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Quantitative Assessment of Limb Position Sense Following Stroke

Sean P. Dukelow, MD, PhD,[1] Troy M. Herter, PhD,[2] Kimberly D. Moore,[2] Mary Jo Demers,[3] Janice I. Glasgow, PhD,[2] Stephen D. Bagg, MD, MSc,[2,3] Kathleen E. Norman, PhD,[2] and Stephen H. Scott, PhD[2]

Abstract

Background. Impairment of position sense of the upper extremity (UE) may impede activities of daily living and limit motor gains after stroke. Most clinical assessments of position sense rely on categorical or ordinal ratings by clinicians that lack sensitivity to change or the ability to discriminate subtle deficits. *Objective*. Use robotic technology to develop a reliable, quantitative technique with a continuous scale to assess UE position sense following stroke. *Methods*. Forty-five patients recruited from an inpatient stroke rehabilitation service and 65 age-matched healthy controls performed an arm position matching task. Each UE was fitted in the exoskeleton of a KINARM device. One UE was passively placed in one of 9 positions, and the subject was told to match his or her position with the other UE. Patients were compared with statistical distributions of control data to identify those with deficits in UE position sense. Test–retest sessions using 2 raters established interrater reliability. *Results*. Two thirds of left hemiparetic and one third of right hemiparetic patients had deficits in limb position sense. Left-affected stroke subjects demonstrated significantly more trial-to-trial variability than right-affected or control subjects. The robotic assessment technique demonstrated good interrater reliability but limited agreement with the clinical thumb localizing test. *Conclusions*. Robotic technology can provide a reliable quantitative means to assess deficits in limb position sense following stroke.

Keywords

position sense, stroke, rehabilitation, robotics, proprioception

Introduction

Proprioception is the perception of the position, motion, and force generated by the body based on sensory information from muscle spindles, Golgi tendon organs, joint and cutaneous receptors, and efference copy of motor commands.[1-4] Position sense denotes the awareness of the relative position of a body segment, which is impaired in approximately one third to one half of stroke patients.[5,6] Reports indicate that intact position sense following stroke strongly correlates with motor recovery of the hemiplegic arm[7-11] and predicts the extent of long-term motor recovery.[12] However, these reports must be interpreted with some caution given the limitations of the clinical tools used for evaluating position sense.

Clinicians commonly assess position sense based on the ability of the patient to accurately discriminate the upward or downward position of a finger and toe[13] or of more proximal single joints.[14] Some clinicians use the thumb localizing test.[15] These clinical tools, however, have very poor interrater reliability and sensitivity and poor or absent normal value criteria.[14,16,17] Although more quantitative measures for joint position sense exist,[18-20] they examine position sense at a single joint[18,19] and require manual repositioning of the limb.[18,20]

Our objectives for the present study were (*a*) to develop a reliable, quantitative assessment tool for multijoint limb position sense and (*b*) to explore and further characterize the nature of position sense deficits in patients after stroke.

[1]University of Calgary, Calgary, Alberta, Canada
[2]Queen's University, Kingston, Ontario, Canada
[3]Providence Care, St Mary's of the Lake Hospital, Kingston, Ontario, Canada

Corresponding Author:
Stephen H. Scott, Centre for Neuroscience Studies, Queen's University, Botterell Hall, Room 219, Kingston, Ontario, Canada K7L 3N6
E-mail: steve@biomed.queensu.ca

Methods

Subjects

Subjects with stroke were recruited from the inpatient stroke rehabilitation ward within approximately 4 weeks (median = 32 days) of their stroke. Stroke lesion locations were documented by computed tomography or magnetic resonance imaging. We refer to stroke subjects by the *most affected side of their body* based on their clinical presentation, recognizing that some stroke subjects can present with unilateral lesions and bilateral deficits. Subjects were excluded from the study if they demonstrated a Folstein Mini-Mental Status Exam score of 24 or less[21] and their score could not be readily explained by expressive aphasia or illiteracy. Healthy control subjects with no history of neurologic impairment or orthopedic upper extremity problems were recruited from the community. The standardized robotic and clinical assessments were performed at Providence Care, St Mary's of the Lake Hospital site (Kingston, Ontario, Canada).

Robotic Assessment

Robotic device. The robotic assessment was performed using the KINARM device (Figure 1A; BKIN Technologies Ltd, Kingston, Ontario, Canada).[22] Subjects sit in the wheelchair base with each arm snugly fit within an exoskeleton, which was adjusted to the dimensions of the subject's body. The device constrains the subject's arms in the horizontal plane, monitors shoulder and elbow motion, and can apply mechanical loads at the shoulder and/or elbow. Subjects are allowed free head movement but vision of their arms and hands was occluded.

Description of the robotic matching task. Subjects were instructed to relax 1 arm (passive hand) and let the robot move it to 1 of 9 different spatial locations (targets; Figure 1B and C). The central target was positioned such that the shoulder was in 30° of horizontal abduction and the elbow in 90° of flexion. The robot moved their arm in a linear path from one target to another using a bell-shaped speed profile (max speed <1 m/s). When the robot stopped moving, subjects were asked to move their opposite hand (active hand) to the mirror location in space (Figure 1B and C). Subjects notified the examiner when they completed each trial and the examiner then triggered the next trial. Target locations were randomized within a block. Each subject completed 6 blocks for a total of 54 trials. Due to slight variations in muscle tone of the passively moved limb, we observed marginal variations of the passive hand position relative to the desired robotic target location (see Figure 1C). Our analysis removed these by computing the active hand error relative to the position of the passive hand for a given target and trial (see section "Robotic Data Analyses"). After completion of all trials using 1 arm (selected randomly), the same protocol was repeated with the opposite arm.

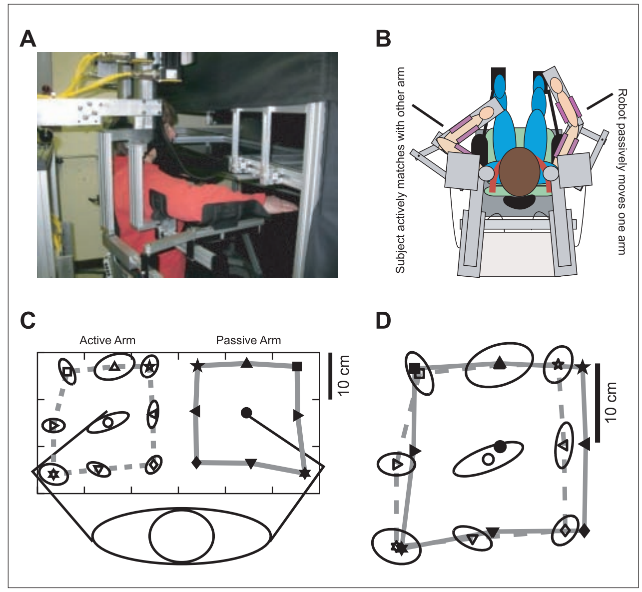

Figure 1. KINARM robotic device. (A and B) Picture and schematic of device. (C) Typical control subject data. The right hand was actively moved to 9 spatial locations by the robot (filled symbols). The subject mirror matched with the left hand (open symbols). Ellipses around the targets represent 1 standard deviation. (D) Data from right hand are mirror transformed to quantify discrepancies between the passive robotically moved hand position and the active hand position.

Interrater reliability. In a subset of subjects (n = 15 stroke subjects; n = 7 controls), we examined the interrater reliability of the robotic assessment. Subjects completed the entire experimental protocol (both robotic and clinical assessments). They were then removed from the KINARM device, all KINARM alignment settings were reset, and a second experimenter (blinded to the first assessment) repeated the robotic assessment. The retest was usually completed within a few minutes of the first assessment to avoid time as a confounding factor.

Robotic Data Analyses

Matching performance was quantified using the Cartesian positions of the tip of the index fingers of both hands at the end of each trial (Figure 1C). Position of the passive hand was mirrored across the x coordinate (Figure 1D), thereby allowing us to compare actual (active) and desired (passive) hand positions. Most quantitative studies of position sense have limited their analyses to mean absolute errors along a single dimension or joint.[23,24] This measure does not capture the breadth of errors that we observed during careful

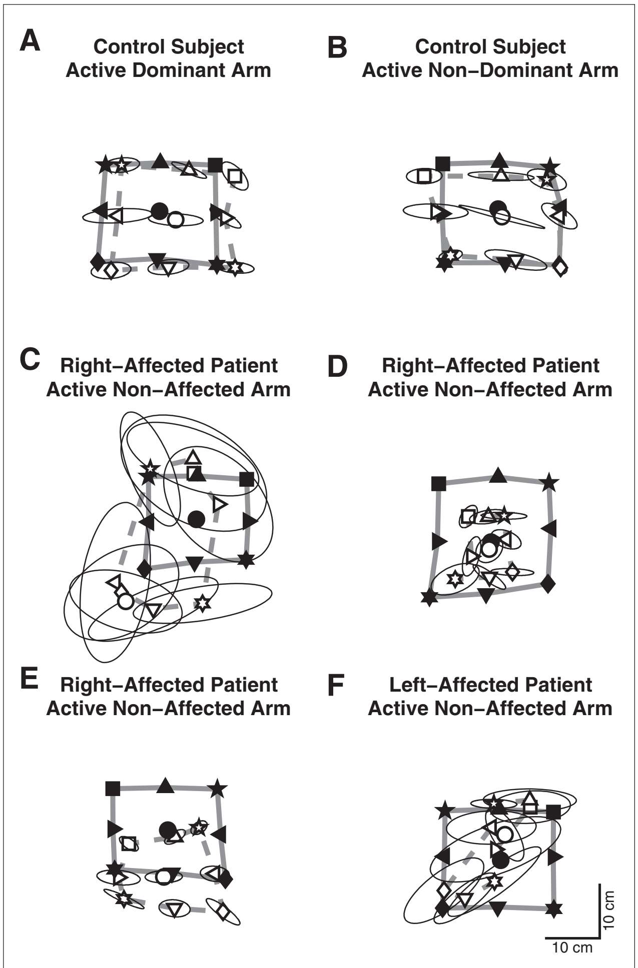

Figure 2. Data from 6 representative subjects. (A and B) Control subjects. Format same as Figure 1D. (C and F) Right middle cerebral artery (MCA) stroke subjects. (D and E) Left MCA stroke subjects.

inspection of the data from many subjects. Accordingly, we calculated 3 measures that reflected distinctive patterns of errors commonly observed: (*a*) trial-to-trial *variability* of the active hand (Figure 2C), (*b*) *contraction/expansion* of the overall spatial area matched by the active hand (Figure 2D), and (*c*) *systematic shifts* between the active and passive hands (Figure 2E). Our analysis focused primarily on the ability of subjects to match from the affected (passive) to the unaffected (active) hand because of the potential confound of weakness when matching in the opposite direction. Nonetheless, for completeness, data for position matching from the unaffected (passive) to the affected (active) hand are also presented in Figure 3.

Variability. Variability describes trial-to-trial consistency of the active hand. Some variability results from noise inherent in spindle afferent firing rates,[25] and damage to regions of the brain involved in sensory processing would presumably increase variability. This measure was calculated by finding the standard deviation of the active hand's position for each target location, then calculating the mean of standard deviations for all target locations in the x coordinate (var_x), y coordinate (var_y), and the linear variability for both coordinates combined (var_{xy}):

$$var_{xy} = \sqrt{var_x{}^2 + var_y{}^2} \tag{1}$$

Spatial contraction/expansion. Spatial contraction/expansion describes the range/area of the workspace matched by the active hand relative to that of the passive hand. This parameter (along with systematic shifts) examines deficits in spatial awareness leading to shifts or biases in perception and action in certain spatial regions.[26-28] Spatial contraction/expansion along the x axis ($cont/exp_x$) was obtained by finding the difference between the mean x position for the 3 right and 3 left targets (see Figure1D) for the active as compared with the passive hand using:

$$cont/exp_x = \frac{\text{range}_{x\_\text{active}}}{\text{range}_{x\_\text{passive}}}. \tag{2}$$

Values below 1 (spatial contraction, Figure 2D) were obtained when the range of the active hand was less than the passive hand, and values above 1 (spatial expansion) represent the opposite. A similar procedure was performed for calculating $cont/exp_y$. Spatial contraction/expansion along both coordinates ($cont/exp_{xy}$) was computed by finding the area spanned by the active hand for the 8 peripheral targets, then normalizing it by the total spatial area spanned by the passive hand.

Systematic shifts. Systematic shifts describe constant errors between the active and passive hands (Figure 2E). These were calculated by finding the mean error between the active and passive hands for each target location, then calculating the mean of means for all target locations. Systematic shifts were obtained for the x coordinate ($shift_x$), y coordinate ($shift_y$), and both combined ($shift_{xy}$):

$$shift_{xy} = \sqrt{shift_x{}^2 + shift_y{}^2}. \tag{3}$$

Statistical comparisons. Differences in the distribution and means of matching performance between groups (left-affected, right-affected, and control subjects) were assessed with Kolomogorov–Smirnov and t tests, respectively. Individual deficits in position matching were identified by comparing individual stroke subjects with confidence boundaries that included 95% of the data from the control subjects.

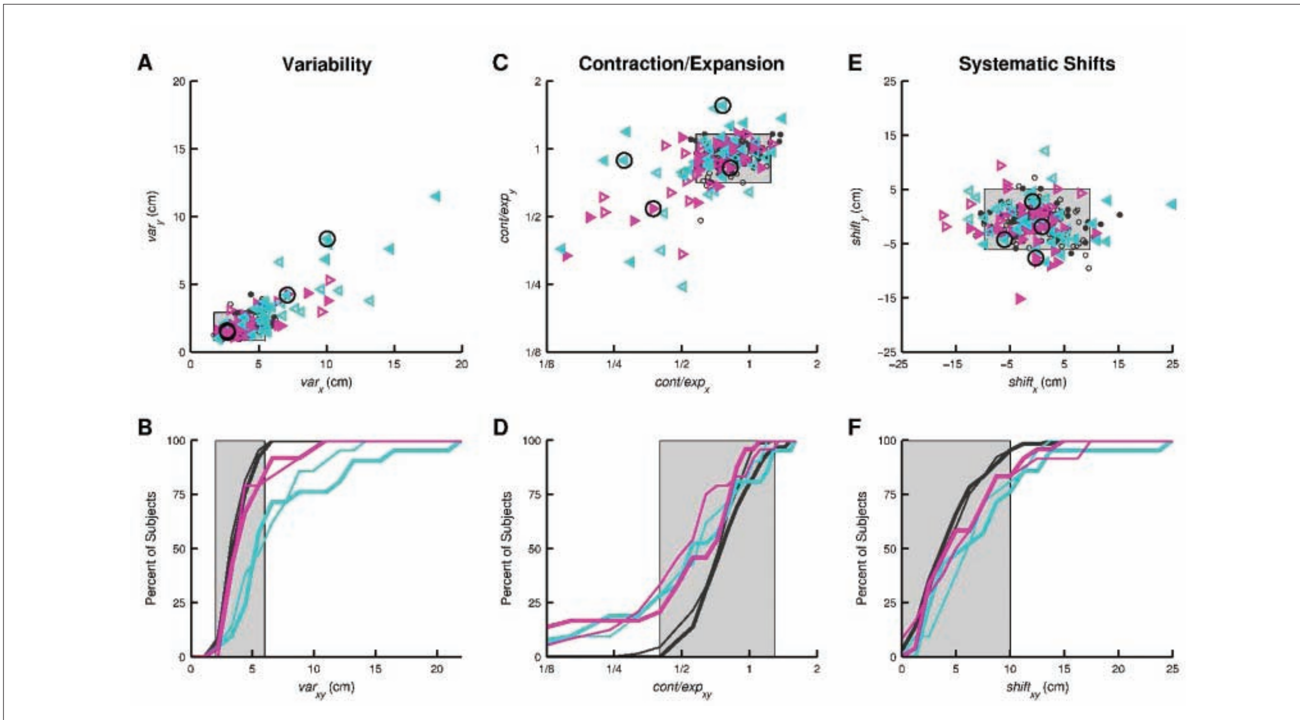

Figure 3. Variability, spatial compression/expansion, and systematic shift. (A, C, and E) Black circles, cyan triangles, magenta triangles: control, left- and right-affected stroke subjects, respectively. Filled symbols: matching performed with dominant (control) or unaffected (stroke) arm (open denotes opposite limb). The box contains 95% of control subjects. The 4 large open black circles represent the exemplar subjects from Figure 2C-F. (B, D, and F) Colors denote same groups as in panel A. Thick line denotes matching with dominant (control) and unaffected (stroke) arms (thin line denotes opposite limb). Gray boxes represent the 95% bounds for controls.

Clinical Assessments

A broad range of clinical assessment tools were used to obtain an overview of our subject sample by classifying and qualifying the sensory, motor, visuospatial, cognitive, and functional impairment levels of subjects using standard clinical assessment tools. Clinical assessments were performed by either a physician (SPD) or physiotherapist (MJD) with expertise in stroke rehabilitation who were blinded to the results of the robotic assessment. Many of the clinical measures collected are commonly administered at our hospital. Because there is currently no criterion or "gold" standard test of position sense, we measured position sense with a clinical test that served as a reference standard for comparison to the robotic assessment.

Clinical test of position sense. Proprioceptive function was assessed using the thumb localizing test,[1,15,22] an assessment used in many other studies involving stroke.[15,29-37] As described by Hirayama et al,[15] the subject, with eyes closed, extends one thumb and the examiner moves that arm to a position in front of the subject at or above eye level, lateral to the midline. The subject is then asked to pinch the extended thumb with the opposite thumb and forefinger. Subjects are scored 0 (accurately does the task) to 3 (subject is unable to find his or her thumb and does not climb up the affected arm to locate it). Stroke subjects localized the thumb on their affected arm, whereas controls localized the thumb on their dominant arm.

Although there are distinct differences between the thumb localizing test and the robotic matching task (subjects must cross the midline to perform the thumb localizing test), this clinical assessment was more similar to the robotic matching task than any other technique we found in the literature. Despite the differences between the techniques, we hypothesized that there should be some systematic overlap between the 2 measures given that both rely on upper extremity limb position sense.

Clinical tests of motor and other functions. Standardized scales were used to grade reflexes,[13] muscle power,[38] and tone.[39] Handedness was documented with the Edinburgh Inventory.[40] Motor impairment was evaluated with the Purdue Peg Board test (LaFayette Instrument Co, LaFayette, IN) and the Chedoke–McMaster Stroke Assessment (CMSA) arm and hand impairment inventories.[41] Visual acuity was determined using a Snellen Eye chart, and field defects were evaluated using confrontation technique.[13] Visuospatial

Table 1. Subject Characteristics[a]

Measure	Group: Stroke, Left Affected {n = 21}	Stroke, Right Affected {n = 24}	Control {n = 65}
Age	66 (22-90)	66 (29-84)	63 (22-93)
Gender	9 males, 12 females	16 males, 8 females	25 males, 40 females
Dominant hand	18 R, 0 L, 2 A	24 R, 0 L, 0 A	59 R, 2 L, 4 A
Type of stroke	21 ischemic, 0 hemorrhagic	19 ischemic, 4 hemorrhagic {n = 23}	—
Days since stroke	30 (11-206)	31 (15-76)	—
Thumb localizing score [0-3]	[8, 3, 7, 3]	[18, 4, 1, 0] {n = 23}	[60, 4, 1, 0]
CMSA affected arm [1-7]	[0, 4, 0, 3, 0, 1, 13]	[1, 1, 3, 1, 3, 2, 13]	—
CMSA unaffected arm [1-7]	[0, 0, 0, 0, 0, 0, 21]	[0, 0, 0, 0, 1, 2, 21]	[0, 0, 0, 0, 0, 0, 65]
MAS affected arm [0-4]	[13, 4, 3, 1, 0, 0]	[12, 9, 1, 1, 0, 0]	—
MAS unaffected arm [0-4]	[20, 1, 0, 0, 0, 0]	[22, 1, 1, 0, 0, 0]	[60, 0, 0, 0, 0, 0] {n = 60}
Purdue Peg Board affected	6 (0-11) {n = 20}	6 (0-15)	—
Purdue Peg Board unaffected	11 (6-15)	11 (6-14)	13 (6-18) {n = 51}
FIM	92 (50-119)	101 (46-124)	—
BIT	145 (138-146)	144 (131-146)	—
Folstein MMSE	29 (20-30)	28 (17-30) {n = 23}	—

Abbreviations: R, right; L, left; A, ambidextrous; CMSA, Chedoke–McMaster; MAS, Modified Ashworth Score; FIM, Functional Independence Measure; BIT, Behavioral Inattention Test; MMSE, Mini-Mental Status Exam.

[a]A small number of clinical assessments were not carried out on some subjects. For those assessments with missing subjects, the actual number of subjects is indicated within curly brackets. Age, Purdue Peg Board, FIM, BIT, and Folstein MMSE scores are indicated as the median followed by the range within parentheses. Thumb localizing, C-M, and MAS are shown as the number of subjects within each category within brackets. For example, there are 6 values for the MAS, corresponding to the number of subjects that scored a 0, 1, 1+, 2, 3, or 4. Thumb localizing scores indicate the score when subjects were localizing their affected/dominant thumb. C-M, MAS, and Purdue Peg Board scores of controls are for the dominant arm.

ability was scored with the conventional subtests of the Behavioural Inattention Test (BIT).[42] Functional ability was measured with the Functional Independence Measure (FIM).[43] Control subjects were assessed using all the aforementioned measures except for the last two.

Results

Subject Pool

Data were collected from 21 left-affected and 24 right-affected stroke subjects and 65 controls. Demographic and clinical features of the groups are shown in Table 1. The groups were similar with respect to age, gender, and hand dominance. Almost all subjects were right-hand dominant. Four control subjects scored as ambidextrous on the Edinburgh Handedness inventory,[40] but each reported being right-hand dominant. They were treated as such for the purpose of further analysis. Two left-affected stroke subjects also scored as being ambidextrous prestroke.

Robotic Position Matching Assessment

Individual subject exemplars. Figures 1D, 2A, and 2B illustrate exemplar matching behavior of 3 control subjects. Overall, the active arm (unfilled symbols) mirrors the position of the passive arm (filled symbols) relatively well. These 3 subjects demonstrated modest trial-to-trial variability (confidence ellipses, ±1 SD), which ranged from 1.5 to 5.9 cm, depending on the subject and target. They also showed negligible spatial contraction/expansion or systematic shifts. Relative to the control subjects, many patients exhibited greater errors in matching the position of their affected (passive) arm with their unaffected (active) arm. Figure 2C-F shows data from 4 stroke subjects matching with their unaffected side to illustrate various patterns of variability, spatial contraction, and systematic shifts. Figure 2C depicts data from a left-affected subject with a right middle cerebral artery (MCA) territory stroke. This subject demonstrated high variability (mean var_{xy} = 13.1 cm) with modest systematic shift (mean $shift_{xy}$ = 7.4 cm) and moderate spatial expansion ($cont/exp_{xy}$ = 1.25). Figure 2D displays data from a right-affected subject with a left MCA territory stroke who displayed considerable spatial contraction ($cont/exp_{xy}$ = 0.19) without much systematic shift (mean $shift_{xy}$ = 2.1 cm) or increased variability (mean var_{xy} = 3.1 cm). Figure 2E shows data from a right-affected subject with a left MCA territory stroke. This subject exhibited a systematic shift ($shift_{xy}$ = 15.2 cm) toward the body, whereas variability about the targets remained similar to the controls in Figure 2A and B (mean var_{xy} = 3.7 cm; range = 2.1-6.5 cm). Figure 2F illustrates the matching performance of a left-affected subject with a right MCA territory stroke whose matching data were characterized by high variability (mean var_{xy} = 8.3 cm), substantial spatial contraction ($cont/exp_{xy}$ = 0.26), but only a small systematic shift (mean $shift_{xy}$ = 2.9 cm).

Variability: group analysis. The upper range of variability in the x (var_x) and y (var_y) dimensions was 5.5 cm and 2.9 cm, respectively, for 95% of the control group (Figure 3A). Control subjects displayed a similar distribution of variability (var_{xy}) when matching with their dominant and nondominant arms (Figure 3B; Kolmogorov–Smirnov test, P = .68), thus dominant and nondominant arm data were grouped together for comparisons with stroke subjects. Grouping of the dominant and nondominant arm data was also performed for similar reasons in the following sections on spatial contraction/expansion and systematic shift.

The variability of many stroke subjects, particularly left-affected, dramatically exceeded that of the controls for var_x and var_y (Figure 3A) as well as var_{xy} (Figure 3B). Relative to the controls, both left-affected and right-affected stroke subjects, as a group, showed greater variability (var_{xy}) matching with their unaffected arm (t tests; left-affected, $P < 10^{-12}$; right affected, $P < .01$). Interestingly, left-affected subjects displayed significantly higher variability than right-affected subjects when matching with their unaffected arm (t test, $P < .01$). In addition, 9 of 21 (43%) left-affected subjects exhibited variability that was greater than 95% of controls, whereas only 4 of 24 (17%) of right-affected subjects were beyond the normal range.

As with the control subjects, we observed similar distributions of variability when stroke subjects matched with their affected and unaffected arms (Kolmogorov–Smirnov tests; left-affected, P = .80; right-affected, P = .86). Furthermore, matching with the affected or unaffected arm also revealed similar distributions for spatial contraction/expansion and systematic shift.

Spatial contraction/expansion: group analysis. The control group demonstrated a larger range of spatial contraction/expansion over the x dimension ($cont/exp_x$, 95% range = 0.58-1.24; Figure 3C) than was seen in the y dimension ($cont/exp_y$, 95% range = 0.71-1.16). The mean of each measure was significantly different from unity (t tests; $cont/exp_x$ = 0.85, $P < 10^{-12}$; $cont/exp_y$ = 0.94, $P < 10^{-6}$; $cont/exp_{xy}$ = 0.80, $P < 10^{-12}$).

Many stroke subjects demonstrated the phenomenon of spatial contraction as seen with the subject in Figure 2D, whereby all positions of the active arm were compressed into a smaller area of workspace than those of the passive arm (ie, $cont/exp_{xy} < 1$). Relatively fewer subjects demonstrated the opposite phenomenon of spatial expansion (ie, $cont/exp_{xy} > 1$) and most of these demonstrated expansion only in 1 dimension.

In the stroke group, both left-affected and right-affected subjects showed greater spatial contraction ($cont/exp_{xy}$) than the controls (t tests, $P < .002$ and $P < .018$, respectively) but there was no significant difference between the 2 stroke groups (t test, P = .77; Figure 3D). Importantly, 7 (33%) left-affected subjects and 5 (21%) right-affected subjects exhibited greater spatial contraction than 95% of controls (Table 2). Only a single stroke subject (left-affected) matching with the unaffected limb was outside the bounds of controls for spatial expansion ($cont/exp_{xy}$).

Table 2. Number of Stroke (Nonaffected Arm) and Control Subjects (Both Arms) With Deficits Determined by Each Assessment[a]

	Group		
Measure	Left Affected (n = 21)	Right Affected (n = 24)	Control (2 Arms) (n = 130)
Thumb localizer	13 (62%)	5 (21%)	9 (7%)
var_{xy}	9 (43%)	4 (17%)	6 (5%)
$cont/exp_{xy}$	7 (33%)	5 (21%)	6 (5%)
$shift_{xy}$	5 (24%)	4 (17%)	6 (5%)
Any one	14 (67%)	8 (33%)	17 (13%)
Any two	6 (29%)	3 (13%)	1 (1%)
All three	1 (5%)	2 (8%)	0 (0%)

[a]Results are shown for the nonaffected arms of stroke subjects and both arms of control subjects.

Systematic shifts: group analysis. The 95% range of $shift_x$ for control subjects extended from 9.0 cm medial to 9.6 cm lateral (Figure 3E, small circles). The mean $shift_x$ of controls (0.1 cm) was not statistically different than 0 (t test, P = .89). The 95% range of $shift_y$ for the control group was smaller, 6.1 cm toward the body to 5.1 cm away. The mean $shift_y$ of controls was 1.0 cm toward the body, which was statistically different from 0 (t test, $P < 10^{-4}$). The 95% range for the control group for $shift_{xy}$ was 0.4 to 10.1 cm.

Compared with control subjects, stroke subjects demonstrated a wider distribution of $shift_{xy}$ values (Figure 3E, cyan and magenta triangles). As a group, left-affected stroke subjects matching with their unaffected arms exhibited a mean $shift_x$ of 3 cm lateral that was not significantly different from 0 (t test, P = .09) and a mean $shift_y$ toward the body of 1.7 cm that was significantly different from 0 (t test, P = .04). As individuals, 1 left-affected subject shifted significantly medially, 4 shifted significantly laterally, and 2 shifted significantly toward the body.

As a group, matching by right-affected patients with their unaffected arms showed a mean $shift_x$ (0.6 cm medial) that was not significantly different from 0 (t test, P = .55), but $shift_y$ (3.5 cm toward the body) was significantly different from 0 (t test, $P < .001$). As individuals, 2 right-affected stroke subjects shifted significantly medially, 1 shifted significantly laterally, and 6 shifted significantly toward the body.

Overall, when examining the $shift_{xy}$, stroke subjects exhibited greater mean systematic shifts than controls

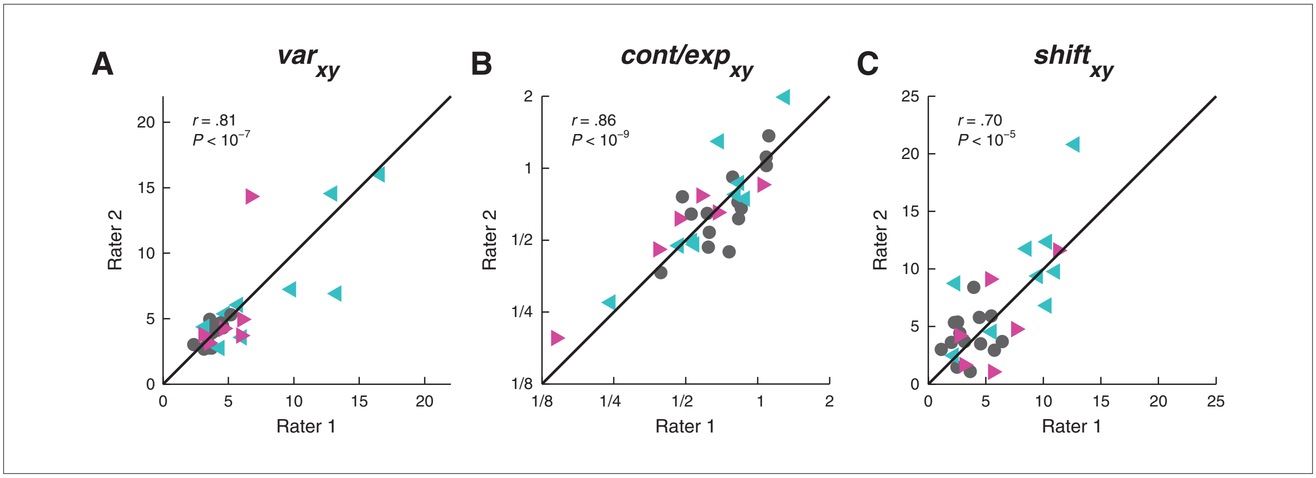

Figure 4. Interrater reliability: group data. Colors denote same groups as in Figure 3. Axes are identical to those of the *x* axis in Figure 3B, D, and F, respectively.

matching with their unaffected arm (Figure 3F; *t* tests, left-affected, $P = .003$; right-affected, $P = .028$). There was no significant difference between the mean $shift_{xy}$ for left-affected and right-affected stroke groups (*t* test, $P = .52$). Overall for $shift_{xy}$, 5 of 21 (24%) left-affected subjects compared with 4 of 24 (17%) right-affected subjects (Table 2) were abnormal when matching with their unaffected arm.

Interrater reliability. A subset of 22 subjects underwent 2 robotic assessment sessions conducted by 2 different examiners (Figure 4). Interrater reliability was assessed using intraclass correlation analysis for the parameters of variability(var_{xy}), spatial contraction/expansion ($cont/exp_{xy}$), and systematic spatial error ($shift_{xy}$). Both variability (var_{xy}) and spatial contraction/expansion ($cont/exp_{xy}$) demonstrated excellent interrater reliability ($r = .81$, $P < 10^{-7}$ and $r = .86$, $P < 10^{-8}$, respectively). Systematic spatial error ($shift_{xy}$) demonstrated moderate interrater reliability ($r = .70$, $P < 10^{-5}$).

Comparison between robotic measures. Within the control group, 6 individual arms (5%) were defined as abnormal on each robotic measure. One control subject fell outside the 95% bounds of controls on 2 robotic measures.

Within the stroke group, 14 (67%) left-affected and 8 (33%) right-affected stroke subjects were abnormal on any single measure (Table 2). In this group, 6 (29%) left-affected and 3 (13%) right-affected subjects had abnormalities on 2 robotic measures. Only 1 left-affected and 2 right-affected stroke subjects were abnormal on all 3 robotic measures.

Clinical Assessment

Timing of the assessment from stroke onset, FIM, BIT, Mini-Mental Status Exam, and Purdue Peg Board Scores for the left-affected and right-affected stroke subjects were similar (Kolmogorov–Smirnov tests, $P = .91$, .73, .49, .13, and 1.0, respectively). Forty-two percent of stroke subjects had significant hemiparesis as documented by the CMSA. The incidence of position sense deficits as measured with the robotic matching task was the same (47%) in subjects with and without hemiparesis when matching from the affected to the unaffected extremity. No subject demonstrated hemispatial neglect on the conventional subtests of the BIT (score <129). A total of 62% of left-affected, 21% of right-affected, and 7% of control subjects demonstrated impairments on the thumb localizing test. Eight left-affected and 11 right-affected stroke subjects had some evidence of spasticity (range of scores: 1-2, Modified Ashworth Scale). Spasticity, if present, was typically mild as only 2 subjects scored 2. Seven left-affected and 1 right-affected stroke subjects demonstrated evidence of visual field deficits, most commonly hemianopsia.

Comparison of Thumb Localizing Test to Robotic Measurement

The thumb localizing test[15] and robotic test identified a similar number of patients with deficits in limb position sense (Table 2). An examination of categorical overlap between the 2 tests (Table 3) demonstrated a random relationship between the thumb localization test and variability, spatial contraction/expansion, and systematic shifts (Fisher exact probability tests, $P > .1$). However, when we grouped all subjects together, we found a systematic overlap between the thumb localizing test and both variability and systematic shifts but not spatial contraction/expansion (Fisher exact probability tests, $P < .001$, $P = .02$, and $P = .13$, respectively).

Table 3. Agreement Between the Thumb Localizer Task and Robotic Measures[a]

	Group			
Measure	Left-Affected (n = 21)	Right-Affected (n = 24)	Control (2 Arms) (n = 130)	All Subjects (n = 175)
var_{xy}	[6, 3, 7, 5]	[1, 3, 4, 16]	[2, 4, 7, 117]	[9, 10, 18, 138]***
$cont/exp_{xy}$	[4, 3, 9, 5]	[1, 4, 4, 15]	[0, 6, 9, 115]	[5, 13, 22, 135]**
$shift_{xy}$	[4, 1, 9, 7]	[1, 3, 4, 16]	[1, 5, 8, 116]	[6, 9, 21, 139]*

[a]Numbers within brackets indicate the number of subjects flagged by (both tests, robotic test only, thumb localizing only, neither test). Results are shown for the nonaffected arms of stroke subjects and both arms of control subjects. Fisher exact probability tests were used to identify whether subjects raters exhibited systematic overlap: *$P < .05$, **$P < .01$, ***$P < .001$.

Discussion

Clinical Implications

Fifty percent of our stroke subjects had some element of position sense impairment, indicating that this is a common problem. Despite this, recognition and treatment has been limited. A systematic review of evidence for sensory retraining following stroke identified only 14 controlled studies of sufficient quality to be included.[44] The authors criticized the included studies for failing to use outcome measures that were reliable and sensitive to changes in impairments.

The technique we report is ideal for monitoring position sense in clinical trials given its sensitivity and reliability. Notably, our robotic assessment uses continuous scales that, compared with coarse ordinal scales, are more likely to discriminate subtle degrees of deficit and changes over time. A reliable technique for measurement of position sense may allow accurate serial measures of position sense following stroke to examine relationships between position sense and motor recovery. This tool may allow better prediction of sensory and motor recovery after stroke and aid in decisions regarding use of health care resources.

Although the cost of purchasing robotic technology for assessment is expensive relative to the current clinical assessments, the technology could provide distinct cost savings in the long term. For example, a technician could carry out a battery of assessments to reduce physician and therapist costs and provide highly reliable data.

Hemispheric Lateralization and Spatial Awareness

Left-affected patients demonstrated significantly more variability on the robotic assessment than right-affected patients, despite no subject having evidence of hemispatial neglect. This finding, considered with the established importance of the right hemisphere in spatial awareness,[26-28] points to the possibility of right cerebral dominance in proprioceptive spatial tasks.

Methodological Advantages of the Robotic Matching Task

Given its previous use in several stroke studies,[15,29-37] the thumb localization test served as a clinical reference standard to which to compare the new robotic matching test. Although the thumb localizing test and the robotic matching task identified a similar total number of subjects with position sense abnormalities, many of the stroke subjects (40%) identified by the thumb localizing test were not necessarily identified by the robotic measures and vice versa. In fact, we observed a random relationship between these tests within our sample of stroke subjects (Table 3). Methodological differences may help explain some of the lack of overlap in the individuals identified by the 2 tests, but there are a number of significant advantages of the current matching task over the thumb localizing test and many other clinical position sense measurement tools. First, the robotic matching task is inherently objective and requires no interpretation on the part of a human examiner. Second, robotic measurements of position are continuous variables with no floor or ceiling effects. This contrasts with ordinal scales used by other clinical measures and should help in clarifying the suggested relationship between position sense and motor recovery, which remains somewhat uncertain because of the poor measures of position sense used in previous studies.[7-11] Third, our normative data allow statistical determination of the performance of patients relative to age-matched controls. Finally, we have shown that the test–retest reliability of the matching task was excellent for variability and spatial contraction/expansion and moderate for systematic shifts. However, we believe the latter measure may have better reliability than reported as the subgroup that participated in the test–retest experiment did not demonstrate the full range of $shift_{xy}$ values recorded in the larger group. In contrast, a variant of the thumb localizing with a simple binary scoring system demonstrated very poor interrater reliability.[14]

On a practical note, the robotic assessment does not require the assessor to physically manipulate the passive limb, and the robot can accurately perform complex multijoint movements. Automated measurement of joint angles and hand position allow for faster measurements (our assessment required between 3 and 6 minutes) and less chance of error than manual techniques, which require constant vigilance by assessors.[18,45-48]

Limitations of the Current Task

Position sense involves not only information from muscle afferents but also cutaneous information due to contact and pressure with the arm troughs on the robotic device. Cutaneous information would likely be transmitted, however, in any technique that passively moved the limb. Our task was also limited to movements in the horizontal plane. Although the shoulder and elbow possess more degrees of freedom than were tested, we suggest that the present measures of performance broadly reflect position sense of these joints given that muscle (and other) afferents involved in specifying position sense in this task would also be involved for other degrees of freedom.

Although not necessarily a limitation of the task per se, our study assessed patients whose FIM scores at 1 month poststroke may be somewhat higher than found in other inpatient rehabilitation facilities. Future studies with larger samples can examine relationships between scores on clinical assessments such as the FIM or CMSA, performance on robotic tasks, and more discerning quantitative assessments of motor control to better understand the relative role of motor deficits when matching from the unaffected to the affected arm. A final limitation is that the current experimental task examined one aspect of proprioception, position sense. As indicated above, the present technology could be used to explore several aspects of proprioceptive function, including different tests for limb position sense, kinesthesia, and sense of force.

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Declaration of Conflicting Interests

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