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Assessment of Upper-Limb Sensorimotor Function of Subacute Stroke Patients Using Visually Guided Reaching

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Abstract

Objective. Using robotic technology, we examined the ability of a visually guided reaching task to assess the sensorimotor function of patients with stroke. *Methods*. Ninety-one healthy participants and 52 with subacute stroke of mild to moderate severity (26 with left- and 26 with right-affected body sides) performed an unassisted reaching task using the KINARM robot. Each participant was assessed using 12 movement parameters that were grouped into 5 attributes of sensorimotor control. *Results*. A number of movement parameters individually identified a large number of stroke participants as being different from 95% of the controls—most notably initial direction error, which identified 81% of left-affected patients. We also found interlimb differences in performance between the arms of those with stroke compared with controls. For example, whereas only 31% of left-affected participants showed differences in reaction time with their affected arm, 54% showed abnormal interlimb differences in reaction time. Good interrater reliability ($r > 0.7$) was observed for 9 of the 12 movement parameters. Finally, many stroke patients deemed impaired on the reaching task had been scored 6 or less on the arm portion of the Chedoke-McMaster Stroke Assessment Scale, but some who scored a normal 7 were also deemed impaired in reaching. *Conclusions*. Robotic technology using a visually guided reaching task can provide reliable information with greater sensitivity about a patient's sensorimotor impairments following stroke than a standard clinical assessment scale.

Keywords

stroke, robots, assessment, reaching, KINARM

Introduction

Following stroke, impairments are often measured using the Chedoke-McMaster Stroke Assessment Scale[1] (CMSA) and Fugl-Meyer Assessment[2] (FMA), whereas disability is most commonly measured using the Functional Independence Measure[3] (FIM). However, there are 2 major limitations with these assessments. First, although reliability has been well established for these and other clinical assessments, their scoring systems are relatively coarse, making it difficult to quantify impairment and disability or detect subtle but clinically relevant changes. Second, many measurements of impairment focus on the ability of a patient to perform a specific movement or activity but fail to clearly identify the nature of the underlying neurological deficit. For example, in stage 4 of the CMSA, patients are asked to do the following: "Reach across and touch <their> opposite knee with <their> elbow straight, then without stopping, touch the ear on <their> weak side." Whereas this task was developed to assess the presence of extension and flexion synergies in the arm, it does not assess the details of the performance (How

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quickly do they respond? How quickly can they perform the movements?) or the reason for task failure (Do they have weakness? Are they apraxic? Do they have impaired sensation?). In addition, other clinically used measures of impairment, including range of motion, strength, and spasticity, have not been found to correlate to activity[4] nor account for neurological processes involved in successful motor performance. However, basic research in motor control has identified how tasks such as reaching for an object reflect a range of processes, including identifying the location of the object, planning the impending movement, feed-forward initiation, and feedback correction processes.[5-7]

Over the past few decades, robotic technologies have played a crucial role in basic research, expanding our knowledge of sensory and motor function,[8-12] and have shown potential for rehabilitation therapy.[13-15] These successes are a result of this technology's ability to objectively, repeatedly, and reliably measure behavior and/or apply perturbations to the limb(s).

The purpose of this study was to use robotic technology and a reaching task to examine sensorimotor impairments of the upper limbs in individuals with stroke. Using 12 movement-related parameters, it was possible to statistically quantify 5 attributes of motor control: upper-limb postural control, reaction time, feed-forward (initiation) control, feedback (corrective processes) control, and total movement metrics. We hypothesized that many stroke patients would show deficits in one or more of the attributes of sensorimotor performance. Furthermore, we also expected to find performance asymmetries across their 2 upper limbs.[16] Thus, we quantified their performance not only with their affected limb but also with their unaffected limb in order to quantify any interlimb differences in performance.

A number of studies have examined visually guided reaching movements with and without robotic assistance in the affected or unaffected arms of patients with stroke, illustrating a range of deficits in performance as compared with controls.[16-25] This study adds to this knowledge in several key ways. First, we used a large cohort of controls to statistically define normal performance. Second, we sought to determine whether each individual stroke patient's behavior was atypical, rather than focusing on group differences. It is important to note that between-group differences offer insight, but for an assessment to be clinically useful, it must be able to identify atypical behavior in individuals.[26] Third, although previous studies on reaching performance have examined the affected and unaffected arms, only limited comparisons have been made between the 2 limbs. As there is generally a broad range in performance across different patients, these interlimb differences may provide a valuable source of information for quantifying subtle impairments in sensorimotor performance.

Material and Methods

Participants

Participants were included in this study (1) after admission to St Mary's of the Lake Hospital, Kingston, Ontario, (2) approximately 2 to 3 weeks poststroke, and (3) if they had a single stroke that resulted in cortical, subcortical, brainstem, cerebellar, or mixed lesions. Every attempt was made to recruit all patients admitted to St Mary's of the Lake Hospital. Participants were excluded if they had a history of nonstroke neurological impairments, an acute medical illness, or ongoing musculoskeletal compromise of the shoulder or elbow. Participants had to understand the instructions for the testing procedure and provide informed consent. The Mini-Mental Status Exam (MMSE) score had to be >24, unless they had expressive aphasia or were illiterate. The study was approved by the ethics boards of Queen's University and Providence Care.

Although the performance of participants was examined at the individual level, stroke patients were broadly categorized based on the most affected body side. For example, those with right-cortical strokes or left-cerebellar strokes were categorized as left-affected patients. The most impaired limb was labeled affected and the other limb was labeled unaffected.

Clinical Evaluation

The clinical evaluation involved a number of standard clinical exams to serve as a reference from which to compare the results of our current robotic assessment. Handedness of participants was assessed using the Modified Edinburg Handedness inventory.[27] Physical impairments of the hand and arm were assessed using the impairment portion of the CMSA.[1] The CMSA is a 2-part measure of physical impairment and disability. For this study, we only used the hand (CMSAh) and arm (CMSAa) impairment portions of the scale, which determine the presence and severity of physical impairments. Impairments are quantified using a 7-point scale based on Brunnstrom's stages of recovery.[28] The FIM provides a metric of a participant's ability to perform activities of daily living.[29] In this study, we used a patient's FIM score collected at the time of their admission to St Mary's of the Lake Hospital. In addition, cognition was assessed using the Folstein MMSE,[30] and visual spatial attention was assessed using the conventional subset of the Behavioural Inattention Test (BIT).[31] Controls completed the same assessments as stroke patients except that they did not perform the FIM, the MMSE, or the BIT.

Experimental Setup

Reaching movements were monitored using a bilateral robotic exoskeleton called KINARM[9,32,33] (BKIN Technologies Ltd, Kingston, ON, Canada). The robotic device provides full gravitational support of the arms, forearms, and hands and permits only horizontal motion involving flexion and extension of the shoulder and elbow. Participants were seated in the KINARM chair with their arms abducted into the horizontal plane. The angle of abduction was chosen such that the arm, forearm, and hands were in the same plane as the shoulder (~80°). Each arm segment (arm, forearm plus hand) was supported by an exoskeleton that consisted of plastic arm troughs that are attached to an adjustable 4-bar linkage. The experimenter then adjusted the exoskeleton so that it comfortably fit and supported the participant's arms. Other than providing gravitational support, the robot did not assist the participant in completing the task. A virtual reality system displayed visual targets so that they appeared in the same plane as the arms. Direct vision of the participant's arms was occluded. Hand position feedback was provided by a computerized representation (small white circle, 0.4 cm radius) of the tip of the participant's index finger.

Experimental Task

The goal of the task was to make unassisted reaching movements "quickly and accurately" from a centrally located target (1.0 cm radius) to 1 of 8 peripheral targets (1.0 cm radius) distributed uniformly on the circumference of a circle (10 cm from the center target to each peripheral target). The center target was selected to be near the center of the arm's workspace (90° of elbow flexion and 30° of shoulder flexion). Participants began each trial by holding their index finger tip within the central target for 1250 to 1750 ms. After this, a peripheral target was illuminated. Participants were then given 3000 ms to complete the reach. The 8 peripheral targets were presented once each in a random block design and repeated 8 times for a total of 64 trials.

To examine the reliability of this robotic-based reaching task, 6 of our controls and 8 of our stroke participants performed the robotic assessment twice, each with a different experimenter. The second assessment was always performed by an experimenter who was blinded to the first assessment. It typically occurred within minutes of the first, although occasionally, they were separated by 24 hours.

Movement Onset and Offset

Movement onset and offset are typically identified with the use of a single velocity threshold (eg, 5 mm/s or 5% peak velocity). However, this method did not reliably identify movement onset or offset for many stroke patients, and new algorithms were developed. To begin, 2 statistical thresholds based on hand speed during the central target hold time were calculated for each participant: (1) lower speed threshold—the median hand speed across all trials for the 500 ms before the illumination of the peripheral target—and (2) upper speed threshold—the 95th percentile of hand speed during this same time period.

Movement onset. The algorithm first identifies the time point, after the illumination of the peripheral target, when the hand exited and remained outside the center target. The algorithm then moves backward in time to the first instance of one of the following:

1. a local minimum in hand speed that is below the upper speed threshold or
2. when the hand speed drops below the lower speed threshold.

If the hand speed never exceeded the upper speed threshold (ie, it moved very slowly), movement onset was set to the time when the hand left the central target.

Movement onset was not identified if (1) the hand never dropped below the upper speed threshold prior to the illumination of the peripheral target (ie, a potential false start) or (2) the hand left the central target later than 2000 ms after the illumination of the peripheral target.

Movement offset. This algorithm begins by identifying the point in time when the hand entered the peripheral target. Movement offset is then defined as follows:

1. the first local minimum in hand speed that is below the upper speed threshold or
2. when the hand speed dropped below the lower speed threshold.

Movement offset was not identified if the hand did not enter the peripheral target.

Movement Parameters

To characterize performance, 12 movement parameters were calculated from each trial (Figure 1). These parameters were broadly categorized into 5 attributes of sensorimotor control: (1) upper-limb postural control, (2) reaction time, (3) feed-forward control (initiation of movement), (4) feedback control (corrective responses), and (5) total movement metrics.

Upper limb postural control. This attribute has 1 parameter; it characterizes a participant's ability to keep his or her hand steady within the center target:

1. postural hand speed (m/s) is the mean hand speed for 500 ms before peripheral target illumination.

Reaction time: Two parameters characterize the ability of a participant to respond to a visual stimulus:

1. reaction time (s) is the time between illumination of the peripheral target and onset of movement, and

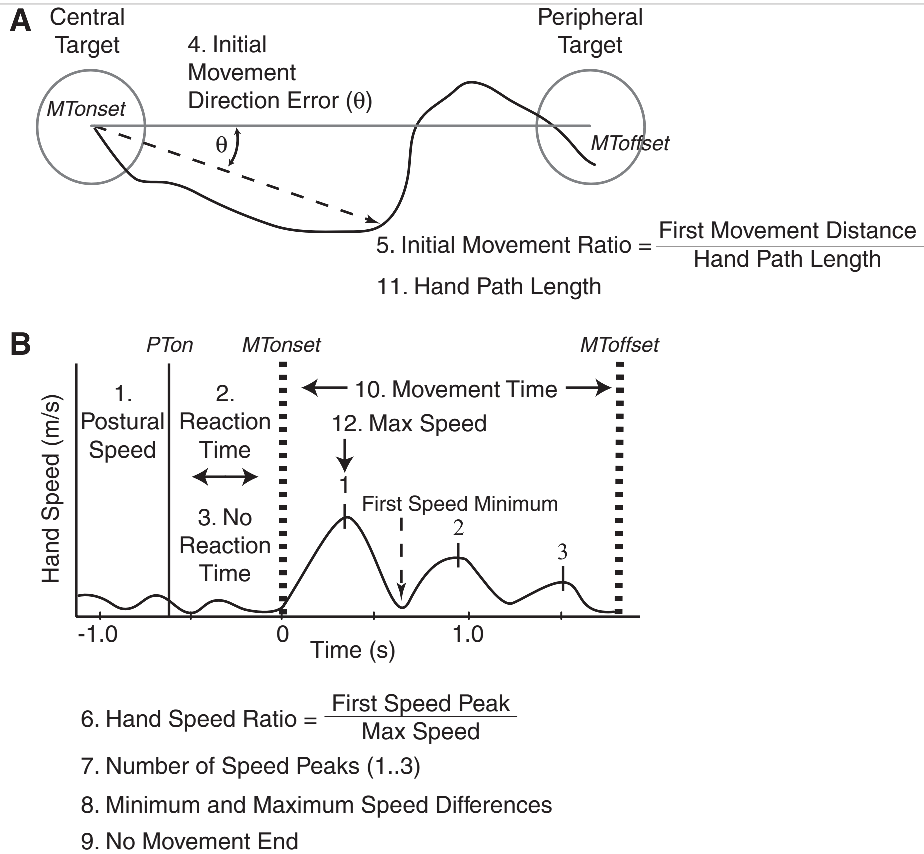

Figure 1. Movement parameters: schematic illustrating the 12 movement parameters used to characterize performance in the reaching task. The parameters are derived from (A) the hand position signal and (B) the hand speed signal. Participants made center-out reaches from a central target to 8 peripheral targets. The initial movement phase was from movement onset to first speed minimum

Abbreviations: MTonset, movement onset; MToffset, movement offset; PTon, peripheral target light on.

2. no reaction time is the number of trials for which no movement onset was detected (ie, the participant did not move).

Feed-forward control. Three parameters characterize a participant's initial phase of movement. The time period was from movement onset to the first minimum hand speed. First minimum hand speed was the first local minimum after the first maximum hand speed:

1. initial movement direction error (in degrees) is the angular deviation between (*a*) a straight line from the hand position at movement onset to the peripheral target and (*b*) a vector from the hand position at movement onset to the hand position after the initial phase of movement;
2. initial movement ratio is the ratio of (*a*) the distance the hand traveled during the participant's initial movement to (*b*) the distance the hand traveled between movement onset and offset; and
3. hand speed ratio is the ratio of (*a*) the maximum hand speed during the participant's initial movement to (*b*) the global hand speed maximum of the trial.

Feedback control. This attribute has 3 parameters and characterizes how participants adjust or correct their movements after their initial motor response:

1. number of speed peaks is the number of hand speed maxima between movement onset and offset;
2. differences between speed maxima and minima (m/s) are the differences between local speed peaks and minima; and
3. no movement end is the number of trials for which no movement end was detected, for example, the participant did not reach or stabilize at the peripheral target.

Total movement metrics. This attribute contains 3 parameters and characterizes the movement as a whole:

1. movement time (s) is the total time elapsed from movement onset to offset;

Table 1. Demographic and Clinical Data

Measure	Left-Affected Participants (n = 26)		Right-Affected Participants (n = 26)		Controls (n = 91)	
Age[a]	63 (22, 90)		66 (29, 92)		61 (21, 82)	
Gender (M/F)	13/13		14/12		39/52	
Handedness (R/L/A)	23/1/2		25/1/0		87/4/0	
Type of stroke (I/H)	25/1		21/5		N/A	
Stroke location (C/SC/B/Cr/M)[b]	5/4/2/2/13		9/5/5/0/7		N/A	
Days since stroke[a]	31 (11, 206)		31 (15, 94)		N/A	
BIT[a]	145 (109, 146)		144 (130, 146)		N/A	
MMSE[a]	28 (20, 30)		29 (17, 30)		N/A	
FIM intake score[a]	87 (53, 119)		102 (47, 124)		N/A	
Limb	Unaffected	Affected	Unaffected	Affected	Nondominant	Dominant
CMSAh score[c]	[0,0,0,0,0,2,24]	[0,3,3,1,4,5,10]	[0,0,0,0,0,5,21]	[1,2,3,1,3,6,10]	[0,0,0,0,0,0,90]	[0,0,0,0,0,0,90]
CMSAa score[c]	[0,0,0,0,0,3,23]	[0,3,2,4,2,2,13]	[0,0,0,0,0,2,24]	[1,0,4,1,3,4,13]	[0,0,0,0,0,0,90]	[0,0,0,0,0,0,90]

Abbreviations: M/F, male/female; R/L/A, right handed/left handed/ambidextrous; I/H, ischemic/hemorrhagic; BIT, Behavioural Inattention Test; MMSE, Mini-Mental Status Exam; FIM, Functional Independence Measure; CMSAh, Chedoke-McMaster Stroke Assessment Scale hand; CMSAa, Chedoke-McMaster Stroke Assessment Scale arm.

[a]The median value is given, with minimum and maximum values in parentheses.

[b]C/SC/B/Cr/M represents cortical/subcortical/brainstem/cerebellum/mixed.

[c][n_1, n_2, n_3, n_4, n_5, n_6, n_7] represents number of participants with Chedoke-McMaster scores of [1, 2, 3, 4, 5, 6, 7].

2. hand path length (m) is the total distance traveled by the hand between movement onset and offset; and
3. maximum hand speed (m/s) is the maximum speed that the hand traveled.

Data Analysis

All statistical analyses were performed using MATLAB (Mathworks Inc, Natick, MA). A participant's performance on most movement parameters was characterized by the median values across all trials and targets. For 3 parameters (number of speed peaks, hand speed ratio, and differences between speed maxima and minima), mean values were used because of the relatively small range in values across trials and targets.

Impairments were defined as participant performance falling either below 95% of controls (initial distance ratio, initial speed ratio, and maximum speed) or above 95% of controls (reaction time, total movement time, posture speed, no reaction time count, no movement end count, path length, initial direction error, number of speed maxima, and differences between speed maxima and minima). In the case of multiple testing of related parameters, we used a Bonferroni correction.

Results

Participant Pool

Demographic data on participant age, gender, and handedness are shown in Table 1. Clinical and robotic assessments were carried out on 52 patients with stroke (26 left- and 26 right-affected) and 91 age-matched controls. There were no differences in the distributions of age across the 3 participant groups nor between male and female controls (Kolmogorov-Smirnov [KS], $P > .05$), and all but a few participants (n = 8/143) were right-hand dominant. Whereas the majority of stroke participants had ischemic strokes (25/26 left- and 21/26 right-affected), there was a range in the locations of stroke, including cortical, subcortical, brainstem, cerebellum, and mixed. There were differences in the performance between male and female controls on 2 movement parameters (total movement time and maximum hand speed; t tests, $P < .05$). For these parameters, male stroke patients were compared with male controls and female stroke patients with female controls.

Clinical Measures

Clinical measures for both control and stroke participants are displayed in Table 1. All control participants obtained a perfect score with each limb on both the arm and hand portion of the CMSA (CMSAa and CMSAh).

Not surprisingly, left-affected stroke participants obtained worse scores with their affected arm as compared with their unaffected arms for CMSAh (2-sided signed rank test, $P < .001$) and CMSAa (2-sided signed rank test, $P < .001$). Similarly, right-affected participants obtained worse scores with their affected as compared with the unaffected arm on CMSAh (2-sided signed rank test, $P < .001$) and CMSAa (2-sided signed rank test, $P < .001$).

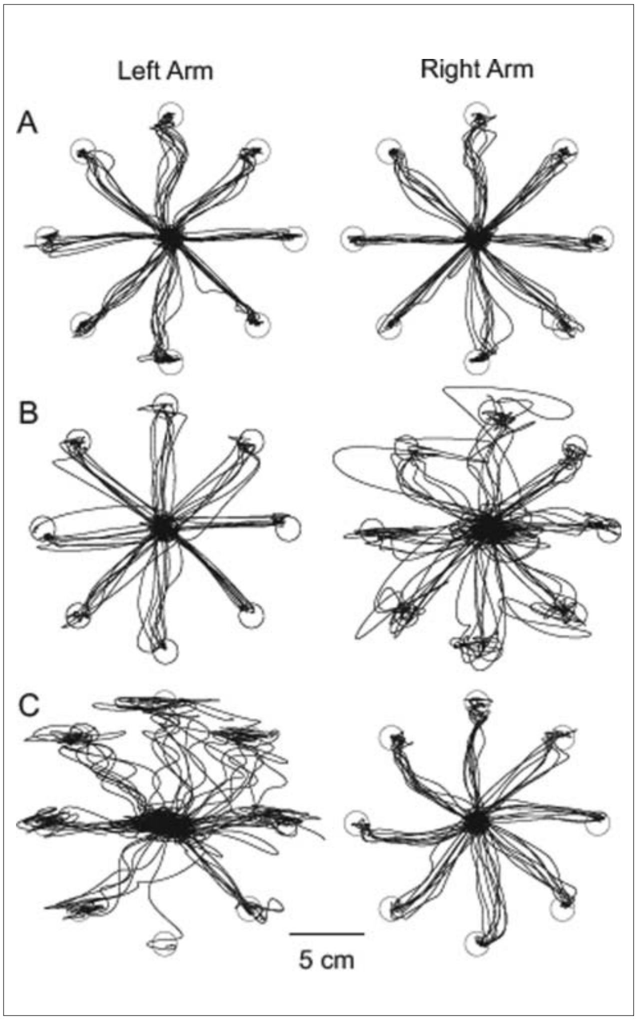

Figure 2. Hand paths for 3 representative participants: hand paths for (A) 62-year-old, right-handed, male control participant (#399) and (B) 79-year-old, male, right-handed, and right-affected stroke participant (#287). This participant had a stroke in the left middle cerebral artery territory; he obtained CMSAa/CMSAh scores of 7/7 with his left hand arm/hand and CMSAa/CMSAh scores of 6/5 with his right arm/hand. (C) Hand path for an 83-year-old, female, right-handed, and left-affected stroke participant (#320); she had a stroke in the right middle cerebral artery territory. She obtained CMSAa/CMSAh scores of 6/6 with her left arm/hand and CMSAa/CMSAh scores of 7/7 with her right arm/hand.
Abbreviations: CMSAa, arm impairment score of the Chedoke-McMaster Stroke Assessment Scale; CMSAh, hand impairment score of the Chedoke-McMaster Stroke Assessment Scale.

No differences were observed between the affected arms of left- and right-affected participants or between the unaffected arms on either the CMSAh or the CMSAa (2-sided rank sum tests, $P > .05$). In addition, no differences were observed between left- and right-affected participants on the FIM, BIT, or MMSE (2-sided rank sum tests, $P > .05$).

The affected arms of left- and right-affected stroke participants were worse than those of controls as seen from the CMSAh and CMSAa (2-sided rank sum tests, $P < .001$) scores. Performances of the unaffected arms of left- and right-affected participants were also worse compared with those of controls as evident from CMSAh and CMSAa (2-sided rank sum tests, $P < .05$) scores.

Robotic Assessment

As expected, the hand paths of the exemplar control participant, shown in Figure 2A, were relatively straight, with small corrective movements and modest amounts of trial-to-trial variability. In contrast, the hand trajectories of the affected arm of the right-affected participant in Figure 2B were highly variable and often required large corrective movements. Those for the affected arm of the left-affected participant (Figure 2C) were highly erratic and illustrated that the participant often failed to move toward targets located near her body.

In Figure 3A, movement times are plotted for all participants. A high correlation was observed between the dominant and nondominant limbs of control participants ($r = 0.83$; $P < .001$). In addition, there was no difference in the distributions of movement times between the 2 limbs of controls (Figure 3B; KS, $P > .05$). When we examined the relationship between the control participants' dominant (thick black) and nondominant (thin black lines) limbs across the other 11 parameters (Figure 4), we again did not observe any statistical differences between the 2 limbs (KS, $P > .05$), except in the number of speed peaks (KS, $P = .04$). As a result, normal behavior was calculated from the 95th percentile of combined data from both limbs of control participants.

Across the 2 groups of stroke participants, movement times were longer for the affected arms than for the unaffected arms (Figure 3A). In Figure 3B, the data are replotted in a cumulative sum histogram, and a couple of trends emerge. First, movement times for the affected arms of left- (thick blue) and right-affected participants (thick red) are longer as compared with those for controls (KS, $P < .05$), with 58% of left- and 38% of right-affected participants taking longer than 95% of control participants. Second, although there was no difference in movement times between the unaffected limbs of left- (thin blue lines) and right-affected (thin red lines) participants (KS, $P > .05$), there was a trend for longer movement times for left-affected participants. Figure 4 displays the histograms for all 12 movement parameters, and again, a number of trends emerge. First, left-affected participants using their affected arms generally displayed the worst performance. This is illustrated by the distance of the thick blue curves compared with the black curves (ie, the black and thick blue curves do not overlap). In addition, statistical analyses showed that left-affected participants using their affected arm did not perform as well as controls on any parameter (KS, $P < .05$). Furthermore, these participants did not

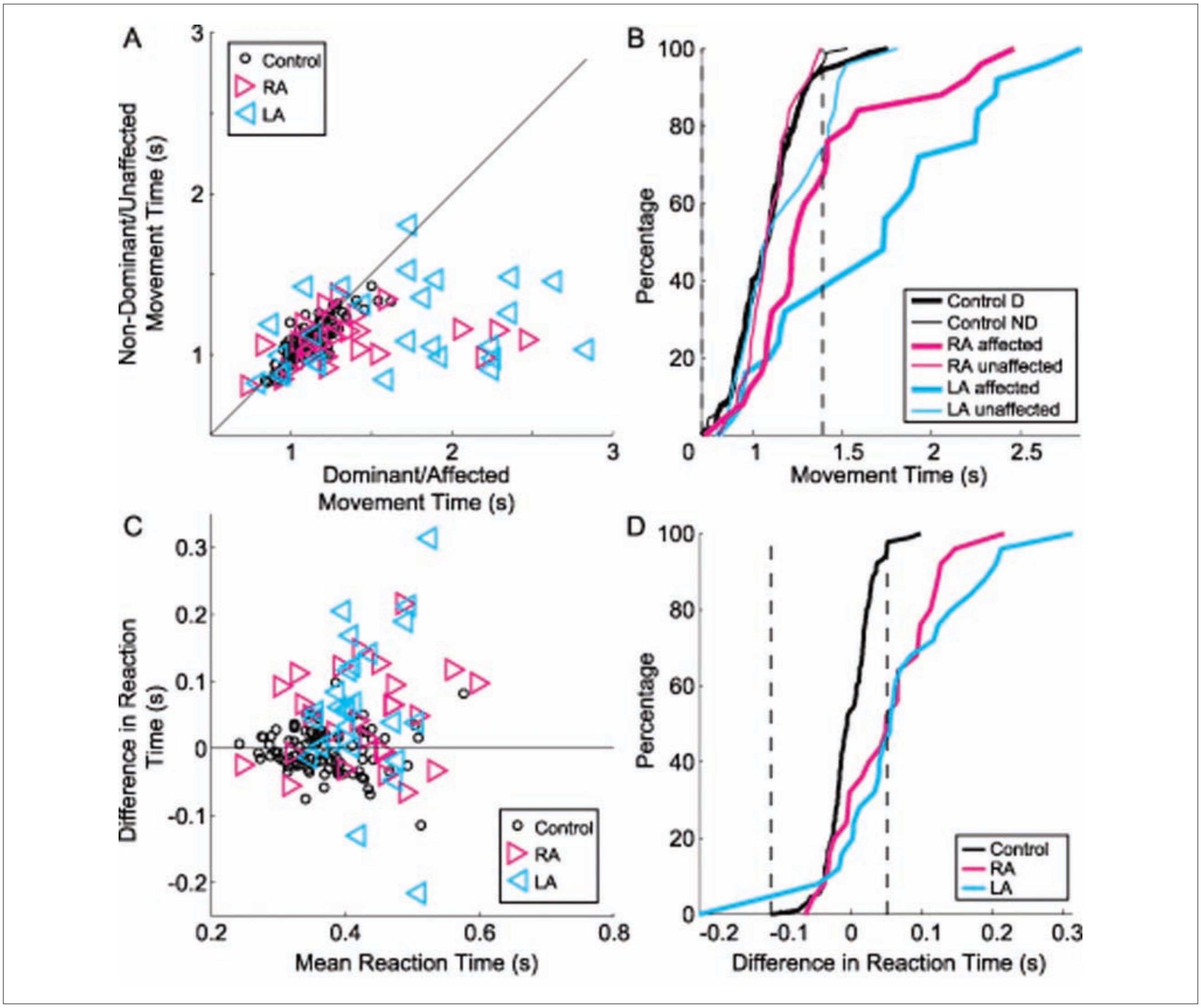

Figure 3. Movement time and interlimb differences in reaction time: (A) movement times obtained from the dominant arm of controls and affected arms of stroke participants are plotted against the movement times obtained from the nondominant and unaffected arms. (B) Cumulative sum histograms (CUSUM) of movement times are plotted for each of the participant groups. Movement times within each participant group were sequentially ordered from fastest to slowest, summed and plotted against the percentage of the participant group. Dashed vertical lines represent the minimum value and the 95th percentile value of controls (left-most line is at 0 s). (C) Mean reaction times are plotted against the differences in reaction time between the 2 limbs for controls, left-affected, and right-affected participants. Positive differences indicate slower reaction times for dominant/affected limbs, and negative differences indicate slower reaction times for nondominant/unaffected limbs. (D) CUSUM histogram of limb differences in reaction time for each of the 3 participant groups. Dashed vertical lines represent the minimum value and the 95th percentile value of controls

Abbreviations: D, dominant arm; ND, nondominant arm; RA, right-affected participants; LA, left-affected participants; RA affected, right arm of right-affected participant; RA unaffected, left arm of right-affected participant; LA affected, left arm of left-affected participant; LA unaffected, right arm of left-affected participant.

perform as well as right-affected participants using their affected arms on 7 parameters (initial direction error, initial distance ratio, initial speed ratio, number of speed peaks, no movement end count, total movement time, path length; KS, $P < .05$).

Second, there are a number of parameters that individually identified a large percentage of stroke participants as being different from controls based on their affected arms (Table 2, Figure 4). The parameters that identified the highest number of stroke participants as abnormal were the following: initial direction error (81% of left- and 50% of right-affected; see also Figure 4D) and initial distance ratio (73% of left- and 35% of right-affected; see also Figure 4E). The parameters that identified the least number

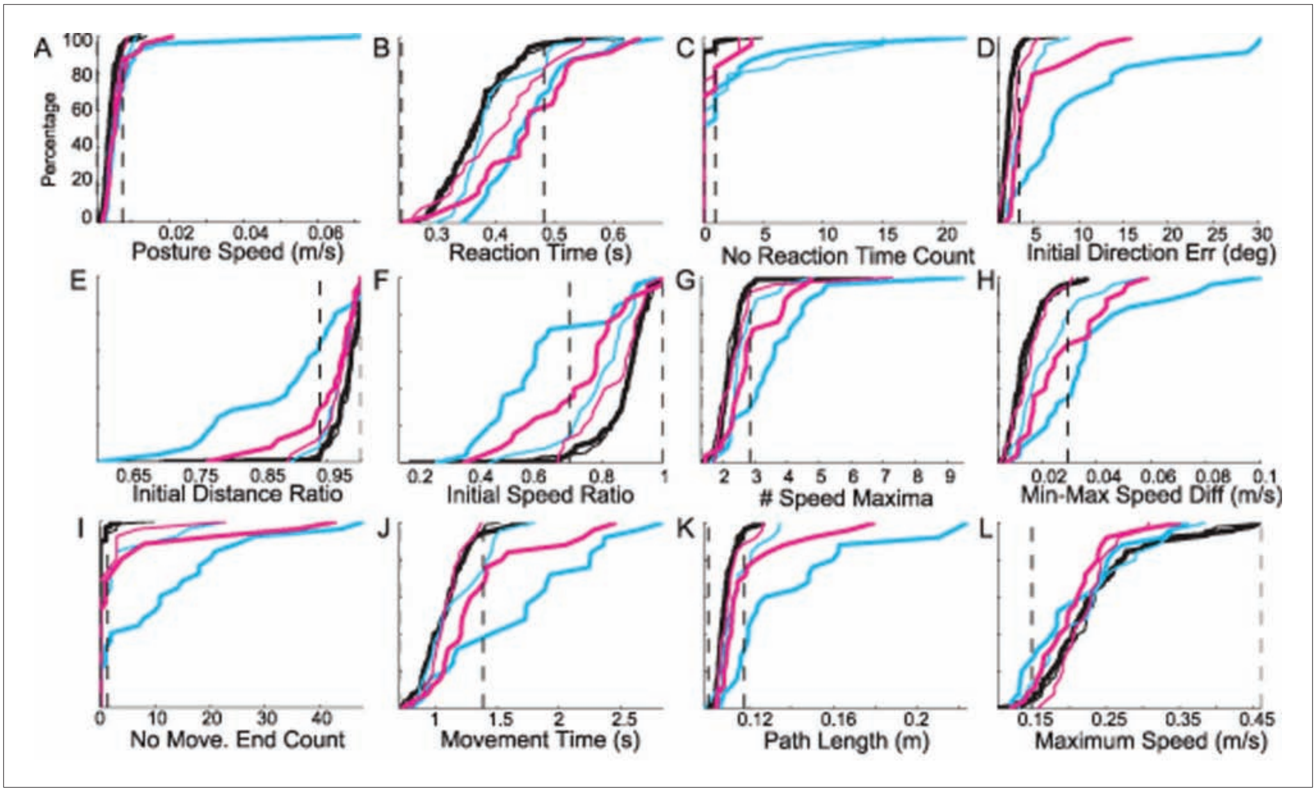

Figure 4. Cumulative sum histograms (CUSUMs) for all movement parameters: CUSUM histograms for each movement parameter are plotted. Dashed vertical lines represent the minimum value and the 95th percentile value of control participants (E, initial distance ratio; F, initial speed ratio; and L, maximum speed) or 5th percentile value to the maximum value (A, posture speed; B, reaction time; C, no reaction time count; D, initial direction error; G, number of speed maxima; H, differences between speed maxima and minima; I, no movement end count; J, movement time; and K, path length). Color legend the same as in Figure 3B.

of stroke participants as abnormal were the following: maximum hand speed (27% of left- and 19% of right-affected; see also Figure 4L) and no reaction time count (27% of left- and 15% of right-affected participants; see also Figure 4C).

Third, movements made with the unaffected limbs of left-affected stroke participants were also worse than those of controls for 7 parameters (Figure 4C, no reaction time count; 4D, initial direction error; 4E, initial distance ratio; 4G, number of speed maxima; 4H, difference between speed minima and maxima; 4I, no movement end count; and 4K, path length; KS, $P < .05$). In addition, right-affected participants using their unaffected arms were worse than controls for 3 parameters (Figure 4A, posture speed; 4B, reaction time; 4D, initial direction error; KS, $P < .05$).

Interlimb Differences

We directly compared the performance between the 2 limbs (nondominant and dominant arms of individual control participants, and affected and unaffected arms of individual stroke participants). In Figure 3C, differences in reaction time are plotted against mean reaction times of the 2 limbs. Positive differences indicate slower reaction times for dominant/affected limbs, and negative differences indicate slower reaction times for nondominant/unaffected limbs. The key feature within the control group is that although the range of mean reaction times was 243 ms to 577 ms, the range of interlimb differences was only –115 ms to 98 ms. This means that although there was a broad range in reaction times across control participants, individual control participants had similar reaction times with both arms. Furthermore, no systematic bias was apparent: approximately equal numbers of participants responded faster with their dominant (n = 49) and nondominant arms (n = 42).

In contrast to controls, the range of mean reaction times for left-affected participants was 348 ms to 526 ms, and the range of differences was –216 ms to 314 ms (Figure 3C). For right-affected participants, the range of mean reaction times was 247 ms to 597 ms, and the range of differences was –66 ms to 216 ms. In addition, both left- and right-affected participants tended to respond more quickly with their unaffected arms (21/26 left- and 17/26 right-affected participants).

In Figure 3D and Table 2, we see that 54% of left-affected and 46% of right-affected participants fall outside

Table 2. Percentage of Participants Who Differed From Normal Behavior and Correlation Coefficients From Interrater Assessment

		Left-Affected Participants				Right-Affected Participants				
Attribute	Parameter	Unaffected Arm	Affected Arm	Interlimb Difference	Combined[a]	Unaffected Arm	Affected Arm	Interlimb Difference	Combined[a]	Interrater Assessment, r
Postural control	Posture speed	15	31	42	38	8	23	23	23	0.77[b]
Reaction time	Reaction time	19	31	54	50	19	38	46	54	0.80[b]
	No reaction time count	31	27	23	27	15	15	15	15	0.60[b]
Feed-forward control	Initial direction error	42	81	69	77	19	50	54	58	0.77[b]
	Initial distance ratio	15	73	62	73	15	35	46	38	0.88[b]
	Initial speed ratio	12	65	62	65	15	31	23	23	0.91[b]
Feedback control	No. of speed maxima	23	69	62	68	8	35	31	38	0.85[b]
	Minimum, maximum speed difference	19	65	58	69	8	38	65	58	0.83[b]
	No movement end count	38	65	50	58	27	31	19	23	0.49[b]
Total movement metrics	Movement time	15	58	54	58	4	38	46	46	0.91[b]
	Path length	27	69	62	73	12	31	38	35	0.62[b]
	Maximum hand speed	12	27	35	38	4	19	19	31	0.97[b]

[a]Combined is the combination of affected limb of interlimb difference.
[b]$P < .05$; r is the interclass or Spearman correlation.

the 95th percentile of controls. Furthermore, although no difference was observed between the distributions of times between left- and right-affected participants (KS; $P > .05$), both left- and right-affected participants had distributions that differed from those of controls (KS; $P < .05$).

In Table 2, we see that similar to results with individual limbs, a greater proportion of left- versus right-affected participants were identified as abnormal, based on interlimb differences for almost all parameters. The parameter that identified the largest number of stroke participants as abnormal was initial direction error (69% of left- and 54% right-affected participants), whereas the parameter that identified the least number of participants as abnormal was no reaction time count (23% of left- and 15% of right-affected participants).

Interrater Reliability

To assess the reliability of each parameter, a subset of 14 participants (6 controls and 8 participants with stroke) performed the reaching task twice, with 2 different experimenters. We found that all 12 movement features displayed significant correlations across the 2 assessments (Table 2). Nine parameters displayed good interrater reliability (interclass correlation, $r > 0.7$; $P < .05$), including 7 with interclass correlations above 0.8. No reaction time count, no movement end count, and path length were excluded from the remaining analyses presented in this article because they exhibited low interrater reliability (Spearman correlation, $r = 0.60$ and $r = 0.49$, and interclass correlation, $r = 0.62$, respectively).

Assessing Neurological Impairments

We also examined each individual stroke participant's performance in the 5 attributes of motor control as compared with control participants (Figure 5). As predicted by earlier analyses, left-affected participants show greater differences from controls based on the performance of their affected arms (Figures 5A and 5B), unaffected arms (Figures 5C and 5D), or differences in performance between both arms (Figures 5E and 5F). This is denoted by the greater number of black and gray bars. Several left-affected participants are identified as different from controls in all 5 attributes for the affected arm and for interlimb differences between the 2 arms. Second, most left- and right-affected participants with impairments in feed-forward control also had impaired feedback control (Fishers' exact probability test, $P < .05$). Finally, and perhaps most interesting, performance deficits with the affected arm do not correlate well with performance deficits with the unaffected arm. This is illustrated by the absence of a top-to-bottom gradient in the unaffected arms (Figure 5C and 5D), even though participants are in the same order as for the affected arm.

Comparisons Between Robotic and Clinical Assessments

We identified the participants with stroke who were different from our control participants based on our 5 sensorimotor attributes and examined whether the CMSAa identified the same cohort. Table 3 displays the number of participants deemed abnormal by a sensorimotor attribute and CMSAa, only a sensorimotor attribute, only CMSAa, or neither. In general, left-affected participants displayed a significant association between the sensorimotor attributes and CMSAa (Fisher's exact probability test, $P < .05$), except between upper-limb postural control and CMSAa. Furthermore, the movement-related attributes (feed-forward, feedback, and total movement metrics) identified several participants as different from controls, even though they had scored 7 in the CMSAa. For example, 13 left-affected participants using their affected arm were found to have abnormal feed-forward control and had scores less than 7 on the CMSAa. The remaining 13 participants obtained perfect scores of 7 on CMSAa, including 5 who had abnormal feed-forward control. For right-affected participants, a significant association was observed between most sensorimotor attributes and CMSAa (Fisher's exact probability test, $P < .05$), except upper-limb postural control and feed-forward control (Fisher's exact probability test, $P > .05$).

Discussion

Previous studies have identified differences in reaching performance between stroke and control participants.[16,20,22-24] In contrast, our objective was to use a reaching task to identify neurological impairments in individual participants. A key feature of this study was the use of a large cohort of controls, providing a basis for statistically identifying when the performance of individual participants was different from normal behavior.

Visually guided reaching provides several pieces of information related to sensorimotor function. First, the ability of the participants to stabilize their hand within the central target provides information on their upper-limb postural control. Posture and movement are distinct aspects of limb motor function demonstrating substantive changes in neural processing,[34] and neurological disorders can selectively impair 1 of these 2 tasks (ie, postural vs kinetic tremors).[35] Second, this task provides information on the use of vision for action reflected in the time to respond to the onset of the peripheral visual target.[36] Third, the reaching movement can be broadly separated into 2 components, related to initiating movement (feed-forward control) followed by corrective movements (feedback control). Although motor function may not be neatly segregated into separate feed-forward and feedback control processes,[6,37]

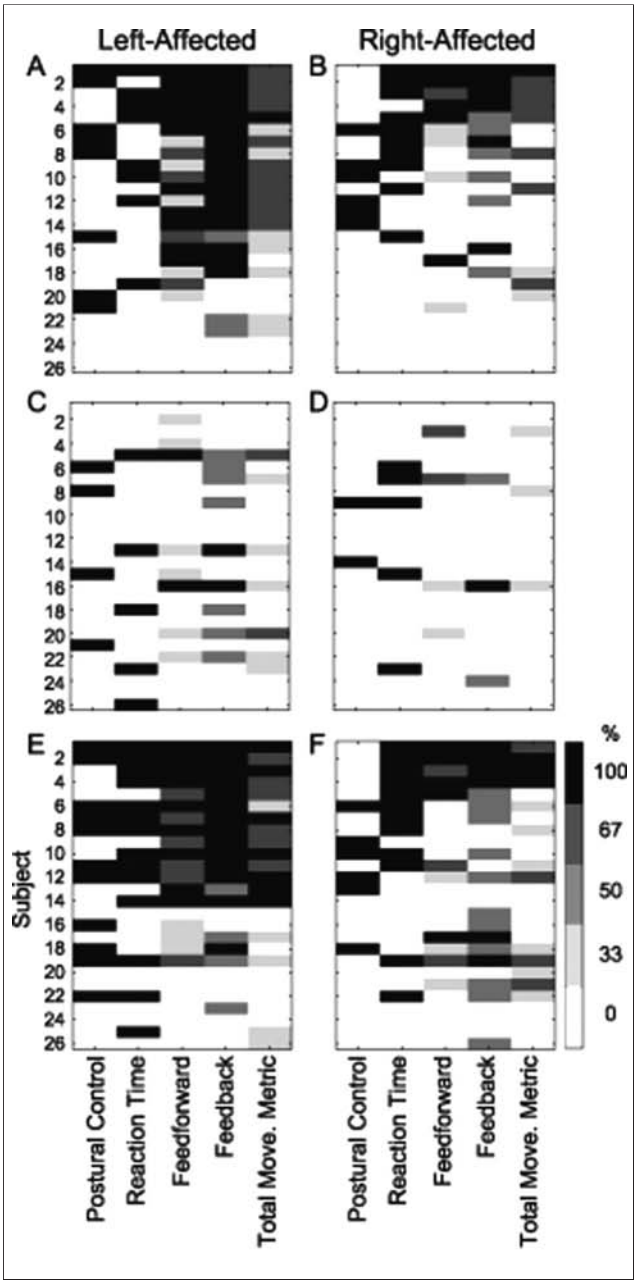

Figure 5. Attributes of motor control: individual participant's performances within the 5 attributes of motor control are plotted for their affected arm, unaffected arm, and interlimb differences. Participants are ordered from those with the greatest number of impaired parameters to the least, based on the affected arm (A, B). The ordering of participants is maintained for the panels displaying unaffected limb performance (C, D) and interlimb differences (E, F). White bars denote no difference from controls on any parameter within that attribute, whereas black denotes that all parameters within that attribute were different from those for controls. Gray bars represent intermediate values as is represented in the color bar.

these distinctions were made to reflect that some impairments can influence certain aspects of motor function. Thus, this single task provides several different attributes of sensorimotor function of the upper limb.

Male Versus Female Control Participants

We observed statistical differences between male and female controls on 2 movement parameters (total movement time and maximum hand speed). Male control participants tended to move faster and therefore completed the reaches in less time than female controls. These results are consistent with other studies that have demonstrated gender differences in speed in simple movement tasks.[38] In addition, we also observed that male control participants tended to have a stronger grip and pinch than female controls. This is also consistent with other studies demonstrating gender differences in strength[39,40] and supports the finding of male control participants moving faster than female control participants.

Left-Affected Versus Right-Affected Participants

Our results illustrated that left-affected participants tend to display greater deficits in performance with both their affected and unaffected limbs as compared with right-affected participants. This finding was preserved when we examined a subset of participants who had middle cerebral artery strokes (data not shown). Interestingly, this pattern has not always been observed across different voluntary motor tasks.[19,21,24,41] The disparity between our study and others may partially reflect differences in the population of participants sampled across studies. No clinical study, including ours, can be viewed as a truly random sample of participants with stroke because patients must volunteer to participate and be able to access the experimental facilities. As a result, studies tend to focus on individuals with mild to moderate deficits. Differences across studies also likely reflect factors such as movement complexity and participant skill level and attention, each of which influence the relative contributions of each hemisphere.[42]

Comparison With Clinical Assessments

An important question is how well our robotic-based assessment compares to a standard clinical assessment tool, CMSA. Good statistical overlap was found between our reaction time and movement-related attributes (feedforward control, feedback control and total movement metrics) for left- and right-affected participants and those scoring less than a perfect 7 on the arm portion of the

Table 3. Comparison of Sensorimotor Attributes and Arm Impairment Score of the Chedoke-McMaster Stroke Assessment Scale

	Attributes of Sensorimotor Control				
Stroke Group	Postural Control	Reaction Time	Feed-forward Control	Feedback Control	Total Movement Metrics
Left affected					
Affected arm	[7, 4, 6, 9]	[11, 3, 2, 10][b]	[13, 5, 0, 8][b]	[13, 5, 0, 8][b]	[13, 5, 0, 8][b]
Interlimb difference	[4, 4, 9, 9]	[7, 1, 6, 12][b]	[13, 7, 0, 6][b]	[12, 8, 1, 5]	[12, 7, 1, 6][b]
Right affected					
Affected arm	[3, 3, 10, 10]	[10, 2, 3, 11][b]	[8, 3, 5, 10]	[11, 6, 2, 7][b]	[10, 3, 3, 10][b]
Interlimb difference	[2, 4, 11, 9]	[6, 4, 7, 9]	[7, 3, 6, 10]	[9, 3, 4, 10][b]	[8, 2, 5, 11][b]

Abbreviation: CMSAa, Chedoke-McMaster Stroke Assessment Scale arm.
The numbers in brackets refer to the following: [abnormal attribute and abnormal CMSAa, abnormal attributes only, abnormal CMSAa only, neither attributes nor CMSAa are abnormal].
[b]Fisher's exact probability test, $P < .05$.

CMSAa. Interestingly, we were also able to classify several participants who received a perfect 7 as having deficits in their reaching performance as compared with our control population. This was particularly notable for left-affected participants. There was a clear lack of statistical overlap between CMSAa and our upper-limb postural control attribute for both stroke groups. This suggests that although this reaching task is able to measure postural stability deficits in stroke participants, these deficits do not appear to substantially influence performance in the CMSAa.

Interlimb Differences

As in previous studies, we observed that control participants instructed to reach "quickly and accurately" displayed a broad range of reaction times.[43-45] This likely reflects differences in their ability to respond to the visual stimuli as well as the opposing requirements of the task instruction, "to move quickly and accurately." Thus, some individuals may focus on moving quickly, whereas others may focus on being accurate, contributing additional variability to reaction times across a population.

This breadth of variability in reaction time for control participants was not observed when comparing values across the limbs for each individual control participant. We found that reaction time was highly conserved across the 2 limbs, with controls almost always showing differences that were less than 50 ms. Furthermore, there was no systematic bias between dominant and nondominant limbs. This suggests that a participant's strategy and neural processing time to initiate a visually guided movement is similar for both limbs.

This symmetry provides a subtle, but measurable approach for identifying changes in brain processing following stroke. Because of the anatomical organization of the brain and vasculature, a stroke almost always causes damage principally to one side of the brain, resulting in greater deficits to one side of the body. These deficits may not be sufficient to cause participants' performance to fall outside the range observed for control participants but may be sufficient to generate an asymmetry in performance across the 2 limbs. For example, 64% of stroke participants fell within the normal range for reaction time with their affected limb, but 34% of these participants displayed interlimb differences that were greater than those of controls. Thus, interlimb comparisons provide a potentially important measure for identifying a neurological impairment in sensorimotor function.

Limitations

One feature of the KINARM robotic system is that it provides full weight support of the upper limb as participants move in the horizontal plane. On the one hand, this weight support uncouples the strength and motor coordination necessary for performing daily activities such as reaching to grab an object in the environment. On the other hand, this uncoupling permits us to break down daily activities (ie, reaching) into specific impairments that underlie disability. It is known that those with cerebellar lesions tend to have impairments in motor coordination without loss of strength,[46] whereas those with cerebral lesions associated with the motor cortex have reduced strength capabilities. Several patients with severe weakness noted that although they had no ability to use their limb for daily activities, they were able to generate some motor actions while their limb was supported in the horizontal plane. In effect, the present task permits examination of the ability of participants to coordinate their motor patterns at the shoulder and elbow without the additional need for strength to support the limb against gravity.[47] Thus, participants may be able to perform as well as control participants with this weight support, even if there is a clear neurological impairment or weakness. An obvious extension is to have participants make the same reaching movements while they maintain full or partial weight support. Sensors on the robot could be added to monitor and provide feedback regarding the amount of this support. Comparisons across the 2 conditions (ie, reaching with full vs no weight support) would provide additional information regarding a participant's strength versus their coordination skills.

Because of the nature of the task, only trials in which participants successfully completed a reach were included in the analysis. The parameters no reaction time count and no movement end count were meant to capture incomplete trials, but they were found to have weak interrater reliability. This meant that we were in effect analyzing only a participant's "best movements." Future studies involving loading the limb would address this problem by potentially increasing the number of trials participants may be unable to complete and by examining end-point positions of the hand.

Conclusions

This study used visually guided reaching movements to quantify sensorimotor impairments in individual stroke participants with mild to moderate stroke severity as compared with controls. The use of weight support permitted us to explore impairments in motor coordination with minimal influence of loss of muscle strength on motor performance. We used a continuous scoring system in the form of 9 movement parameters to quantify neurological impairments related to reaching. We found that more than 80% of left-affected and 50% of right-affected stroke participants were found to be impaired on at least 1 sensorimotor attribute. In addition, we found that interlimb differences in performance were also valuable in quantifying impairments in individuals with stroke. The findings from this study indicate that robotic technology can provide reliable information about a participant's sensorimotor impairments.

Declaration of Conflicting Interests

SHS is the cofounder and chief scientific officer of BKIN Technologies, the company that commercializes the robotic technology used in this study.

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