroke and our specific paradigm, may not be generalizable to different subpopulations of people with hemiparesis after stroke or to the myriad movement tasks and kinematic variables used for the assessment of reaching performance in people after stroke.

Stroke is the leading cause of disability in adults in the United States,[1] affecting an estimated 730,000 people per year.[1,2] Upper-extremity (UE) function is commonly impaired after stroke, with approximately 80% of people experiencing acute hemiparesis and approximately 40% experiencing chronic hemiparesis.[3–5] Because of the high incidence and persistence of UE impairment after stroke, numerous outcome measures have been developed to evaluate UE movement in people with hemiparesis after stroke (see Barak and Duncan[6] for a review). These outcome measures are used for 3 general purposes: to discriminate UE motor performance of people with stroke from that of people without stroke (discriminative measure), to predict future UE motor performance (predictive measure), and to evaluate longitudinal change in UE motor performance (evaluative measure).[6,7]

Three-dimensional (3D) kinematic analysis of reaching performance has the potential to serve as both a discriminative measure and an evaluative measure of UE motor performance in people with hemiparesis after stroke. Cross-sectional kinematic studies have yielded considerable information about how UE movement control is altered after stroke,[8–23] provided insight into compensatory movement control strategies in people with hemiparesis after stroke,[10,11,15] and illustrated differences in motor performance based on the severity of impairment after stroke.[13–17] Longitudinal kinematic studies have provided information regarding changes in UE movement control associated with motor recovery[24–26] and responses to various therapeutic interventions, including strength (force-generating capacity) training,[27] task-specific training,[27,28] constraint-induced movement therapy,[29] robotic training,[30,31] and bilateral UE motor retraining.[32]

The ability of kinematic data to function as a discriminative or evaluative outcome measure depends on the presence of sound, purpose-specific psychometric properties. For use as a discriminative measure, kinematic data must demonstrate construct validity (relationship between outcome measure and external measures at a single point in time) and reliability based on stable between-subject variations. For use as an evaluative measure, kinematic data must demonstrate longitudinal construct validity (relationship between changes in outcome measure and changes in external measures over time), reliability based on stable within-subject variations, and responsiveness (the ability to detect minimal clinically important change).[7,33]

Surprisingly, the psychometric properties of kinematic outcome measures of reaching performance in people with hemiparesis after stroke have not been thoroughly investigated. Cross-sectional construct validity and longitudinal construct validity have been supported by the relationship between kinematic measures of reaching performance and the degree of sensorimotor impairment[9–11,17–19,23,26,34] or scores from clinical rating scales.[9,11,13–16,35] However, there is limited or no information regarding test-retest reliability (reproducibility)[36] or the responsiveness of kinematic outcome measures of reaching performance in people with hemiparesis after stroke. That is, there is no detailed report of the psychometric properties of kinematic outcome measures of reaching performance to support the use of these measures for evaluating longitudinal change in UE motor performance in people with hemiparesis after stroke.

It is evident that a comprehensive assessment of the psychometric properties of kinematic outcome measures of reaching performance is needed to support or refute the continued use of these measures for evaluative purposes. Specifically, the reproducibility of kinematic outcome measures must be established in order to determine how much difference is needed to detect a real change in reaching performance, considering random variation or measurement error. Reproducibility is assessed in terms of both relative reliability and absolute reliability. Relative reliability, which examines the relationship between 2 or more sets of repeated measures, can be obtained by calculating the intraclass correlation coefficient (ICC). Absolute reliability, which describes the within-subject variability attributable to repeated measures, is obtained by calculating the standard error of measurement (SEM). The SEM then can be used to estimate the minimal detectable change (MDC), defined as the minimal amount of change that is not likely to be attributable to a chance variation in measurement.[37] Estimates of SEM and MDC enable clinicians and scientists to determine whether the change observed in motor performance, as indicated by kinematic measures, represents real improvement.

The purposes of this study were to determine the reproducibility of 3D kinematic analysis of reaching tasks and to define the MDC for kinematic outcome measures of reaching performance in people with hemiparesis after stroke. These data were reported previously in abstract form.[38]

Method

Participants

Fourteen people with hemiparesis resulting from stroke participated in this study. The study sample included the first group of subjects participating in "Mechanisms of Upper-Extremity Motor Recovery in Post-stroke Hemiparesis" (MOR), a single-center, randomized controlled trial conducted at the Rehabilitation

R&D Center at the VA Palo Alto Health Care System (VAPAHCS) to investigate physiologic mechanisms of motor recovery in the hemiparetic UE. Participants were recruited from community referral sources in addition to the VAPAHCS and Stanford Medical Center clinics. All participants provided informed consent in accordance with the Declaration of Helsinki.

Participants with the following characteristics were included: a single, unilateral stroke within 6 to 26 months of admission into the study (with confirmatory neuroimaging); the ability to move the UE in the horizontal plane in a manner corresponding to a "poor" (2/5) manual muscle test grade[39] in the major shoulder and elbow musculature; at least 10 degrees of active wrist extension, 10 degrees of active abduction of the thumb, and 10 degrees of active extension of any 2 digits, 3 times within 1 minute[40]; and freedom from any significant UE joint pain, limitations in passive range of motion (ROM), or marked sensory deficits, as evidenced by absent proprioception at the elbow or shoulder joint. Participants were excluded if they had experienced multiple or bilateral cerebrovascular accidents, lesions involving the brain stem or cerebellum, upper-limb pain, or cognitive deficits affecting their ability to follow 3-step commands. Participant characteristics are shown in Table 1.

Protocol

The MOR study design involves a preintervention, repeated-baseline assessment of all clinical and kinematic outcome measures. The nominal design projected a 4-week interval between the first (session 1) and second (session 2) baseline assessments. This interval was selected to monitor any spontaneous motor recovery, the magnitude and rate of which would be used as a covariate in an analysis of the intervention data, and to provide balance to the study by use of an appropriate period of no treatment without compromising the opportunity to induce motor recovery or participant motivation. The mean intervals between session 1 and session 2 were 33 (SD=8.9) and 37.3 (SD=9.8) days for clinical and kinematic assessments, respectively. For each baseline session, the clinical battery and kinematic testing were conducted on 2 separate days, with averages of 6.4 (SD=5.1) days between the clinical battery and kinematic testing for session 1 and 4.7 (SD=4.1) days for session 2. Efforts were made to provide stability of test conditions across sessions (such as using identical instructions and data collection protocols and having the same physical therapist perform all clinical assessments in the same location); however, because of the schedules of the participants, the kinematic data were collected by 2 equally trained people, and the timing of the assessments varied from session to session.

Clinical Assessment

The upper-limb sections of the Fugl-Meyer Assessment Scale[41] and the Modified Ashworth Scale (MAS)[42] were administered to characterize the severity of sensorimotor impairment of the hemiparetic UE. The Fugl-Meyer Assessment Scale motor section scores and MAS scores are shown in Table 1. The MAS scores shown in Table 1 represent the range (minimum to maximum) and average of scores from 7 muscle groups (shoulder flexor, abductor, and external rotator muscles; elbow flexor and extensor muscles; and wrist flexor and extensor muscles).

Measurement of Reaching Performance

Participants performed forward reaching tasks while seated in a straight-back chair. The trunk was stabilized to the back of the chair to minimize compensatory trunk movements.[11] The start position for each task was with the tested UE resting on the ipsilateral thigh, such that the shoulder was in approximately 0 degrees of flexion/extension and 0 degrees of internal rotation, the elbow was in 75 to 90 degrees of flexion, and the wrist rested palm down, with the finger joints in slight flexion. Minor modifications (such as increased shoulder internal rotation) were allowed for some participants to minimize any positional discomfort.

From the start position, participants were instructed to reach forward toward a 2.2-cm-wide piece of tape located at the superior end of a 0.5-cm-diameter vertical rod attached to a solid circular base. The target was positioned directly in front of the affected (contralateral to lesion) shoulder at 110% of arm's length. This distance was selected to promote maximal excursion of the hemiparetic arm during the reaching task. Each participant performed 4 different reaching tasks produced by the combination of 2 target heights (low and high [109 and 153 cm from the floor, respectively]) and 2 instructed speeds of movement (self-selected and as fast as possible). The resulting tasks were as follows: low self-selected speed (LSR), low fast speed (LFR), high self-selected speed (HSR), and high fast speed (HFR). Participants were given the following instructions for the self-selected speed reaching tasks: "Look at the target. When I say 'go,' reach toward the target at your own pace. When you have reached as close to the target as you can, hold your position until I ask you to return to the start position." Participants were given similar instructions for the reaching tasks performed at the fast speed, except that they were instructed to "reach toward the target as fast as you can." No further instructions were given. The reaching tasks were

Table 1.
Subject Demographics and Fugl-Meyer Assessment Scale Scores for 14 Subjects With Kinematic Data[a]

Subject No.	Age (y)	Sex	Time After Stroke (mo)	Fugl-Meyer Assessment Scale Score						MAS	
				Upper Extremity (UE)							
				Total		Motor		Shoulder/Elbow			
				Session 1	Session 2	Session 1	Session 2	Session 1	Session 2	Session 1	Session 2
1	61	F	25.2	79	81	24	24	9	10	1–2 (1.8)	1.5–2.0 (1.7)
2	70	M	24.4	90	94	39	39	15	14	0–1.5 (0.9)	1–1.5 (0.9)
3	63	M	18.5	83	81	29	29	14	18	0–3 (1.3)	1–3 (1.4)
4	66	M	19.8	82	83	26	26	9	10	0–2 (1.2)	0–1.5 (1.1)
5	73	M	20.2	86	92	26	34	16	21	0–3 (0.7)	0–1.5 (0.6)
6	50	M	11.1	104	100	45	44	22	20	0–1.5 (0.6)	0–1.5 (0.7)
7	47	M	13.2	79	81	27	29	15	17	0–2 (0.4)	0–1.5 (0.2)
8	62	M	13.6	84	87	31	33	16	17	0–1.5 (0.8)	0–1.5 (0.7)
9	72	M	6.8	90	94	42	44	25	28	0–0 (0)	0–0 (0)
10	55	M	7.2	107	105	50	49	29	29	0–1 (0.1)	0–1 (0.1)
11	22	M	6.8	107	108	48	48	27	27	0–2 (0.3)	0–1.5 (0.2)
12	82	F	10.6	96	87	40	38	15	14	0–0 (0)	0–0 (0)
13	52	M	12.6	82	86	30	34	10	12	0–1.5 (0.9)	0–1.5 (0.9)
14	63	F	6.5	82	81	29	29	13	13	0–1 (0.4)	0–1 (0.4)
Group mean	59.9		14.0	89.4	90.0	34.7	35.7	16.8	17.9	0.67	0.64
Group SD	14.6		6.5	10.2	9.2	9.0	8.1	6.5	6.4	0.53	0.53

[a] MAS=minimum and maximum (mean) modified Ashworth score calculated for 7 muscle groups (shoulder flexor, shoulder abductor, shoulder external rotator, elbow flexor, elbow extensor, wrist flexor, and wrist extensor muscles), F=female, M=male. Mean MAS value represents average MAS scores for all 7 muscle groups. Maximum scores: Fugl-Meyer UE total=126 points; Fugl-Meyer UE motor=66 points; Fugl-Meyer shoulder/elbow=30 points; MAS=5 points.

performed sequentially in blocks of 2 in the following order: LSR, LFR, HSR, and HFR. For each reaching task, participants were provided 1 or 2 practice trials prior to recording to familiarize themselves with the tasks and the instructions. In an attempt to minimize fatigue, data collection was limited to 2 trials for each task. This measure was taken because the participants were undergoing additional clinical and kinematic assessments in conjunction with their participation in this study.

Three-dimensional movements were recorded at 120 Hz with a 7-camera Qualisys Motion Capture System.* Prior to data collection, the motion capture system was calibrated in accordance with manufacturer guidelines, with system calibration being accepted only when the average residual for each camera was ≤1.6 mm. The manufacturer estimates the accuracy of our Qualisys system to be 1.5 to 3.0 mm. A total of sixteen 1.5-cm reflective markers were placed on the trunk (n=4), upper arm (n=4), forearm (n=5), and hand and fingers (n=3) for reaching tasks. Movements were recorded simultaneously with each camera and stored on a computer disk for further analysis.

Kinematic Analysis of Reaching Performance

Kinematic data were analyzed offline with Qualisys Track Manager* and Visual3D software† to extract position, velocity, and angular data during the reaching tasks. Specifically, right-hand coordinate systems (x=medial-lateral, y=anterior-posterior, and z=inferior-superior) were embedded into 3 segments (trunk, upper arm, and forearm). Joint center locations and joint axes were defined by use of previously reported methods,[43] except that the location of the shoulder joint was assumed to be 5 cm inferior to the acromion marker. The position of the joint center served as the origin for the local coordinate system of each segment. A series of Euler rotations, sequenced x-y-z, were used to express the joint angles of the distal segment with respect to the proximal segment.

* Qualisys North America Inc, 9301 Monroe Ave, Suite B, Charlotte, NC 28270.

† C-Motion Inc, 15821-A Crabbs Branch Way, Rockville, MD 20855.

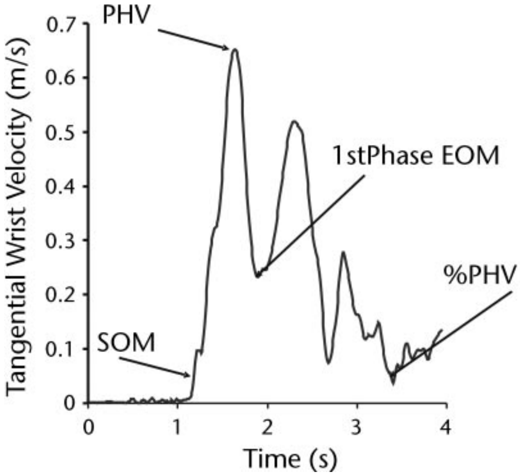

Figure 1.
Sample tangential hand velocity profile for a self-selected reach to the high target for a subject with hemiparesis. Data shown are from the initiation of data collection to the end of data collection at the time of maximum shoulder flexion range of motion (ROM). 1stPhase EOM=end-of-movement definition for first-phase analysis, %PHV=percent peak hand velocity, %PHV EOM=end-of-movement definition for %PHV analysis, SOM=start of movement.

Joint flexion-extension was measured about the x-axis, joint abduction-adduction was measured about the y-axis, and joint internal-external rotation was measured about the z-axis. Marker dropout was infrequent because of the redundant camera system; however, when markers were obscured, they were interpolated by use of a cubic spline. Tracked data were filtered with a low-pass filter at 6 Hz by use of a second-order bidirectional Butterworth filter.

Two methods commonly used to analyze reaching trajectories were compared. For both methods, start of movement (SOM) was defined as the time at which the tangential wrist velocity exceeded 5% of maximum velocity. The first-phase method defines end of movement (EOM) as the time at which the tangential wrist velocity drops to a minimum prior to subsequent corrective movements (submovements) (Fig. 1); this method was used to analyze kinematic data from the first phase of reach prior to submovements.[19,21,23,25,26] The percentage of peak hand velocity (%PHV) method defines EOM as the time at which the tangential wrist velocity drops below 5% of maximum (Fig. 1); this method was used to analyze the performance of the entire reaching task, including submovements.[9,11,16,22,44] All kinematic variables were calculated from SOM to EOM, regardless of which method was used to calculate EOM.

Variables that characterize speed, efficiency, smoothness, interjoint coordination (IJC), reach extent, and ROM during reaching were calculated from the kinematic trajectories. Peak hand velocity, reach path ratio, trajectory smoothness, and endpoint error were used to quantify speed, efficiency, smoothness, and accuracy of reaching, respectively.[21,23,25,26,45] We considered an efficient movement to be direct movement to the target without extraneous or abnormally circuitous movements. Peak hand velocity represented the maximum tangential linear velocity of the hand attained between SOM and EOM. Reach path ratio was calculated as the ratio of the actual wrist path traveled to an ideal straight line between the start position and the end position. A reach path ratio of 1 represents a straight path (normal), whereas a reach path ratio of greater than 1 represents either an abnormally curved path or multiple attempts to reach for the target. Trajectory smoothness was calculated by counting the number of peaks in the velocity profile.[27,44,45] Endpoint error was calculated as the 3D distance from the third metacarpal marker to the target at EOM.

The temporal IJC of shoulder flexion ROM and elbow extension ROM was quantified by use of cross-correlation analysis at zero time lag.[46,47] The cross-correlation coefficient ranges from −1 to 1. A high positive correlation occurs when joint motion is tightly coupled and in the same direction. A correlation coefficient of zero occurs when the motion of the 2 joints is entirely independent. A high negative correlation indicates that joint motion is tightly coupled but that the movement occurs in opposite directions.[46] Age-matched participants without disability produced IJC values ranging from 0.48 to 0.78 during performance of the reaching tasks described above (Joanne M Wagner and Christine A Dairaghi, unpublished data, February–March 2007). Reach extent, which represents the overall extent of UE movement during a reaching task, was calculated as the length of the straight line joining the initial and final endpoint positions.[30] Maximum shoulder flexion and abduction and minimum elbow extension (where 0 degrees represents full elbow extension) ROM values were calculated from angular data.

Data Analysis

Descriptive statistics were calculated for the kinematic variables in the 2 test sessions by both analytical techniques. Reliability statistics and MDC scores were derived from the mean of 2 individual reaching trials for each task (LSR, LFR, HSR, and HFR). Statistica software (version 6)[‡] was used for all statistical analyses.

Relative reliability. Relative reliability was estimated by calculation of the ICC (2,2). Repeated-measures analysis of variance, with test session as the independent variable, was used to partition the total variance for each variable into effects attributable to differences between participants, test sessions, and error variance. If BMS represents the between-participants mean square, EMS represents the error mean square, RMS represents the between-sessions mean square, and n represents the number of participants, then[48]:

(1)

$$\text{ICC}(2,2) = \frac{\text{BMS} - \text{EMS}}{\text{BMS} + ((\text{RMS} - \text{EMS})/\text{n})}.$$

Absolute reliability. Bland-Altman plots were constructed by plotting the between-session difference for each variable versus the test-retest mean for each kinematic variable.[49] From the Bland-Altman plots, the data were examined for their magnitude, range, and distribution around the zero line. The 95% confidence intervals (CIs) were calculated to identify any systematic trends or outliers. The 95% CIs were derived as:

$$(2) \qquad \text{CI} = \bar{d} \pm 2.179(\text{SE}),$$

where $\bar{d}$ is the mean difference between test and retest scores, 2.179 is the value obtained from the t-table with 12 (n−1) degrees of freedom, and SE is the standard error of $\bar{d}$. The standard error of $\bar{d}$ was calculated as:

$$(3) \qquad \text{SE of } \bar{d} = SD_{diff}/\sqrt{n},$$

‡ StatSoft Inc, 2300 East 14th St, Tulsa, OK 74104.

where SD_{diff} is the standard deviation of the differences between the 2 test sessions.

Measurement error indicates the within-subject variability across repeated trials. Such variability may result from performance differences or nonspecific sources of error (such as the instrument or the experimental paradigm). Measurement error was evaluated by use of the SEM, which was calculated as:

$$(4) \qquad \text{SEM} = \text{SD}_x \times \sqrt{(1 - \text{R}_x)},$$

where SD_x is the standard deviation for all observations from test sessions 1 and 2 and R_x is the test-retest reliability coefficient (ICC). Measurement error also was expressed as the SEM%, the within-subject standard deviation as a percentage of the mean, which was defined as:

$$(5) \qquad \text{SEM\%} = (\text{SEM}/\text{mean}) \times 100.$$

The SEM% indicates measurement error independent of the units of measurement. The SEM% represents the limit for the smallest change that indicates a real improvement for a group of subjects.

MDC. The MDC, which represents the magnitude of change necessary to exceed the measurement error of 2 repeated measures at a specified CI,[37,50] was calculated for the 95% CI (MDC_{95}) as:

$$(6) \qquad \text{MDC}_{95} = \text{SEM} \times 1.96 \times \sqrt{2},$$

where 1.96 is the 2-sided tabled z value for the 95% CI and $\sqrt{2}$ is used to account for the variance of 2 measurements.

So that the MDC could be independent of the units of measurement, it was expressed as a percentage (MDC%), which was defined as:

$$(7) \qquad \text{MDC\%} = (\text{MDC}_{95}/\text{mean}) \times 100,$$

where mean is the mean for all of the observations for test sessions 1 and 2. The MDC% represents the smallest change that indicates a real change in a single individual.

Results

Assessment of UE Motor Stability in Participants With Hemiparesis

For the establishment of test-retest reliability, 2 measurements are required from a stable population. Test-retest scores on the UE motor section of the Fugl-Meyer Assessment Scale were used to determine the stability of motor function in our cohort of participants with hemiparesis after stroke. Specifically, the MDC_{95} for the UE motor section of the Fugl-Meyer Assessment Scale was calculated to determine the magnitude of change over and above measurement error that would constitute real change attributable to motor recovery. The MDC_{95} for the UE motor section of the Fugl-Meyer Assessment Scale was 5.2 points. Participants with a session-to-session difference of greater than 5.2 points on the UE motor section of the Fugl-Meyer Assessment Scale were considered to have demonstrated unstable motor performance across sessions and were removed from the subsequent reliability analysis. One subject (subject 5) showed a difference of 8 points on the UE motor section of the Fugl-Meyer Assessment Scale and was thus removed from the reliability analysis, resulting in a total of 13 participants for the reliability analysis.

Reaching Performance

Visual inspection revealed that kinematic data varied depending on the analysis method used to quantify reaching performance, confirming that different aspects of the reaching task were analyzed with the 2 different analysis methods. Specifically, the %PHV method yielded higher values for movement time, reach path ratio, shoulder flexion and abduction

Table 2.
Minimum and Maximum Intraclass Correlation Coefficients (ICCs), Standard Error of Measurement (%SEM), and Minimal Detectable Change (%MDC) Calculated for Kinematic Variables by First-Phase and Percent Peak Hand Velocity (%PHV) Analysis Methods[a]

Analysis Method	Variable	Range (Minimum–Maximum) for:		
		ICC	SEM%	MDC%
First phase	Movement time (s)	.04–.82	15.8–35.6	43.8–98.9
	Peak hand velocity (m/s)	.74–.95	8.8–22.1	24.4–61.3
	Time to peak hand velocity (s)	.11–.83	16.5–29.5	45.8–81.8
	RPR	.08–.90	2.9–7.6	7.9–20.9
	EE (m)	.65–.87	7.2–11.44	19.9–27.5
	Reach extent (m)	.66–.95	9.6–25.1	26.6–69.7
	Maximum SF range of motion (ROM) (°)	.78–.95	8.8–19.4	24.3–53.7
	Maximum SAb ROM (°)	.57–.91	9.8–20.4	27.2–56.6
	Min EExt ROM (°)	.83–.91	8.4–11.6	23.2–30.4
	IJC	.60–.79	4.5–7.0	12.4–19.4
%PHV	Movement time (s)	.11–.82	14.0–28.2	38.9–70.0
	Peak hand velocity (m/s)	.74–.95	8.8–22.1	24.4–61.3
	Time to peak hand velocity (s)	.11–.83	16.5–29.5	45.8–81.8
	RPR	.33–.95	2.7–10.4	7.4–28.9
	EE (m)	.68–.85	9.2–12.1	25.5–33.5
	Reach extent (m)	.93–.99	4.3–9.3	12.0–25.8
	Maximum SF ROM (°)	.93–.95	8.8–11.9	24.4–33.1
	Maximum SAb ROM (°)	.58–.77	13.8–19.4	38.3–53.9
	Minimum EExt ROM (°)	.86–.91	11.0–14.0	30.5–38.8
	IJC	.66–.92	3.7–6.6	10.2–18.2
	Trajectory smoothness	.43–.84	20.9–76.8	24.4–67.6

[a] RPR=reach path ratio, EE=endpoint error, SF=shoulder flexion, SAb=shoulder abduction, EExt=elbow extension, IJC=interjoint coordination.

ROM, and reach extent and lower values for endpoint error and elbow extension ROM; however, it yielded IJC values similar to those obtained with the first-phase method. There were no differences in peak hand velocity and time to peak hand velocity because the first-phase and %PHV methods used identical calculations for these variables. Trajectory smoothness was calculated only for the %PHV method because the first-phase method truncates data after the first velocity peak.

Independent of the analytical approach, kinematic data varied depending on the specific demands (target height and instructed speed of movement) of the reaching task. Temporal variables were scaled to the demands of the motor task, such that shorter movement times and higher peak hand velocities were observed during fast movements than during self-paced movements. Higher endpoint error, shoulder flexion and abduction ROM, and reach extent values were revealed for movements to the high target than for movements to the low target. However, reach path ratio, elbow extension ROM, and IJC values did not differ systematically between movements to the low target and movements to the high target, regardless of the instructed movement speed.

Relative Reliability

Intraclass correlation coefficients in the range of .5 to .6 are fair, those in the range of .6 to .7 are good, and those above .75 are excellent.[51] On the basis of these criteria, relative (test-retest) reliability was found to be good to excellent (.57–.99) for most of the kinematic variables but was found to be low (<.50) for the kinematic variables movement time, time to peak hand velocity, reach path ratio, and trajectory smoothness, depending on the analytical technique and the motor demands of the reaching task (speed of movement and target height) (Tab. 2). With few exceptions, namely, movement time and reach path ratio, the 2 analysis methods yielded similar ranges of ICCs (.57–.99) for the same variable during performance of the same motor task.

Absolute Reliability

Bland-Altman statistics revealed no systematic variance (ie, zero was included in the 95% CI of $\bar{d}$) (Figs. 2A, 2C, and 2D) in group performance from session to session for most of the variables, regardless of the analysis method or demands of the motor task. However, session-to-session systematic group variance (ie, zero was not included in the 95% CI of $\bar{d}$) (Fig. 2B) was noted for endpoint error during fast movements and minimum elbow extension ROM during HFR when data were analyzed with the first-phase method and for trajectory smoothness during LSR and IJC during HSR when data were analyzed with the %PHV method. That is, our participants were less accurate (higher endpoint error values) during LFR and had less elbow extension ROM during HFR at the second session than at the first session when data were analyzed with the first-phase method. In contrast, our participants had smoother movements (fewer velocity peaks) during LSR and more coordinated movements (as evidenced by lower IJC values) during HSR at the second session than at the first session when data were analyzed with the %PHV method.

Visual inspection of all Bland-Altman graphs revealed uniform variability across mean performance for the majority of kinematic variables (Figs. 2A, 2B, and 2C). However, there were a few examples of nonuniform relationships between the difference from session to session and the magnitude of the mean (heteroscedasticity) (Fig. 2D). Greater differences in mean performance were observed for IJC for people with lower IJC scores than for those with higher IJC scores for both analytical methods during LSR. During LFR, greater differences in mean performance were observed for reach path ratio for people with higher reach path ratio values than for those with lower values (first-phase method), shoulder flexion ROM for people with lower ROM values than for those with higher values (%PHV method), and trajectory smoothness for people with a larger number of peaks in the velocity trace than for those with fewer peaks (%PHV method). No heteroscedasticity was observed in the graphs of HSR and HFR tasks for either analytical method.

Lower SEM% values reflect lower measurement error than do higher SEM% values. Measurement error (SEM%) ranged from 2.7% to 76.8%; however, the majority of kinematic variables had SEM% values of less than 35% (Tab. 2). With few exceptions, namely, movement time, reach extent, and maximum shoulder flexion ROM, the 2 analytical methods yielded similar SEM% values for the same variable during performance of the same motor task. The SEM% values changed systematically for a few variables as the speed of movement and the target height increased. Specifically, measurement error increased for endpoint error and shoulder flexion active ROM but decreased for movement time (first-phase method), time to peak hand velocity, and reach extent as the speed of movement and the target height increased. No other systematic changes in the SEM% values were observed for the remaining variables. No particular movement task (LSR, LFR, HSR, or HFR) or analysis method consistently produced the lowest SEM% values for all variables.

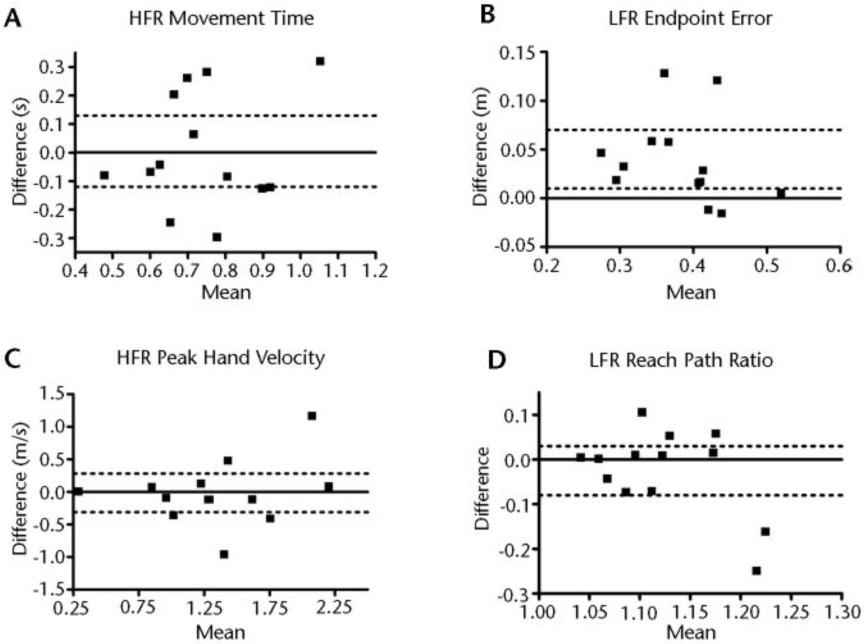

Figure 2.
Bland-Altman plots for selected kinematic variables demonstrating no systematic variance in group performance from session to session (A, C, and D), systematic variance in group performance from session to session (B), uniform relationships between the difference from session to session (ordinate) and the mean performance from session to session (abscissa) (A–C), and nonuniform relationships (heteroscedasticity) between the difference from session to session (ordinate) and the mean performance from session to session (abscissa) (D). Data in panels A, B, and D were calculated with the first-phase (1stPhase) method. Data in panel C were calculated with the percent peak hand velocity (%PHV) method. HFR=high target, fast speed; LFR=low target, fast speed; ROM=range of motion. Dashed line represents 95% confidence interval for $\bar{d}$. Solid line is drawn at zero.

MDC

Lower MDC% values reflect greater responsiveness than do higher MDC% values. The MDC% values ranged from 7.4% to 98.9% (Tab. 2). With a few exceptions, namely, movement time, reach extent, and maximum shoulder flexion ROM, the 2 analytical methods yielded similar MDC% values for the same variable during performance of the same motor task. The MDC% values changed systematically for a few variables as the speed of movement and the target height increased. Specifically, the MDC% values decreased for endpoint error and shoulder flexion active ROM but increased for movement time (first-phase method), time to peak hand velocity, and reach extent (%PHV method) as the speed of movement and the target height increased. Regardless of the target height, the MDC% values for trajectory smoothness were higher during fast movements than during self-selected speed movements. No other systematic changes in the MDC% values were observed for the remaining variables. No particular movement task (LSR, LFR, HSR, or HFR) or analysis method consistently produced the lowest MDC% values for all variables.

Discussion

In the present study, we investigated the reproducibility and MDC% of kinematic variables used to evaluate reaching performance in people with hemiparesis after stroke. In our sample of participants, the relative test-retest reliability (ICC) was good to excellent for the majority of variables; systematic variance in group performance from session to session was minimal (Bland-Altman plots); estimates of measurement error (%SEM) were low to moderate (<35%) for most variables; and the minimal difference necessary to infer a meaningful change in reaching performance (MDC%) varied depending on the specific variable of interest, the analysis method, and the demands of the motor task. Overall, our results suggest that select kinematic outcome measures are reliable measures of motor performance in people with hemiparesis after stroke. However, because of the magnitude of within-subject measurement error (SEM%), some variables must change considerably (>50%) to indicate a real change (ie, over and above measurement error) in individual participants.

Relative Reliability

The ICC is the commonly used test-retest correlation coefficient.[52,53] In the present study, the ICCs ranged from .04 to .99 but were good to excellent for the majority of kinematic variables.[51] These values are comparable to those reported for a forward reaching task in adults without disability (.45–.92)[29] and people with chronic hemiparesis after stroke (.74–.96)[36]; for a hand-to-mouth task in children with cerebral palsy (.42–.68)[54]; and for other instrumented measures of UE motor performance in people with hemiparesis after stroke, including grip strength (.86),[55] an upper-limb trajectory tracking task (.51–.80),[56] and UE muscle performance during isokinetic testing (.64–.98).[57] Similar to our data, the ICCs reported in those studies varied depending on the specific motor demands of the task (speed of movement) and the variable used to quantify performance (torque versus power).

Absolute Reliability

We used the SEM and the SEM% to assess the measurement error of the kinematic variables. The SEM and the SEM% represent the limit for the smallest change that indicates a real improvement for a group of subjects.[58] The SEM% is independent of the units of measurement and therefore is more easily interpreted. The SEM% values in the present study ranged from 2.7% to 76.8%, and SEM% values were less than 35% for 10 of the 11 kinematic variables. Our estimates of SEM% values are similar to those reported in people with hemiparesis after stroke for a forward reaching task (1.1%–31.6%),[36] grip strength (20%),[55] an upper-limb trajectory tracking task (19%–36%),[56] and UE muscle performance during isokinetic testing (0.36%–33.9%).[57] These results indicated that most of the kinematic variables demonstrated levels of measurement error similar to those of other instrumented measures of UE motor performance. Importantly, our data revealed that moderate (measurement error of <35%) changes were needed to indicate a real change in reaching performance for a group of subjects with hemiparesis after stroke.

Bland-Altman analysis was used to evaluate systematic variance in mean group performance from session to session. Our data revealed stable group performance on repeated testing for most variables. There were a few examples of systematic differences from session to session, but there were no consistent changes in performance, revealing that both improvement in performance and degradation in performance were occurring. These data suggest that experience or practice in performing the reaching tasks in session 1 did not lead to improvement in performance in session 2; that is, there was no learning effect.

The Bland-Altman graphs revealed nonuniform changes (heteroscedasticity) in mean reaching performance from session to session for a few kinematic variables. For these variables, greater differences in mean performance were consistently observed for participants with poor kinematic performance than for participants with better performance. These data suggest that the severity of motor impairment, as assessed by kinematic outcome measures, may have influenced the stability of reaching performance from session to session.

MDC

The results of our reliability assessment were used to calculate the MDC and the MDC%. The MDC and the MDC% represent the limit for the smallest change that indicates a real improvement in reaching performance in a single individual (in the present study, an individual who had survived stroke). The MDC is synonymous with the smallest real difference[59] and the reliable change index.[60] The MDC% is independent of the units of measurement and therefore, like the SEM%, is more easily interpreted. The MDC% estimates for the kinematic variables ranged from 7.4% to 98.9%, indicating that certain kinematic variables required changes of a larger magnitude (MDC%) than other variables to indicate a real change in reaching performance for an individual who had survived stroke.

Estimates of MDC have not been published for kinematic measures of UE motor performance in people with hemiparesis after stroke. There are very few reports regarding the limits of the MDC for instruments used to assess UE motor performance in people with hemiparesis after stroke.[56,57] Our estimates of the MDC% for kinematic variables were lower than or similar to those reported for an upper-limb trajectory tracking task (55%–97%)[56] and UE muscle performance during isokinetic testing (37%–86%).[57] Like our data, the percent smallest real difference values reported in those publications differed depending on the specific variable and the motor demands of the task (speed of movement and muscle group). These data suggest that certain kinematic measures of reaching performance (reach path ratio, endpoint error, and IJC) are better suited to detecting real changes in UE motor performance in people with hemiparesis after stroke than are other kinematic measures (movement time, time to peak hand velocity, and maximum shoulder abduction ROM).

The MDC estimates the limit for the smallest change that indicates a real improvement in reaching performance for a single individual. Even though this information is useful for determining how much change is required to exceed measurement error, it does not assist in answering an essential question for clinicians and researchers: how much change in a kinematic variable is needed to demonstrate a clinically important difference in reaching performance? For example, how much improvement in peak hand velocity must occur for this measure to be considered clinically meaningful? This question can be addressed only by establishing the limits of the minimal clinically important difference (MCID) for kinematic measures of UE reaching performance, defined as the amount of change that is clinically important to patients.[61] There are several methods available for establishing the MCID for kinematic outcome measures of UE reaching performance, including patient self-report,[62,63] expert panel consensus,[64] and the calculation of receiver operating characteristic curves.[64] Unfortunately, our data do not permit an estimation of the MCID, and there are no reports in the literature describing the MCID for measures of UE motor performance in people with hemiparesis after stroke. Future research is needed to determine the MCID of kinematic outcome measures of UE reaching performance to clarify the usefulness of kinematic outcome measures in evaluating longitudinal change in UE motor performance in people with hemiparesis after stroke, as well as to indicate whether a measurement tool has the precision to indicate meaningful clinical change (ie, the MCID exceeds the MDC).

Influence of Motor Task and Analysis Method on Psychometric Properties

We purposefully asked participants to perform 4 different forward reaching tasks (LSR, LFR, HSR, and HFR) to determine whether the instructed movement speed and spatial location of targets influenced the reproducibility and MDC of the kinematic variables. Our results demonstrated that the ICC, SEM%, and MDC% values of particular variables varied depending on the demands of the motor task but that no particular movement task consistently produced the most desirable reproducibility or limits of the MDC%. These findings suggest that researchers may use their own discretion when selecting a forward reaching task. Future research is needed to determine the influence of other spatial locations (eg, contralateral and ipsilateral target locations) on the reproducibility of kinematic variables of UE reaching performance.

Studies that have used kinematic variables to evaluate reaching performance in people with hemiparesis after stroke have used 2 analysis methods that differ in the definition of EOM[9,11,16,19,21–23,26,35,44]; in the present study, we have termed these methods the first-phase method and the %PHV method. We analyzed our data using these 2 methods in order to assess how the ICC, SEM%, and MDC% values differed when calculated by the first-phase method versus the %PHV method. For most variables, the ICC, SEM%, and MDC% values were comparable for the 2 methods, indicating that kinematic analyses of reaching performance were reproducible regardless of whether the data analyses included submovements. However, it is important to note that the reproducibility of 3 kinematic variables (movement time, reach extent, and maximum shoulder flexion ROM) differed depending on the analysis method used to calculate the variables. For example, the %PHV method produced greater reproducibility (lower SEM% values) and lower MDC% values for reach extent and maximum shoulder flexion ROM than did the first-phase method. One interpretation of these findings is that our participants were more reliable in the completion of the instructed task (maximizing reach extent and shoulder flexion ROM at EOM) than in the execution of the task (diminished reproducibility of reach extent and shoulder flexion ROM at the time of the first submovement).

Limitations

There are several limitations of our study. First, as with any reliability study, the results of our reliability analysis cannot be generalized to the multitude of movement tasks and kinematic variables used to assess reaching performance in people with hemiparesis after stroke. However, these data are important because they demonstrate the importance of establishing the reproducibility and MDC of kinematic measures. Second, our results may not be generalizable to people with more pronounced motor deficits after stroke (such as an inability to produce active wrist extension). Third, our specific reaching tasks, which did not allow participants to touch the target, may have resulted in greater variability in reaching performance than if they were permitted to touch the target because the accuracy constraints were most likely less of a factor in the former task than in the latter task. Fourth, we calculated the mean of 2 trials for each variable for each movement task. It is plausible that the reproducibility of our kinematic variables may have differed with a different number of trials per task. However, there is no consensus on the optimal number of reaching trials to use in an analysis of reaching performance; 2 trials[30] to 10 trials[44] have been reported in the literature. Finally, our sample was small (n=13 for the reliability analysis), and it is likely that our results would have differed with a larger sample size.

Conclusion

To our knowledge, this is the first study to use a comprehensive set of statistical methods to assess the reproducibility and MDC of kinematic measures of UE reaching performance in people with hemiparesis after stroke. Our data establish a range of values for absolute reliability, relative reliability, and MDC% of kinematic measures of UE reaching performance in people with hemiparesis after stroke. These data also illustrate the importance of using a variety of statistical tools to assess the reproducibility of evaluative outcome measures.

Dr Wagner and Dr Patten provided concept/idea/research design, writing, and project management. Dr Wagner provided data collection. Dr Wagner and Ms Rhodes provided data analysis and clerical/secretarial support. Dr Patten provided fund procurement, subjects, facilities/equipment, and institutional liaisons. Dr Wagner, Ms Rhodes, and Dr Patten provided consultation (including review of manuscript before submission). The authors thank Abigail M Andrade, Christine A Dairaghi, and Jeffrey P Jaramillo, PT, MS, for their assistance with data collection. The authors thank the participants for taking part in this study.

All aspects of this study were approved by the Stanford University Panel on Human Subjects in Medical Research.

This research was supported by the Department of Veterans Affairs, Rehabilitation Research & Development Service, Associate Investigator Award B4619H (Dr Wagner) and Merit Review Award B3964R (Dr Patten).

Data have been submitted in abstract form and have been accepted for poster presentation in the Neurology Section at the Combined Sections Meeting of the American Physical Therapy Association; February 6–9, 2008; Nashville, Tenn. The meeting abstract appears in the December 2007 issue of the *Journal of Neurologic Physical Therapy*.

This article was received August 31, 2007, and was accepted January 22, 2008.

DOI: 10.2522/ptj.20070255

References

1 Kelly-Hayes M, Robertson JT, Broderick JP, et al. The American Heart Association stroke outcome classification. *Stroke*. 1998;29:1274–1280.

2 *Heart Disease and Stroke Statistics: 2004 Update*. Dallas, Tex: American Heart Association; 2004.

3 Parker VM, Wade DT, Langton HR. Loss of arm function after stroke: measurement, frequency, and recovery. *Int Rehabil Med*. 1986;8:69–73.

4 Nakayama H, Jorgensen HS, Raaschou HO, Olsen TS. Recovery of upper extremity function in stroke patients: the Copenhagen stroke study. *Arch Phys Med Rehabil*. 1994;75:394–398.

5 Gray CS, French JM, Bates D, et al. Motor recovery following acute stroke. *Age Ageing*. 1990;19:179–184.

6 Barak S, Duncan PW. Issues in selecting outcome measures to assess functional recovery after stroke. *NeuroRx*. 2006;3:505–524.

7 Kirshner B, Guyatt G. A methodological framework for assessing health indices. *J Chronic Dis*. 1985;38:27–36.

8 Trombly CA. Deficits of reaching in subjects with left hemiparesis: a pilot study. *Am J Occup Ther*. 1992;46:887–897.

9 Levin MF. Interjoint coordination during pointing movements is disrupted in spastic hemiparesis. *Brain*. 1996;119:281–293.

10 Archambault P, Pigeon P, Feldman AG, Levin MF. Recruitment and sequencing of different degrees of freedom during pointing movements involving the trunk in healthy and hemiparetic subjects. *Exp Brain Res*. 1999;126:55–67.

11 Cirstea MC, Levin MF. Compensatory strategies for reaching in stroke. *Brain*. 2000;123:940–953.

12 Beer RF, Dewald JP, Rymer WZ. Deficits in the coordination of multijoint arm movements in patients with hemiparesis: evidence for disturbed control of limb dynamics. *Exp Brain Res*. 2000;131:305–319.

13 Reinkensmeyer DJ, McKenna Cole A, Kahn LE, Kamper DG. Directional control of reaching is preserved following mild/moderate stroke and stochastically constrained following severe stroke. *Exp Brain Res*. 2002;143:525–530.

14 Kamper DG, McKenna-Cole AN, Kahn LE, Reinkensmeyer DJ. Alterations in reaching after stroke and their relation to movement direction and impairment severity. *Arch Phys Med Rehabil*. 2002;83:702–707.

15 Roby-Brami A, Feydy A, Combeaud M, et al. Motor compensation and recovery for reaching in stroke patients. *Acta Neurol Scand*. 2003;107:369–381.

16 Cirstea MC, Mitnitski AB, Feldman AG, Levin MF. Interjoint coordination dynamics during reaching in stroke. *Exp Brain Res*. 2003;151:289–300.

17 Reisman DS, Scholz JP. Aspects of joint coordination are preserved during pointing in persons with post-stroke hemiparesis. *Brain*. 2003;126:2510–2527.

18 Takahashi CD, Reinkensmeyer DJ. Hemiparetic stroke impairs anticipatory control of arm movement. *Exp Brain Res*. 2003;149:131–140.

19 Zackowski KM, Dromerick AW, Sahrmann SA, et al. How do strength, sensation, spasticity and joint individuation relate to the reaching deficits of people with chronic hemiparesis? *Brain*. 2004;127:1035–1046.

20 Viau A, Feldman AG, McFadyen BJ, Levin MF. Reaching in reality and virtual reality: a comparison of movement kinematics in healthy subjects and in adults with hemiparesis. *J Neuroeng Rehabil*. 2004;1:11.

21 Lang CE, Wagner JM, Bastian AJ, et al. Deficits in grasp versus reach during acute hemiparesis. *Exp Brain Res*. 2005;166:126–136.

22 Reisman DS, Scholz JP. Workspace location influences joint coordination during reaching in post-stroke hemiparesis. *Exp Brain Res*. 2006;170:265–276.

23 Wagner JM, Lang CE, Sahrmann SA, et al. Relationships between sensorimotor impairments and reaching deficits in acute hemiparesis. *Neurorehabil Neural Repair*. 2006;20:406–416.

24 Trombly CA. Observations of improvement of reaching in five subjects with left hemiparesis. *J Neurol Neurosurg Psychiatry*. 1993;56:40–45.

25 Lang CE, Wagner JM, Edwards DF, et al. Recovery of grasp versus reach in people with hemiparesis poststroke. *Neurorehabil Neural Repair*. 2006;20:444–454.

26 Wagner JM, Lang CE, Sahrmann SA, et al. Sensorimotor impairments and reaching performance in subjects with poststroke hemiparesis during the first few months of recovery. *Phys Ther*. 2007;87:751–765.

27 Thielman GT, Dean CM, Gentile AM. Rehabilitation of reaching after stroke: task-related training versus progressive resistive exercise. *Arch Phys Med Rehabil*. 2004;85:1613–1618.

28 Michaelsen SM, Levin MF. Short-term effects of practice with trunk restraint on reaching movements in patients with chronic stroke: a controlled trial. *Stroke*. 2004;35:1914–1919.

29 Caimmi M, Carda S, Giovanzana C, et al. Using kinematic analysis to evaluate constraint-induced movement therapy in chronic stroke patients. *Neurorehabil Neural Repair*. 2008;22:31–39.

30 Lum PS, Burgar CG, Shor PC, et al. Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke. *Arch Phys Med Rehabil*. 2002;83:952–959.

31 Kahn LE, Zygman ML, Rymer WZ, Reinkensmeyer DJ. Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: a randomized controlled pilot study. *J Neuroeng Rehabil*. 2006;3:12.

32 Summers JJ, Kagerer FA, Garry MI, et al. Bilateral and unilateral movement training on upper limb function in chronic stroke patients: a TMS study. *J Neurol Sci*. 2007;252:76–82.

33 Guyatt G, Walter S, Norman G. Measuring change over time: assessing the usefulness of evaluative instruments. *J Chronic Dis*. 1987;40:171–178.

34 Leonard CT, Gardipee KA, Koontz JR, et al. Correlation between impairment and motor performance during reaching tasks in subjects with spastic hemiparesis. *J Rehabil Med*. 2006;38:243–249.

35 Lang CE, Wagner JM, Dromerick AW, Edwards DF. Measurement of upper-extremity function early after stroke: properties of the Action Research Arm Test. *Arch Phys Med Rehabil*. 2006;87:1605–1610.

36 McCrea PH, Eng JJ, Hodgson AJ. Saturated muscle activation contributes to compensatory reaching strategies after stroke. *J Neurophysiol*. 2005;94:2999–3008.

37 Haley SM, Fragala-Pinkham MA. Interpreting change scores of tests and measures used in physical therapy. *Phys Ther*. 2006;86:735–743.

38 Rhodes JA, Patten C, Wagner JM. Reliability and responsiveness of three-dimensional kinematic analyses of forward reach tasks in adults with hemiparesis after stroke [abstract]. *J Neurol Phys Ther*. 2007;4:210.

39 Daniels L, Worthingham C. *Muscle Testing: Techniques of Manual Examination*. Philadelphia, Pa: WB Saunders Co; 1986.

40 Wolf SL, Winstein CJ, Miller JP, et al. Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: the EXCITE randomized clinical trial. *JAMA*. 2006;296:2095–2104.

41 Fugl-Meyer AR, Jaasko L, Leyman I, et al. The post-stroke hemiplegic patient, 1: a method for evaluation of physical performance. *Scand J Rehabil Med*. 1975;7:13–31.

42 Bohannon RW, Smith MB. Interrater reliability of a modified Ashworth scale of muscle spasticity. *Phys Ther*. 1987;67:206–207.

43 Schmidt R, Disselhorst-Klug C, Silny J, Rau G. A marker-based measurement procedure for unconstrained wrist and elbow motions. *J Biomech*. 1999;32:615–621.

44 Michaelsen SM, Dannenbaum R, Levin MF. Task-specific training with trunk restraint on arm recovery in stroke: randomized control trial. *Stroke*. 2006;37:186–192.

45 Rohrer B, Fasoli S, Krebs HI, et al. Movement smoothness changes during stroke recovery. *J Neurosci*. 2002;22:8297–8304.

46 Newell KM, Van Emmerik REA. The acquisition of coordination: preliminary analysis of learning to write. *Hum Mov Sci*. 1989;8:17–32.

47 Schneiberg S, Sveistrup H, McFadyen B, et al. The development of coordination for reach-to-grasp movements in children. *Exp Brain Res*. 2002;146:142–154.

48 Gross Portney L, Watkins MP. *Foundations of Clinical Research: Applications to Practice*. 2nd ed. Upper Saddle River, NJ: Prentice-Hall; 2000.

49 Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*. 1986;1:307–310.

50 Fragala-Pinkham MA, Haley SM, Goodgold S. Evaluation of a community-based group fitness program for children with disabilities. *Pediatr Phys Ther*. 2006;18:159–167.

51 Fleiss J. *The Design and Analysis of Clinical Experiments*. New York, NY: Wiley; 1986.

52 Rankin G, Stokes M. Reliability of assessment tools in rehabilitation: an illustration of appropriate statistical analyses. *Clin Rehabil*. 1998;12:187–199.

53 Lexell JE, Downham DY. How to assess the reliability of measurements in rehabilitation. *Am J Phys Med Rehabil*. 2005;84:719–723.

54 Mackey AH, Walt SE, Lobb GA, Stott NS. Reliability of upper and lower limb three-dimensional kinematics in children with hemiplegia. *Gait Posture*. 2005;22:1–9.

55 Boissy P, Bourbonnais D, Carlotti MM, et al. Maximal grip force in chronic stroke subjects and its relationship to global upper extremity function. *Clin Rehabil*. 1999;13:354–362.

56 Patten C, Kothari D, Whitney J, et al. Reliability and responsiveness of elbow trajectory tracking in chronic poststroke hemiparesis. *J Rehabil Res Dev*. 2003;40:487–500.

57 Kim M, Kothari DH, Lum PS, Patten C. Reliability of dynamic muscle performance in the hemiparetic upper limb. *J Neurol Phys Ther*. 2005;29:9–17.

58 Flansbjer UB, Holmback AM, Downham D, et al. Reliability of gait performance tests in men and women with hemiparesis after stroke. *J Rehabil Med*. 2005;37:75–82.

59 Beckerman H, Roebroeck ME, Lankhorst GJ, et al. Smallest real difference, a link between reproducibility and responsiveness. *Qual Life Res*. 2001;10:571–578.

60 Stratford PW, Binkley J, Solomon P, et al. Defining the minimum level of detectable change for the Roland-Morris Questionnaire. *Phys Ther*. 1996;76:359–365; discussion 366–368.

61 Jaeschke R, Singer J, Guyatt GH. Measurement of health status: ascertaining the minimal clinically important difference. *Control Clin Trials*. 1989;10:407–415.

62 Wells G, Beaton D, Shea B, et al. Minimal clinically important differences: review of methods. *J Rheumatol*. 2001;28:406–412.

63 Fritz JM, Irrgang JJ. A comparison of a modified Oswestry Low Back Pain Disability Questionnaire and the Quebec Back Pain Disability Scale. *Phys Ther*. 2001;81:776–788.

64 Palombaro KM, Craik RL, Mangione KK, Tomlinson JD. Determining meaningful changes in gait speed after hip fracture. *Phys Ther*. 2006;86:809–816.