

A Novel Robotic Task for Assessing Impairments in Bimanual Coordination Post-Stroke

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Abstract

Background: Bimanual tasks are integral to the performance of many activities of daily living, but impairments in bimanual coordination following stroke are not well quantified with existing clinical tools.

Objective: The current study outlines a novel robotic task for the objective and quantitative assessment of bimanual impairment following stroke.

Methods: We developed a robotic, bimanual assessment task using the KINARM robot. The task involved moving a virtual ball on a bar linking the two hands, to targets displayed using a virtual reality system. Seventy-five healthy control participants and 23 participants with sub-acute stroke were assessed using the task. Task performance of participants with stroke was compared with the healthy control group, as well as to standard clinical tests (Chedoke-McMaster Stroke Assessment (CMSA) arm and hand, Functional Independence Measure (FIM), Montreal Cognitive Assessment (MoCA) and Behavioural Inattention Test (BIT)).

Results: A range of impairments in bimanual task performance was found for participants with stroke. As a group, 85% of participants with stroke had impairments on more task parameters than 95% of healthy controls. Participants with stroke commonly displayed impairments in task success (fewer targets hit); movement metrics (slower movement speed) and bimanual coordination (larger difference in reaction time between hands, greater number of speed peaks with unaffected versus affected limb and greater absolute tilt of the bar). Overall performance of the robotic task (total number of parameters 'failed') was significantly correlated with motor performance scores (CMSA, $r=-0.6$) and strongly correlated with measures of functional ability (FIM motor, $r=-0.8$).

Conclusions: A robotic bimanual task can identify impairments in a population of stroke participants and provides a quantitative measure of bimanual coordination.

Keywords: Stroke; Bimanual; Robotics; Assessment

Introduction

Stroke survivors exhibit a wide range of sensory and motor impairments. These impairments result in disabilities that limit performance of daily activities [1]. While rehabilitation is important to regain function after stroke, assessment of the initial impairment is an essential first step. Accurate assessment of the nature and magnitude of impairment is beneficial both on an individual level, to determine the appropriate course of treatment, and also on a broader scale to guide the development of novel rehabilitation approaches [2].

The majority of assessment tools used for the upper limb examine single limb function, evaluating task performance in one limb or the other [3-7]. These tools have provided valuable insight into sensorimotor impairments following stroke, often categorizing the performance of the affected limb and, in some tasks, contrasting affected with unaffected limb performance [5]. However, we often need to use both limbs in a coordinated manner to perform tasks (i.e., opening a jar or balancing items on a tray held with both hands). In a survey of post-stroke individuals, 90% of patient-selected recovery goals included dressing, washing and eating/drinking, and over one-third of these tasks involved the use of both hands [8]. Moreover, in two recent studies that tracked limb use in daily life post-stroke, it was found that the affected limb was used almost exclusively in bimanual tasks (vs. unimanual) [9] and increased bimanual use was associated with better performance on instrumental activities of daily living [10]. These findings emphasize the need for current assessment and rehabilitation protocols to consider bimanual movements.

Many rehabilitation strategies include a bimanual component, in part to improve bimanual function, but also with the hope that the intact neural circuitry in the contralesional (unaffected) hemisphere will improve neural function in the ipsilesional hemisphere [11,12]. However, the efficacy of bimanual therapy is controversial [13]. In the short term, some studies have found that bimanual movements do not improve the movement of the affected limb, and at times actually decrease performance in the unaffected limb [14-16]. Although motor performance on the specific bimanual training task itself may improve [17] this improvement does not always extend to performance of functional bimanual tasks [18,19]. These divergent results necessitate an improved understanding of bimanual impairments following stroke, starting with accurate assessment of bimanual control.

Previous evaluations of bimanual impairments post-stroke have focused on the ability of the limbs to move with similar metrics towards relatively independent goals. For example, tasks include reaching

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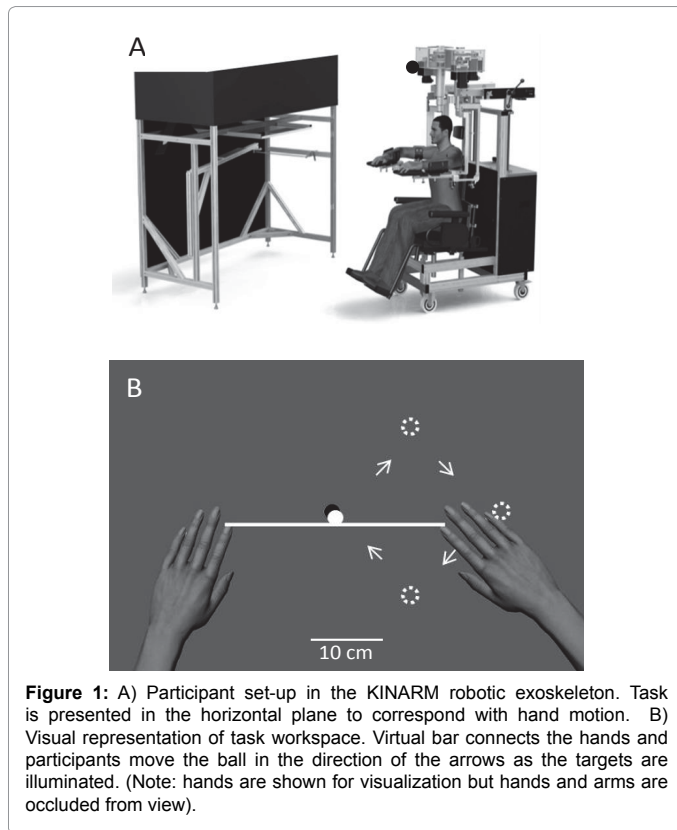


Figure 1: A) Participant set-up in the KINARM robotic exoskeleton. Task is presented in the horizontal plane to correspond with hand motion. B) Visual representation of task workspace. Virtual bar connects the hands and participants move the ball in the direction of the arrows as the targets are illuminated. (Note: hands are shown for visualization but hands and arms are occluded from view).

both arms towards single or dual targets [15,16,20,21], symmetric force production with both arms [22] or simultaneously drawing concentric circles [19]. While these tasks allow a measurement of synchrony or symmetry in the behaviour of each hand, they lack the added complexity of coordination of the two hands towards a common goal. In many functional tasks, the limbs are required to work together, including opposing a motion applied by one limb with the other. A few studies have quantified impairments on more coordinated, functional tasks such as pouring/drinking from a glass or opening a jar [18,23]. However the unconstrained nature of these tasks requires 3D motion capture to evaluate movement metrics, which is complex and time consuming [18]. In addition, the use of these functional tasks necessarily excludes patients with severe motor impairments who cannot perform the task at all [23]. An ideal assessment tool should be quick and easy to administer, repeatable, continuous and captures performance of a wide range of impairment with minimal floor or ceiling effects.

To that aim, we have developed a multi-level robotic task to assess bimanual function. Robotic technology provides an objective approach to quantify sensory and motor function of the upper limb [5-7,24-26]. The basic bimanual task involved a circular ball located on a bar that virtually connected the two hands. The task objective was to move the ball to illuminated targets and task difficulty was modified by altering the relationship between the ball and bar (from fixed to ball rolling on the bar). Multiple targets allowed assessment across a range of the work space and multiple levels of difficulty modified the challenge and thus skill required to perform the task. The goal was to assess various aspects of performance: task success parameters indicated how well participants achieved the task goal, whereas movement parameters quantified deficits in bimanual coordination. We hypothesized that participants with stroke would be less successful in achieving the task goal compared to a healthy control population, and that we would

identify underlying deficits in movement parameters that indicate decreased bimanual coordination. In addition, we hypothesized that as the task increased in difficulty (higher levels) we would identify more participants with impairments.

Method

Participants

Stroke participants were recruited from the inpatient acute stroke unit and stroke rehabilitation units at Foothills Medical Centre and the inpatient stroke rehabilitation units at Dr. Vernon Fanning Care Centres in Calgary, Alberta and St. Mary's of the Lake Hospital in Kingston, Ontario. Control participants were recruited from the Kingston community. Participants with stroke were included in the study if they had a confirmed diagnosis of stroke, were older than 18 years of age, and could understand the task instructions. Participants were excluded if they had significant medical comorbidities (e.g. angina or active cardiac disease), had a previous stroke, or other neurologic or musculoskeletal diagnoses affecting their upper limbs. All participants provided informed consent prior to participation in the study. Ethical approval was provided by Queen's University and the University of Calgary.

Clinical examinations

Clinical evaluations of participants with stroke were administered by a physical or occupational therapist and included the Edinburgh Handedness Inventory for hand dominance as well as the Montreal Cognitive Assessment (MoCA) for assessment of cognitive impairment [27]. The conventional subtests of the Behavioural Inattention Test (BITc) were performed. The BITc consists of a variety of pencil and paper tests (e.g. line bisection, letter cancellation) to screen for the presence of visual neglect [28]. The test is scored out of 146 and a value of 129 or below is indicative of visual neglect. The Modified Ashworth Scale was used to evaluate spasticity at the elbow [3]. The Chedoke-McMaster Assessment of the arm (CMSAa) and hand (CMSAh) was used to assess the upper limb on a 7-point scale reflecting stages of motor recovery following stroke (7-highest recovery stage, 1-lowest recovery; [4]). The Functional Independence Measure (FIM™) was used to rate physical and cognitive disability and level of assistance required, intended to measure the burden of care [29]. The motor portion (FIM motor) measures functional ability, such as washing, dressing, toileting and mobility. The cognitive portion (FIM cognitive) evaluates comprehension, expression, social interaction, problem solving and memory.

Approximately 15-20% of stroke survivors that experience unilateral brain lesions also exhibit mild impairment of their ipsilesional limb [5,30]. The affected side of participants with stroke was characterized using their CMSA scores, and in the current study the affected side reflects the upper limb that was most affected (contralesional limb).

Robotic set-up

All experimental tasks were performed in the KINARM robotic exoskeleton (BKIN Technologies Ltd., Kingston, Ontario). The robot measures kinematics of the shoulder and elbow and can apply joint- or hand-based loads [31]. Full details of the robotic set-up have been described previously [5]. Briefly, participants were seated in a modified wheelchair base with the feet in adjustable rests and arms fully supported in exoskeleton robots with their shoulder and elbow joints aligned with the linkages of the robot (Figure 1A). The seat height was adjusted for each participant to achieve shoulder abduction (~85°). Plastic arm troughs within the frame were adjusted to support

the upper arm and forearm/hand. This allowed free arm movement in the horizontal plane. The robot was calibrated for each participant and the arms and hands were occluded from view. A virtual reality system projected visual targets and visual representation of fingertip location (as a virtual bar linking the two hands) on the screen in the same plane as the arm.

Task characteristics

In the current task, a 30 cm virtual 'bar' (1 cm thickness) was displayed connecting the index fingers of each limb (Figure 1B). The robot modelled the bar (mechanically and visually) as a stiff spring creating repulsive/attractive forces aligned with the bar when the hands moved it from its default length to maintain the bar length at 30 cm. A virtual ball (1 cm radius) rested on the middle of the bar and participants were instructed to move the ball 'quickly and accurately' to four circular targets (1cm in radius) as they appeared on the screen. The four targets were located 10cm from a centrally located origin (Figure 1B). A gravitational constant acted on the virtual environment so that participants felt the 'weight' of the bar and the ball in the frontal plane (bar mass: 0.166 kg; ball mass: 0.4 kg).

Task objectives

Participants were required to use the bar to move the ball to successive targets appearing clockwise around the work space. The targets appeared red, signalling 'go' and once the ball entered the target, and it turned yellow. Participants had to hold the ball in the target for 1 second, after which the next red target appeared. It was more difficult to maintain the ball within the target circle as task difficulty increased. Therefore, the size of the acceptance window (initially 1 cm radius) within which participants had to hold the ball for 1 second increased by 1cm/s, although the visual radius of the target remained constant. This 'logical radius' was included after pilot testing to decrease the task difficulty but still encourage accurate placement of the ball within the target. The task included 6 levels that increased in difficulty by modifying the relationship between the ball and the bar:

Level 1: Ball fixed to center of bar.

Level 2: Ball moved along bar as a function of bar tilt. The greater the tilt the further the ball moved. The ball fell off when the bar tilted $\geq 20^\circ$ relative to the frontal plane.

Levels 3-6: Ball had the ability to 'roll' with no friction on the bar. Ball rolled faster with each increase in level (Supplemental File).

The overall goal of the task was to successfully reach as many targets as possible within one minute (1 min per level, total task time=6 min).

Data processing and analyses

Kinematic data were recorded for the ball and hands (position and velocity) and were sampled at 1000 Hz using Dexter-E software (BKIN Technologies Ltd., Kingston, Ontario). Data were digitally filtered offline with a 4th order dual-pass, Butterworth low pass filter, with a cut-off frequency of 10 Hz using Matlab (The MathWorks Inc., Natick, MA, USA). For each level, 14 parameters were calculated from the kinematic data, reflecting overall task performance, metrics of hand and ball movement and bimanual coordination of movements throughout the task.

Task parameters

Task success parameters:

- i. Hits: Number of successful targets hit.

- ii. Drops: Number of times the ball fell off of the bar. Drops were only possible in Levels 2-6 as the ball was fixed in Level 1.
- iii. Hits/Drop: Number of hits divided by the number of ball drops (only possible for Levels 2-6).

Hand and Ball Parameters

- i. Reaction time + Movement time (RT+MT): Overall time elapsed from when target appears to when ball reaches target.
- ii. Ball speed: Mean ball speed over the entire level.
- iii. Hand speed: Mean hand speed over the entire level.
- iv. Hand speed peaks: Number of hand speed maxima recorded over the entire level.

Bimanual Parameters

- i. Absolute Tilt: Absolute angle of the bar relative to frontal plane and then averaged over the entire level ($^\circ$).
- ii. Reaction time difference (RT diff): (Level 1 only). An algorithm was used to identify movement onset for each limb. First, the algorithm identified the time point when the ball moved 10% of the distance to the next target, then movement onset was defined by searching back in time to the next hand speed minimum. Reaction time (RT) was defined as the time elapsed from target illumination to movement onset. Absolute RT Difference was computed for each movement and averaged over the entire level.
- iii. Change in bar length: Identified if the subject compressed or lengthened the bar throughout the task. Absolute change from the resting length of the bar was computed at each time step and averaged over the entire level.
- iv. Difference in hand speed: The cumulative sum of the absolute difference in speed between the two hands identified at each time point over the entire level.
- v. Difference in hand speed peaks: Difference in the number of speed peaks recorded for each hand over the entire level.
- vi. Difference in hand path length: Difference in the total hand path calculated for each hand over the entire level.

For difference parameters of hand speed peaks and path length, the difference was calculated as the performance of the affected limb subtracted from the unaffected limb for participants with stroke, and the non-dominant limb subtracted from the dominant limb for control participants. Thus positive values reflect lower values for the affected (stroke) or non-dominant (control) limb, and negative values reflect lower values for the unaffected (stroke) or dominant limb (control).

Statistical analyses

Statistical analyses were performed in Matlab (The MathWorks Inc., Natick, MA, USA). The data were age-regressed and Box Cox transforms [32] were used to normalize control distributions. Participants with outliers in any parameter were removed from all analyses for that level. Parameters were then assessed for sex effects. Percentiles were calculated for each parameter and used as cut-off values for comparing individual stroke performance. For one-tailed comparisons, 5th or 95th percentiles were used where appropriate, and for two-tailed comparisons, 2.5 and 97.5 percentiles were used to determine when stroke participant performance fell outside of 95% of controls. Correlations between the number of parameters failed on the task and clinical scores were performed using Spearman's rank correlation.

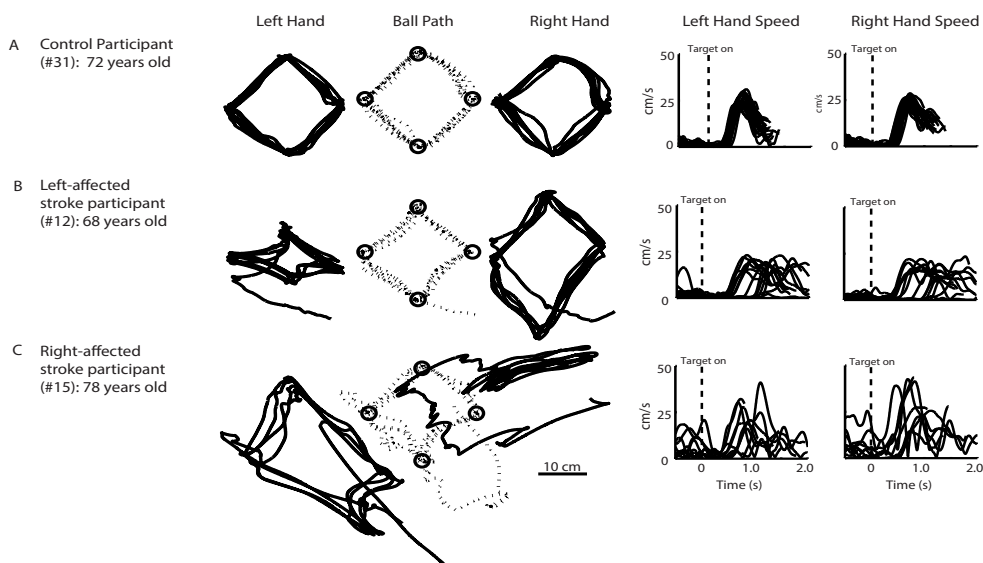


Figure 2: Hand and ball path traces from exemplar participants, for Level 1. A) Traces from a 72 year old control participant. Solid black lines represent hand path of each hand and dotted line represents the path of the ball. At this level, the ball is coupled to the hand path as it is fixed to the bar linking both hands (i.e., ball represents the mid-point of the distance between both hands). Note: traces would normally overlap but are separated for illustrative purposes. Far right plots represent hand speed for the left and right hands overlaid for multiple reaches to each target. Dotted line represents the time point when the target was illuminated. B) Traces from a left-affected stroke participant (68 years old) with a lesion in the right middle cerebral artery (MCA) assessed 26 days post-stroke. This participant scored 7/7 for left (affected) arm CMSA and 4/7 for right (unaffected) arm CMSA. C) Traces from a right-affected stroke participant (78 years old) with a lesion in the left MCA assessed 12 days post-stroke. This participant scored 2/7 for right (affected) arm CMSA and 6/7 for left (unaffected) arm CMSA.

Participant Group	Stroke (n = 23)	Control (n = 75)
Age mean (range)	61 (26-87)	53 (18-87)
Gender	9 F/14 M	41 F/34 M
Handedness	2 LH/21 RH	8 LH/67 RH
Affected Side	18 LA / 5 RA	-
Days Since Stroke	20 (1-46)	-
Type of Stroke (I/H)	21/2	-
BIT	138 (100-146) (n=21)	-
MoCA (/30)	25 (19-30) (n=19)	-
CMSA (possible ratings)	[1,2,3,4,5,6,7]	-
Arm <i>Affected</i>	[0,4,2,2,4,4,6] (n=22)	-
Arm <i>Unaffected</i>	[0,0,0,0,3,5,14]	-
Hand <i>Affected</i>	[1,2,1,1,6,7,4]	-
Hand <i>Unaffected</i>	[0,0,0,0,0,5,17]	-
FIM (cognitive /35)	32 (20-35)	-
FIM (motor /91)	77 (17-91)	-
FIM (total /126)	109 (37-126)	-

Abbreviations: F/M: female/male; LH/RH: left/right-handed; LA/RA: Left/ Right Affected

I/H: Ischemic/Hemorrhagic; C/SC/B/Cr/M/U: Cortical/Sub-cortical/Brainstem/Cerebellum/Mixed/Unknown; BIT: Behavioural Inattention Test; MoCA: Montreal Cognitive Assessment; CMSA: Chedoke-McMaster Stroke Assessment; FIM: Functional Independence Measure

Table 1: Clinical and demographic data

Results

Participant demographics and clinical scores

Data were collected for 75 control (41 Female) and 23 stroke participants (9 Female; Table 1). The stroke participants consisted of more left (n=18) than right affected participants (n=5). The type of stroke was primarily ischemic (21/23) and days post-stroke varied from 1-46 days with the following distribution: ≤ 1week post stroke (n=7), 1-3 weeks (n=6), 3-6 weeks (n=8), >6 weeks (n=2; 43 and 46 days).

Clinical scores show a range of impairment. FIM motor scores (Table 1) ranged from 37 to 126. BIT scores ranged from 100-146, with

3 participants scoring below the cut-off of 129, indicating the presence of visuospatial neglect (28-Wilson et al., 1987). CMSA scores ranged from 1-7 with 16/22 participants scoring 6 or below for the affected arm and 19/22 scoring 6 or below for the affected hand. For the unaffected limb, scores ranged from 5-7 with 8/22 participants scoring 5 or 6 for the arm and 5/22 participants scoring 6 for the hand indicating that 36% of our participants had mild ipsilesional arm impairment and 22% had mild ipsilesional impairment in the hand. Five of the 6 participants with ipsilesional hand impairment also exhibited ipsilesional arm impairment. All participants with ipsilesional upper limb impairment were more impaired on their contralesional side, scoring at least

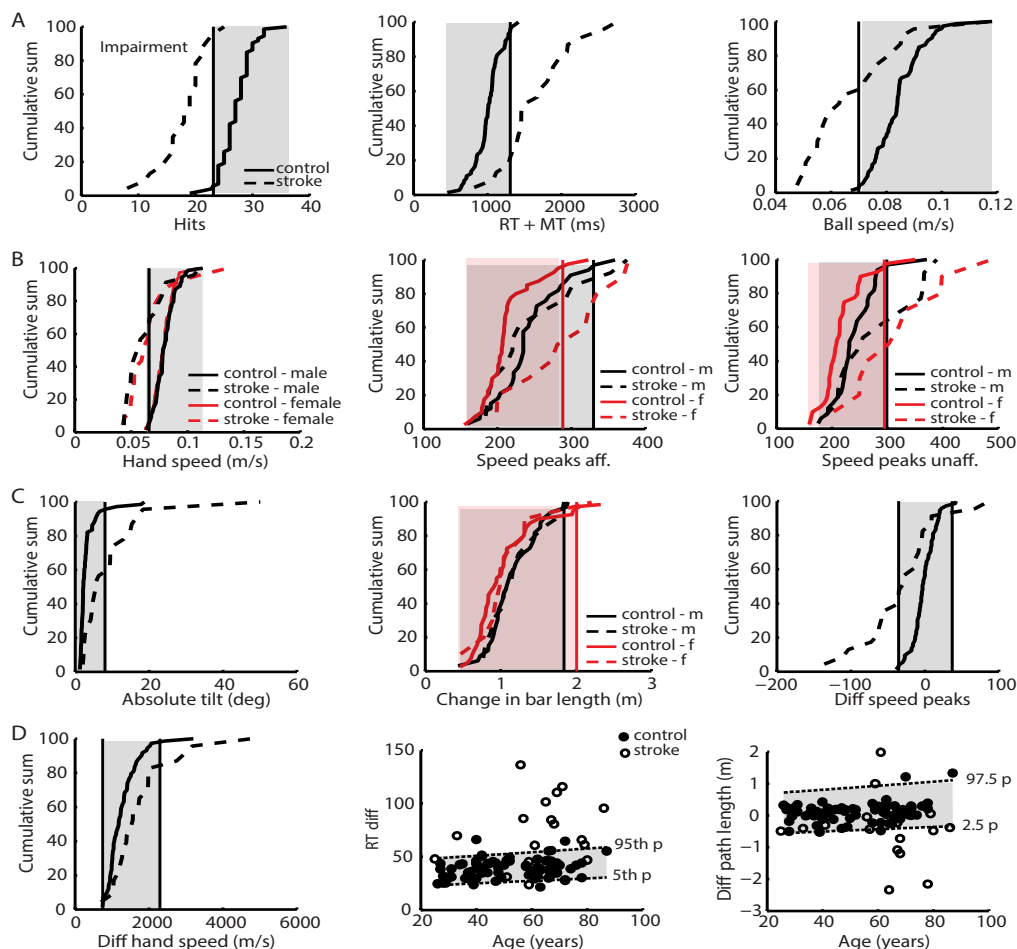


Figure 3: Overall participant performance on parameters at Level 1. Row A: solid black data line (thick) represents control participant data distribution and dashed line represents stroke participant data distribution. Shaded grey areas represent 95% of control performance. Row B: hand speed is presented in the first plot for both affected/non-dominant side for stroke (black dashed) and control (solid black) and for the unaffected/dominant side (red dashed and solid lines respectively). The number of speed peaks is shown in the next two plots in row B, separated into male (black) and female (red) groups. For both plots (as well as bar length changes in row C), significant effects of sex were found at Level 1, therefore comparisons were made with the groups split. Row D: Significant age effects were found for RT diff and Diff in path length; these parameters are plotted against age with age-corrected control percentiles (RT diff was one-tailed; 95th percentile was used, Diff path length was two-tailed; 2.5 and 97.5 percentiles were used; negative values reflect greater path length with unaffected (or dominant for control) side). No data are shown for number of drops or drops/hit at Level 1 because drops are not possible at this level.

one Level lower on the CMSA. MoCA scores were recorded for 19 participants and ranged from 19-30 with a mean of 25.

Bimanual robotic task: LEVEL 1

General participant performance: Overall, participants with stroke had impaired performance on the bimanual task compared to control participants. Exemplar participant hand and ball trajectories for Level 1 indicate that control participants moved their hands relatively straight as they progressed to each target with minimal corrective movements (Figure 2A). Movements were consistent from trial to trial, with low variability in successive reaches to targets. Patterns of hand motions are similar to movements of the ball.

In contrast movements of an exemplar left-affected participant (Figure 2B) and right-affected participant (Figure 2C) were variable from reach to reach. Both participants showed less movement area and smaller path lengths with their affected limb. In particular, for the right-affected participant, the right hand moved back and forth with no 'diamond' shape to the trajectory. In general participants with stroke hit fewer targets and moved more slowly from target to target but with

more speed peaks (i.e. jerky, less smooth movements: right panels, Figure 2).

Performance of healthy controls: Statistical analyses identified which of the parameters were influenced by age and/or sex. Age effects were found for path length difference and RT diff in Level 1, and sex effects were found for bar length changes and hand speed peaks (affected and unaffected). These factors were taken into account when calculating percentiles for the normative ranges for control performance.

Performance of stroke participants on individual parameters: Normative ranges calculated from control data were used to identify the number of stroke participants whose performance fell outside of 95% of healthy controls for each parameter. Cumulative sum histograms of participant performance are illustrated for Level 1 (Figure 3). The parameter that identified the most stroke participants overall was number of hits in Level 1: 96% of stroke participants (22/23) hit fewer targets than 95% of control participants. The parameter that identified the second most participants as impaired was RT+MT (78%) (Figure 3, Table 2).

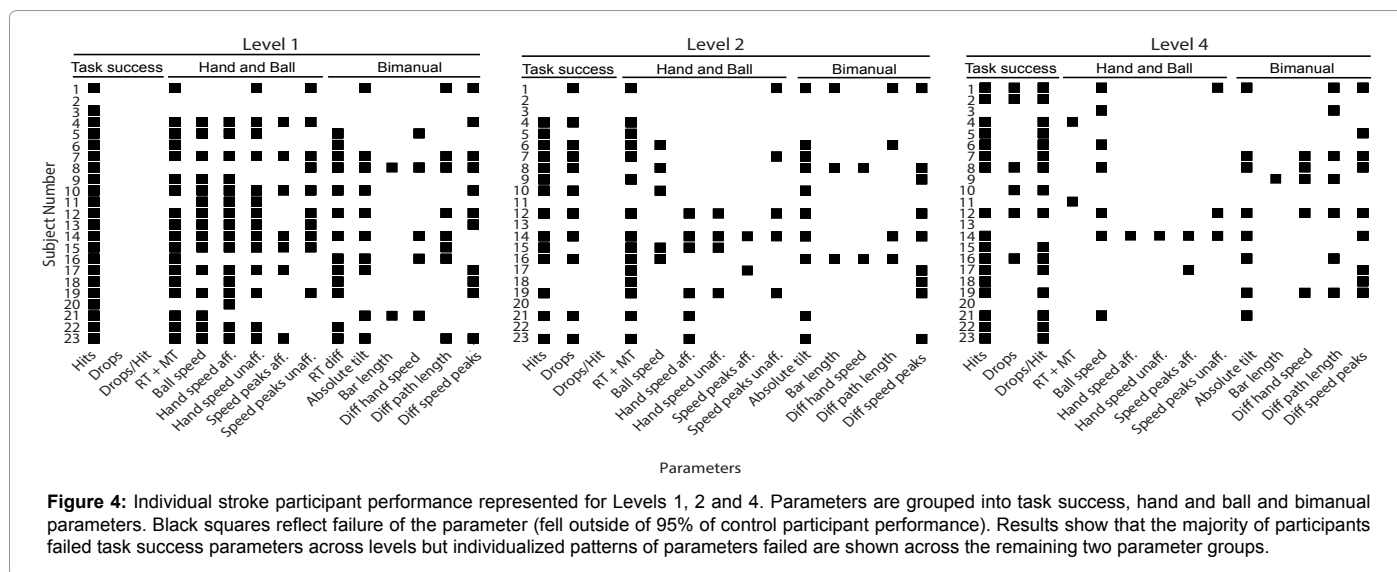


Figure 4: Individual stroke participant performance represented for Levels 1, 2 and 4. Parameters are grouped into task success, hand and ball and bimanual parameters. Black squares reflect failure of the parameter (fell outside of 95% of control participant performance). Results show that the majority of participants failed task success parameters across levels but individualized patterns of parameters failed are shown across the remaining two parameter groups.

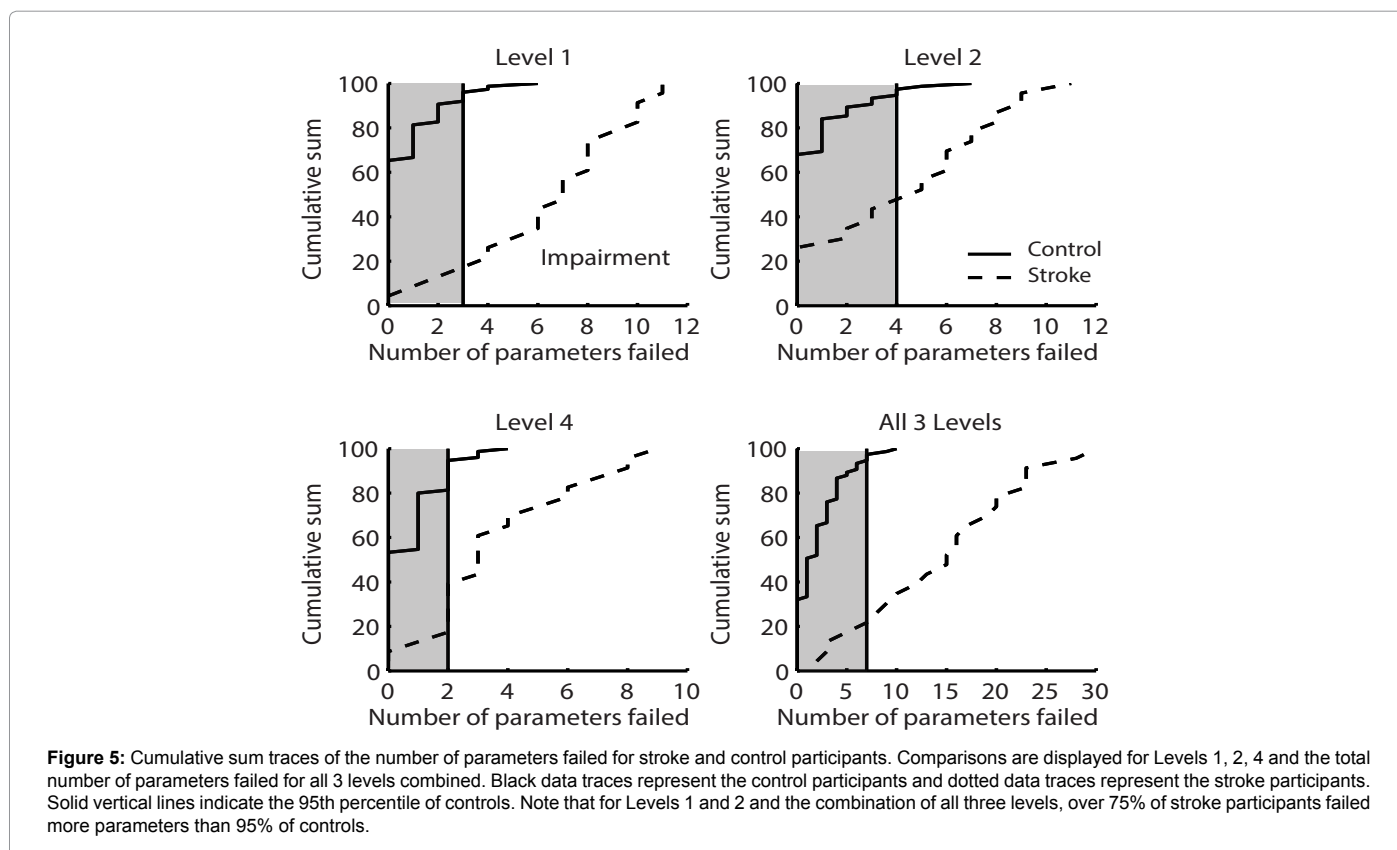


Figure 5: Cumulative sum traces of the number of parameters failed for stroke and control participants. Comparisons are displayed for Levels 1, 2, 4 and the total number of parameters failed for all 3 levels combined. Black data traces represent the control participants and dotted data traces represent the stroke participants. Solid vertical lines indicate the 95th percentile of controls. Note that for Levels 1 and 2 and the combination of all three levels, over 75% of stroke participants failed more parameters than 95% of controls.

With regards to measures that specifically quantified bimanual performance in stroke, the best parameters in Level 1 were RT diff (57%), difference in hand speed peaks, (48%) and absolute tilt (43%). The majority of participants that displayed differences in number of hand speed peaks had more peaks with their unaffected limb (>35 more speed peaks than with affected limb). Impairment in absolute tilt was associated with a greater amount of tilt (>9° on average).

Individual profiles of impairment: A primary aim of the current task was to develop individual profiles of impairment rather than group comparisons. These patterns are displayed in Figure 4 and show the

unique pattern of impairments across participants. In Level 1 some participants had impairments primarily in task success, and hand and ball parameters, but displayed minimal impairments in bimanual performance (i.e. participants 4 and 19). Conversely, some participants failed the majority of bimanual parameters, but passed most of the other parameters (i.e. participants 8 and 16). Several participants were observed to have impairments across all recorded parameter groups (i.e. participants 14 and 23).

Overall, stroke participants failed more task parameters than control participants (Figure 5). Approximately 78% of stroke participants

Level		1	2	3	4	5	6	Overall					
Parameter	Control percentile	Fail #	Fail #	New fails	Fail #	New fails	Fail #	New fails	Fail #	New fails	Fail #	New fails	% failed
Task Success													
Hits	< 5	22	14	0	12	0	17	1	0	0	2	0	100%
Drops	> 95	-	11	11	7	1	6	2	3	0	3	0	57%
Drops/Hit	> 95	-	11	11	11	3	16	4	5	2	2	0	83%
Hand/Ball													
RT+MT	> 95	18	15	0	2	0	2	0	-	-	-	-	83%
Ball sp	< 2.5, > 97.5	15	5	3	8	1	7	2	8	1	1	0	91%
Hand sp aff	< 2.5, > 97.5	16	6	2	2	0	1	0	1	0	1	0	74%
Hand sp unaff	< 2.5, > 97.5	14	4	0	0	0	1	0	1	0	1	0	61%
Sp pks aff	> 95	7	2	0	4	2	2	0	3	0	2	0	39%
Sp pks unaff	> 95	10	5	0	5	1	3	1	1	0	2	0	48%
Bimanual													
Absolute tilt	> 95	10	11	2	7	2	8	0	6	1	8	1	61%
RT diff	< 2.5, > 97.5	13	-	-	-	-	-	-	-	-	-	-	57%
Bar length	> 95	2	3	2	0	0	1	2	0	0	0	0	22%
Diff sp pks	< 2.5, > 97.5	11	9	2	6	0	9	0	8	1	5	0	65%
Diff hand sp	> 95	5	2	0	0	1	5	4	3	1	0	0	43%
Diff path length	< 2.5, > 97.5	8	4	1	10	3	7	0	9	2	11	1	65%
Total num. fails		151	101		74		85		47		38		
Total new fails			32		13		14		8		2		

Abbreviations: sp=speed, pks=peaks, aff=affected side, unaff=unaffected side (affected side always compared to control non-dominant side and unaffected side always compared to control dominant side) Cusum=Cumulative sum; RT+MT=reaction time plus movement time.

Table 2: Number of stroke participants that were identified as outside of 95% of controls (number of fails) on each parameter across each level.

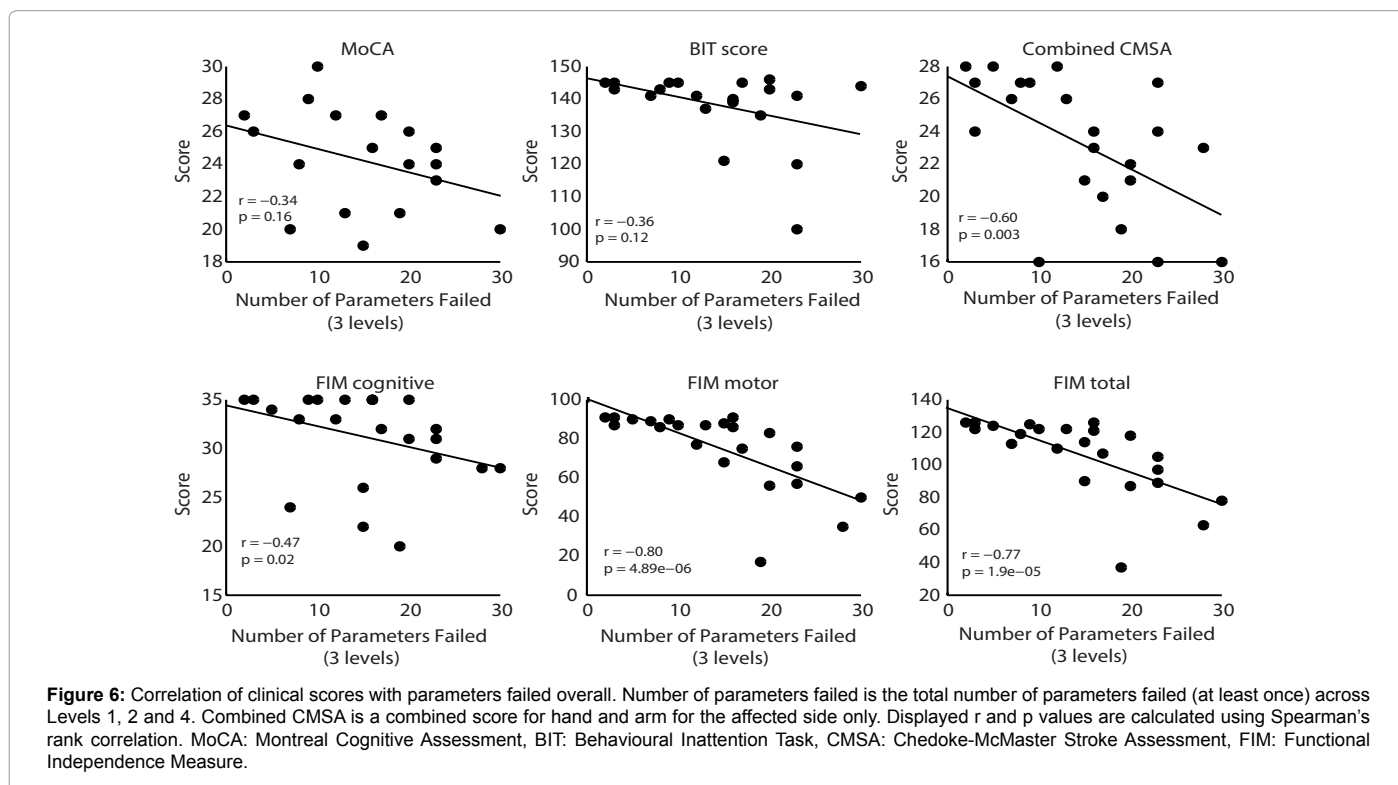


Figure 6: Correlation of clinical scores with parameters failed overall. Number of parameters failed is the total number of parameters failed (at least once) across Levels 1, 2 and 4. Combined CMSA is a combined score for hand and arm for the affected side only. Displayed r and p values are calculated using Spearman's rank correlation. MoCA: Montreal Cognitive Assessment, BIT: Behavioural Inattention Task, CMSA: Chedoke-McMaster Stroke Assessment, FIM: Functional Independence Measure.

failed 4 parameters or more in Level 1 compared to only 5% of control participants who failed 4 or more.

Bimanual robotic task: LEVEL 2-6

Performance of stroke participants across Levels: Level 1 identified the most performance impairments in stroke participants with the highest number of parameters failed (151); (Table 2). Unexpectedly, as the levels progressed in difficulty (Level 2 to 6) the

number of parameters failed tended to decrease (101, 74, 85, 47, 38; Table 2). Performance across levels was analyzed to determine the number of 'new fails' that were introduced at each level (Table 2). Levels 1, 2 and 4 showed the highest ability to identify impairments in participants as they identified the most fails overall, as well as the highest combination of new fails. As a result we focused our further analyses on Levels 2 and 4.

Participant performance: Levels 2 and 4: As in Level 1, the best parameters for identifying participants with stroke in Level 2 were hits (65%) and RT+MT (65%); (Table 2). Absolute tilt was the best bimanual parameter for identifying impairments with stroke (48%). Thirty-two 'new fails' were captured in Level 2 primarily due to the fact that ball drops were possible in this level. Drops and drops per hit identified 11 participants each (48%).

In Level 4, the number of hits was again the best parameter to identify impairment in stroke performance with 17 fails (74%) and the second best parameter was drops per hit (70%). The best bimanual parameters were absolute tilt (35%), difference in speed peaks (39%) and path length difference (30%). Fourteen new fails were captured indicating that 14 participants failed a parameter in Level 4 that they had not previously failed.

Across the Levels 1, 2 and 4, participants with stroke failed more task parameters than healthy control participants (Figure 5). Approximately 78% of stroke participants failed 8 parameters or more when all three levels were combined compared to only 5% of control participants who failed 8 or more.

Finally, robotic task performance was compared between participants with clinically identified, mild ipsilesional impairments ($n=9$) and those without ($n=14$). We found no significant differences for any parameter between these groups (Kolmogorov-Smirnov tests, $p>0.05$).

Correlation with clinical scores: The number of parameters failed was combined across Levels 1, 2 and 4 and was compared to other clinical evaluation scores (Figure 6). Percentage of parameters failed overall was significantly correlated with FIM scores: FIM motor ($r=-0.80$, $p<0.001$) FIM cognitive ($r=-0.47$, $p=0.02$) and FIM total ($r=-0.77$, $p<0.001$). Combined CMSA (arm and hand) score was correlated with percentage of parameters failed ($r=-0.60$, $p=0.003$). Negative correlation values indicate that low clinical scores were correlated with more task parameters failed.

Discussion

Bimanual task performance

The robotic ball on bar task quantified performance on a bimanual activity and identified impairments in participants with stroke. The primary goal of the task was to hit as many targets as possible, which required coordinated movement of both limbs. The higher task levels involved balancing the ball, thus increasing task difficulty which we hypothesized would highlight more impairments in stroke performance. The principle was to stress the motor system with a more complex task to help uncover subtle deficits in coordination to separate participants with stroke from healthy controls. However, the reverse was observed; Level 1 identified the most impairments in participants with stroke. This unexpected result likely reflects that healthy control performance was stereotyped for the initial levels in which participants simply moved the ball to the spatial target, but became more idiosyncratic as balancing the ball became more difficult. This increased the variability of control performance and influenced the 95% criteria used to identify whether a participant with stroke was impaired on a particular parameter. However, we found Levels 2 and 4 did identify new features or individuals as being impaired compared to Level 1. Thus, we thus focused our analysis on Levels 1, 2 and 4 as together they captured the most impairments in performance. Another advantage of reducing the number of levels is the reduction of task time from 6 to 3 minutes. In order to integrate tasks into a standard assessment protocol and avoid fatigue for the patient, shorter task time is highly beneficial. In addition,

the more challenging levels were often frustrating for participants, both patients and controls. Removal of the two most challenging levels makes the task more enjoyable and will encourage patient compliance.

Task success was determined by the number of targets hit and number of drops (times the ball fell off of the bar). In the initial level, the number of hits identified the most participants with stroke of all parameters (96%). Number of hits was the most sensitive parameter overall in the sense that it indicated impaired performance in 100% of participants with stroke when the 3 levels were combined. Failure of this parameter indicates global inability to complete the task but does not provide information about the under-lying impairment that led to task failure; the sub-categories of performance parameters provide this insight.

The present bimanual task captures much motor impairment observed in previous studies. In Level 1 hand and ball-related parameters indicated that participants with stroke moved slower, took longer to respond to target illumination and to move to the target (RT+MT) and exhibited more corrective sub-movements. These findings are in line with previous characterizations of visually-guided reaching with one hand [5,21] or simultaneous reaching with both hands [18,20,21,23]. Further, we found specific deficits in parameters related to bimanual control notably, differences in RT between the two limbs and differences in hand speed. These asymmetries in motor performance are likely related to previous observations of decreased movement synchrony [18,21,23,33]. Interestingly, the difference in RT between the two hands in our bimanual task was less than ~50ms for healthy control participants. When both hands are assessed separately in a reaction time reaching task, the difference in RT was also found to be less than ~50 ms for healthy controls [5]. This highlights that a hallmark of healthy motor control is symmetry between the limbs. Such small differences in motor performance are not easily observable with visual inspection, which highlights the advantages that a robotic paradigm has in capturing subtle differences in performance.

Individual patterns of impairment

A primary aim of the task was to develop an individualized 'finger print' of impairment for each participant, rather than to characterize group differences in performance between stroke and control participants. In a heterogeneous population of stroke participants, different lesion severity and location is likely to lead to vast differences in deficits, for example motor vs. sensory impairment [34]. Unique impairments (or pattern of impairment) seen in one participant may be lost when averaged across participants. Although the current study focused on parameters that identified impairments across many participants, parameters that identified fewer participants are equally important to assess. For example, changes in bar length identified impairments in only 6 individuals. In these individuals, larger cumulative changes in bar length were often caused by relatively small but frequent oscillatory movements on the spring-like bar (data not shown). These oscillations may reflect unique underlying injury or impairment in these participants such as the onset of tremor [35] and may necessitate novel strategies for rehabilitation. For example, the application of biomechanical loads to the limbs can reduce tremor [36] and may evolve as a beneficial rehabilitation component for individuals with tremor-like impairments post-stroke.

Relation to clinical scores

Performance on the task overall was significantly correlated to clinical scores. The number of parameters failed in the task correlated most strongly ($r=-0.80$) with measures of functional motor abilities

(FIM motor). The strength of the correlation with FIM is greater than that found previously for our other robotic tasks: visually-guided reaching [5] and position sense [26] both of which evaluate each limb in isolation. This observation may indicate that performance of functional daily activities is better reflected by a task that assesses the coordinated use of both limbs. We noted that a number of participants failed the majority of parameters on the bimanual task but scored almost perfect on the FIM. Participants may score highly on the FIM if they have learned compensatory strategies (i.e. tying shoes or buttoning a shirt with one hand) or use assistive devices to complete the tasks specific to the FIM. In a novel bimanual task such as ours, in which the use of both hands is necessary, more deficits were apparent. In this way, the bimanual task provides a more sensitive measure of bimanual motor function, and is likely more reflective of performance on daily activities that requires the use of both hands.

Limitations and future considerations

A limitation of the current study is the relatively small sample size that did not afford the systematic comparison of anatomical lesion characteristics and robotic task performance. For example, right- vs. left-affected stroke participants may exhibit hemisphere-specific impairment in different aspects of movement coordination (i.e. trajectory vs. end-point accuracy) [37-39]. However, the cause of bimanual impairment post-stroke is likely multi-faceted. It may be affected by the suppression of inter-hemisphere communication [40] asymmetry in hemispheric inhibition (or dis-inhibition) [41,42], damage to the supplementary motor area [43], unilateral sensory [44] or motor impairments[20] or a combination of these and potentially other factors. Future work will combine the current task with other robotic assessment tasks to provide further insight into whether specific patterns of bimanual impairment is related to lesion anatomy or to identified unilateral sensory and/or motor deficits.

Summary

Our task provides a proof of principle for the quantification of bimanual control post-stroke. Accurate assessment of bimanual coordination is essential to reliably track improvement during traditional or novel rehabilitation approaches [24,25]. Through objective measurement of attributes of bimanual control, the robotic task can provide an accurate baseline from which to assess changes over the course of recovery or rehabilitation.

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Dr. Scott is cofounder and chief scientific officer of BKIN Technologies, which commercializes the KINARM robotic technology.

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