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Bilateral Assessment of Functional Tasks for Robot-assisted Therapy Applications

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Abstract:

This article presents a novel evaluation system along with methods to evaluate bilateral coordination of arm function on activities of daily living tasks before and after robot-assisted therapy. An affordable bilateral assessment system (BiAS) consisting of two mini-passive measuring units modeled as three degree of freedom robots is described. The process for evaluating functional tasks using the BiAS is presented and we demonstrate its ability to measure wrist kinematic trajectories. Three metrics, phase difference, movement overlap, and task completion time, are used to evaluate the BiAS system on a bilateral symmetric (bi-drink) and a bilateral asymmetric (bi-pour) functional task. Wrist position and velocity trajectories are evaluated using these metrics to provide insight into temporal and spatial bilateral deficits after stroke. The BiAS system quantified movements of the wrists during functional tasks and detected differences in impaired and unimpaired arm movements. Case studies showed that stroke patients compared to healthy subjects move slower and are less likely to use their arm simultaneously even when the functional task requires simultaneous movement. After robot-assisted therapy, interlimb coordination spatial deficits moved toward normal coordination on functional tasks.

Keywords: Activities of daily living, Bilateral coordination, Interlimb coordination, Robot-assisted therapy, Reaching, Grasping, Stroke rehabilitation, Upper limb.

1 Introduction

Bilateral functional tasks are a salient part of real activities of daily living (ADLs) and require cooperation from each limb [8]. The division of labor between limbs is characteristic of various functional tasks. At one end of the bilateral functional task spectrum are symmetric tasks that require the two limbs to do similar movements, e.g., simultaneous reach to grab a large ball. At the other end are the more complex asymmetric or discrete tasks that require the two limbs to take on different roles during a task, e.g., the widely studied asymmetrical drawer task [16, 27]. Here, the hands contribute with dissimilar task components in that one hand performs a postural role while the other takes on a manipulative one. Behavioral studies in able-bodied subjects tells us that although the limbs may engage in separate activities, they have strong temporal and spatial interactions including a tendency toward frequency and phase locking between limbs in rapid movements, amplitude coupling, direction coupling, and mutual accommodation or interference [3, 4, 11, 15, 16, 18, 19, 23, 24, 30].

Stroke survivors with hemiparesis have difficulty performing both unilateral and bilateral functional tasks [1, 7, 9, 18, 31, 37]. Depending on the severity of the stroke, the grasping and manipulation aspects of the functional tasks are difficult to be performed. Their hemiparesis results in an upper limb that is characterized by weakness, abnormal synergies, and impaired coordination. The deficits are seen both within the segments of a limb (intralimb) and between limbs (interlimb). Interlimb coordination deficits, both temporal and spatial, often lead to sequential and segmented, poorly timed movements during bilateral functional tasks. In bilateral symmetrical tasks, stroke subjects have more difficulty maintaining the symmetry of the task than their able-bodied counterparts [23, 24, 30]. For example, in a rhythmic circle drawing task, there may be greater phase discrepancy between the limbs of patients with hemiparesis when compared to healthy patients. In asymmetric bilateral tasks, the tendency displayed by healthy persons to synchronize their arms in time and space may be disrupted in stroke survivors resulting in more uncorrelated movements between arms.

The use of robots in rehabilitation to improve upper limb function after stroke has become more common as clinical evidence to support their utility grows [6, 17, 20, 21]. The MIT-MANUS [20] and GENTLE/S [21] are typical examples of end-effector robot-therapy environments focused on unilateral training of an impaired arm. Oftentimes there exists an untested assumption that bilateral performance automatically improves after unilateral robot therapies. Recent studies demonstrate that this assumption is not necessarily valid. Lo and colleagues and other review studies indicate mixed evidence for the utility of robot-assisted therapy for upper arm rehabilitation after stroke [6, 17, 20]. One key criticismis that these interventions do not consistently improve patients' functional ability on unilateral and bilateral ADLs.

We desire to understand how best to administer therapy with robot environments to ensure that they improve both unilateral and bilateral function on real activities. A robot therapy environment focused on the performance of real ADL tasks is being used as a test-bed to examine these issues. Johnson and colleagues developed the ADL and Exercise Robot (ADLER) to administer functional unilateral therapies to stroke subjects [13, 15, 25, 33]. The ADLER environment uses a HapticMaster robot (FCS Moog Robotics) to move an impaired arm along trajectories for real-life tasks and administer customized forces along programmed trajectories. The HapticMaster is an admittance-controlled, 6 degrees of freedom (DOFs) robot. Three active DOFs position the hand in space. The end-effector of the robot can pivot 1 full radian and has a vertical range of 0.40 m. ADLER is developed to permit training of real-life functional task involving reach, grasp, as well as object manipulation and transportation in both 2 and 3 dimensional space. The rational for the environment was born out of existing occupational therapy paradigms which support using purposeful tasks that mimic real ADLs to improve the generalization or carryover of the practiced functional movements to unsupervised environments [8, 27].

One of our main long-term goals is to critically test whether bilateral coordination on ADLs would improve after task-oriented robot therapy focused on reaching and grasping training of the impaired limb. To examine this affordably, we developed and validated the bilateral assessment system (BiAS) system to measure right and left wrist positions pre-, post-, and during training with ADLER. Our requirements were that the BiAS measurement system needed to be low-cost ($2000–$5000), portable to other environments such as the home, easily donned on and off the wrist, able to measure right and left arm wrist kinematics before, during, and after robot-assisted therapy tasks, and finally, able to operate within the workspace of the ADLER robot.

In the following sections, we present results from two separate experimental studies. The *first study goal* was to characterize wrist kinematic measurements using the BiAS on representative drink and pour bilateral functional tasks. The *second study goal* was to determine if kinematic data resulting from the BiAS system were sensitive to changes in bilateral coordination after robot therapy, whether or not clinically significant changes were identified after task-oriented robot therapy.

2 Methods

2.1 Subjects

In *study 1*, data from 10 able-bodied and 7 stroke subjects were included (Table 1). The average ages of the able-bodied and stroke subjects were 47.5 and 62 years, respectively. The stroke subjects all had clinically diagnosed hemiplegia from a stroke occurring more than 6 months before the study. The Upper-extremity Fugl-Meyer (UE-FM) [9] was used to describe motor control in the impaired arm impairment and the rancho los amigos functional test (UE-FT) [35] was used to describe functional disability levels. Only stroke subjects with the ability to grip the objects used such as the cup and pitcher were included in this study. This enabled a true assessment of kinematic trajectories for reaching and grasping; lower functioning subjects would have had difficulty grasping. These moderate functioning patients had UE-FM scores ranging from 39 to 65 with an average score of 56.7 (66 max) and functional hand scores ranging from level 4 to 6 with an average score of level 6 (level 7 max).

Stroke subjects	Age (years)	Dominant hand	Affected side	UE-FM (66: Max)	UE-FT (Level 7: Max)	Healthy subjects	Age	Dominant hand
Study 1								
S14	64	Right	Left	39/66	Level 4	N4	60	Right
S18	61	Right	Right	51/66	Level 4	N11	56	Right
S28	81	Right	Right	50/66	Level 6	N21	25	Right
S27	57	Right	Right	58/66	Level 6	N26	67	Right
S20	52	Right	Left	60/66	Level 7	N24	70	Right
S22	62	Right	Right	65/66	Level 7	N25	25	Right
S4	58	Right	Left	53/66	Level 5	N28	64	Right
						N29	30	Right
						N31	36	Right
						N32	42	Right
Average	62			56.7/66	Level 6		47.5	Right
Study 2								
S-1 (RT)	51	Right	Left	8	Level 2			
S-2 (RT)	68	Right	Left	8	Level 2			
S-8 (RT)	47	Right	Left	19	Level 2			
S-6 (RT)	63	Right	Left	44	Level 5			
Average	57.3							

Table 1 Summary clinical and study information for subjects in Study 1 and 2

In *study 2*, data from 4 stroke subjects, ages 51–68, were included in the study; they were all right hand dominant pre-stroke and diagnosed with left hemiparesis. Three subjects were low functioning with minimum to no finger movement (UE-FM < 20) and one subject was moderate functioning (UE-FM = 44). Our ultimate goal is to treat 24 stroke patients who are at least 6 months post-stroke with functional scores between level 2 and 5, i.e., subjects with a variety of elbow movements and hand function. Subjects with minimum hand function used functional electrical stimulation to aid in grasping [25]. All subjects gave informed consent. The study was approved by the institution review board of the Medical College of Wisconsin, the Clement J Zablocki VA and Marquette University.

2.2 The BiAS

The BiAS system consists of two 3 DOF position measurement devices; each tracker was developed by colleagues at the Cybernetics department at the University of Reading. As shown in Fig. 1a, the trackers are modeled as two 3-DOF robots each consisting of two revolute joints and one prismatic joint. The two revolute joints represent the yaw angle which rotates 3.49 radians (200°) about a vertical *Z*-axis and the elevation angle which rotates 2.27 radians (130°) about a horizontal *Y*-axis; they are both measured using 10k ohm Vishay 157 potentiometers. The prismatic joint which translates 0.91 m (36 in) along the *X*-axis is achieved by a wire wound wheel attached to another 10kohm Vishay 534 potentiometer. Figure 1b also shows the trackers in the ADLER workspace. Each tracker is mounted to the ADLER table to a small rigid base to provide convenient removable attachment. Figure 2a shows a subject seated at a table using the BiAS trackers in a pour task. In a typical bilateral operation, the trackers are attached to each hand using removable Velcro straps around each wrist (about the radial and ulna styloid process). These positions are chosen to prevent interference with the ADLER system and the performance of ADLs in the ADLER workspace. The reflected inertia of the trackers, calculated by measuring forces exerted as they were moved through the work space by ADLER, is on average 0.2 kg, which is not noticeable by users. Figure 2b shows the plane of the ADLER activity table with locations of the origins of ADLER (projected into the plane) and the BiAS system origin. The dots (1–4) are the targets used for placement of tools such as spoon, cup, pitcher, plate etc. used during the functional tasks.

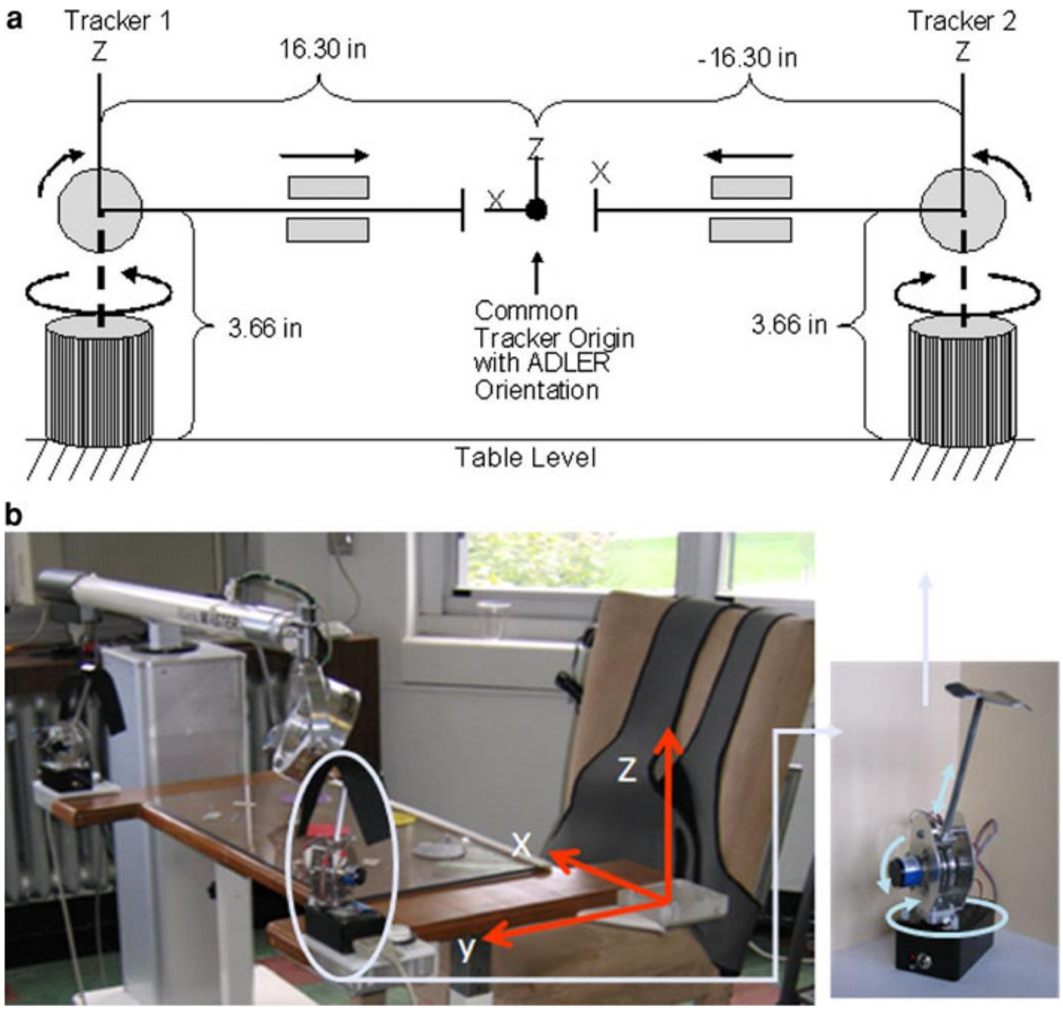

Fig. 1 a Each tracker is a 3 DOF passive robot. There are two revolute joints and one prismatic joint. Prismatic joint has a 0.91 m (36 in) travel. The origin of the trackers is offset from the origin of the ADLER system. b ADLER workspace with trackers attached.

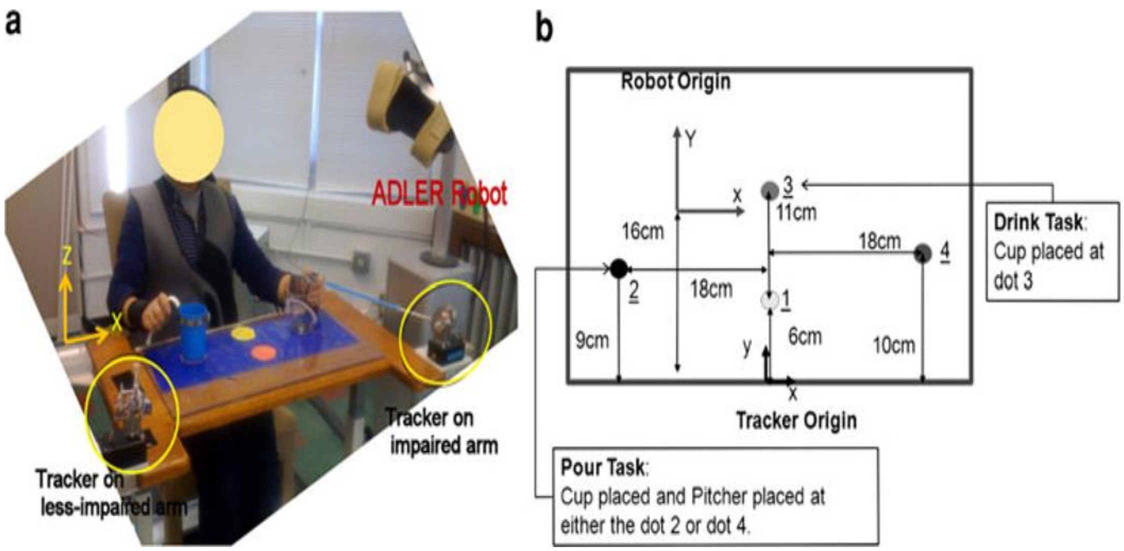

Fig. 2 a Subject seated at ADLER activity table with trackers attached to left and right arms for the pour task. b The trackers origin is offset from the robot origins. The coordination system has positive *x* going toward the left from center, positive *Y* when traveling toward the patient chair, and positive *Z* going upward. Four dots are placed in the workspace to organize and constrain the tasks

Voltages (0–5 V), V_{ext1}, V_{elv1}, V_{yaw1}, V_{ext2}, V_{elv2}, V_{yaw2} from each potentiometer for each tracker were amplified to 0–10 volt range and collected using a custom LabView Virtual Instrument program at 100 Hz. Each tracker was calibrated in relation to a selected common inertial frame in the workspace (Figs. 1a, ,2b,2b, see tracker origin). The common inertial frame is displaced to the far edge of the table (opposite the patient chair), in the center equidistant to both position measurement devices, and in an elevated plane just above and parallel to the table.

Voltages were mapped into the related joint motions of extensions (D_1, D_2 in inches, yaw angles (α, φ in degrees), and elevation angles (β, θ in degrees) using Eqs. 1 and 2. An offset was created to address the issues that the elevation and extension channels are not independent from each other. As the elevation angle changes, the extension wire is wound around its potentiometer. The relationship is linear and an additional offset equation was used to account for these changes in extension length. The conversion coefficients (*a, b, c*) are given in the Table 4 in Appendix.

$$\begin{bmatrix} D_1 \\ \beta \\ \alpha \end{bmatrix} = \begin{bmatrix} a_{11}V_{\text{ext1}} + b_{11}V_{\text{elv1}} + c_{11} \\ a_{21}V_{\text{elv1}} + c_{21} \\ a_{31}V_{\text{yaw1}} + c_{31} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} D_2 \\ \theta \\ \phi \end{bmatrix} = \begin{bmatrix} a_{12}V_{\text{ext2}} + b_{12}V_{\text{elv2}} + c_{12} \\ a_{22}V_{\text{elv2}} + c_{22} \\ a_{32}V_{\text{yaw2}} + c_{32} \end{bmatrix}. \tag{2}$$

	Tracker 1			Tracker 2		
	D	β	α	*D*	θ	φ
a	4.33	−14.92	−35.37	4.29	−15.09	34.71
b	0.01	0	0	0.01	0	0
c	2.26	83.01	212.03	2.49	88.70	219.08

Table 4 Coefficients of trackers' voltage to position conversion equations

A Custom Matlab program was used to process the data. The data were filtered using a 9th order low-pass Chebychev filter with 10 Hz cutoff frequency via the zero-phase digital filtering function filtfilt. The joint variables were then converted to Cartesian coordinates using forward kinematic Eqs. 3 and 4 developed using Denavit-Hartenberg (D-H) principles [5] where L_1 = 0.093 m (3.66 inches) and L_2 = 0.41 m(16.3 inches) (see Fig. 1). Note that units of the resulting wrist positions were inches.

$$\begin{bmatrix} X_{1T} \\ Y_{1T} \\ Z_{1T} \end{bmatrix} = \begin{bmatrix} -D_1 \cos\alpha \sin\beta + L_2 \\ D_1 \sin\alpha \cos\beta \\ D_1 \sin\beta + L_1 \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} X_{2T} \\ Y_{2T} \\ Z_{2T} \end{bmatrix} = \begin{bmatrix} D_2 \cos\phi \sin\theta + L_2 \\ D_2 \sin\phi \cos\theta \\ D_2 \sin\theta + L_1 \end{bmatrix} \tag{4}$$

The HapticMaster robot within the ADLER environment has a position accuracy of 0.001 m and was used to calibrate the BiAS trackers. The BiAS tracker end-effectors were co-located to the end-effector of the ADLER robot to determine offsets between the trackers and ADLER position. The end-effectors were moved five times to each of 17 points that spanned the workspace of the ADLER robot. The position difference between the reference points and the BiAS trackers' readings were averaged across the workspace to determine the calibration offsets for each tracker. These offsets are as follows: *X*: Tracker 1: −89.0 mm and Tracker 2: −140.5 mm, *Y*: Tracker 1: 298.7 mm and Tracker 2: 238.5 mm, and *Z*: Tracker 1: 541.8 mm and Tracker 2: 523.2 mm. The *Z* direction had the largest calibration offset as expected since the ADLER robot system origin is in the center of the ADLER workspace in contrast to the initial BiAS origin at the table edge. The forward kinematic Eqs. 3 and 4 were adjusted by subtracting the above offsets and transforming the units so that the resulting right and left wrist Cartesian positions are in meters. Based on these adjusted kinematic equations, BiAS accuracy in measuring static and dynamic positions was quantified. For *static validation*, the trackers were again attached to the robot end-effector and moved to six additional points. The average differences for each tracker from these six-known robot positions were as follows: *X*: Tracker 1: −4.1 ± 22.6 mm and Tracker 2: 9.0 ± 17.3 mm, *Y*: Tracker 1: −4.3 ± 10.2 mm and Tracker 2: 0.3 ± 20.9 mm, and *Z*: Tracker 1: 3.8 ± 9.0 mm and Tracker 2: −0.1 ± 12.0 mm. The overall static accuracy of the

BiAS system is 0.8 ± 0.8 mm. For *dynamic validation*, the trackers' recordings were measured for dynamic tasks at three velocities (slow: 93 mm/s, medium: 374.0 mm/s, and fast: 780 mm/s) along 8 trajectories spanning the reachable workspace of the ADLER robot (see details in Appendix).The differences in positions were calculated and statistically compared across speeds; these differences were not significant ($P = 0.62$) suggesting that movement at these speeds did not affect the accuracy of the position measurements. The average dynamic accuracy of the BiAS system is 8.6 ± 3.0 mm across all speeds.

2.3 Bilateral coordination evaluation pre- and post-task-oriented therapy

In *study 1*, interlimb coordination was evaluated one time with the BiAS system. In *study 2*, interlimb coordination evaluations were completed pre- and post-task-oriented therapy. For evaluation sessions subjects were seated at an activity table (60 × 30 cm) in the ADLER workspace and asked to perform a series of functional tasks at their own pace while attached to the BiAS trackers (Fig. 2). The drink and pour tasks are reported here. For the drink task, the cup was centered across the width of the table and 18 cm from the inside edge of the table (dot 3). For the pour task, the cup was placed as drink cup and the pitcher of water was placed 10 cm from the edge (dot 4) (see Fig. 2). Subjects started and ended in a resting position with their palms down and shoulder width apart on the edge of table and elbows at a 1.57 radians (90°). For bi-drink, they were instructed to reach out from rest, pick up the two-handled cup, bring it to the mouth for a drink, return the cup to the target location and then return their hands to rest. For bi-pour, they were instructed to reach out and use the dominant/less-impaired arm to stabilize the cup and use the non-dominant/impaired arm to lift and pour about 113.7–170.5 ml (4–6 oz) of water into the cup and then return to rest. The pour task was slightly modified in study 2 in that the cup was placed at dot 2 and the pitcher was at dot 4; subjects reached out to stabilize cup with dominant/less-impaired limb and poured the water with the non-dominant/impaired limb. Tasks were instructed and practiced several times before data collection of the 3 trials for each task.

In *study 2*, task-oriented robot therapy was done using the ADL Exercise Robot (ADLER) [13, 14]. The subjects in study 2 experienced 60 min of training in 1 of 4 task modules 3 times per week for 4 weeks. The modules consisted of a self-care module with tasks such as eating, drinking, and combing task, a games module with tasks such as tic-tac-toe and basketball as well as 3D and 2D reaching modules focused on reaching with or without grasp. If subjects are low-functioning the robot provided adaptive force assistance to complete tasks and if subjects had moderate motor function the robot provided force resistance. Subjects with little or no grasp function were assisted with the use of a custom glove with a functional electrical stimulation (FES) unit to assist in voluntary grasp and release [25]. FES was introduced after session 4 for S1, S2, and S8 approximately for 2 h of the remaining 9 sessions.

2.4 Data Analysis

The raw data were post-processed using the custom MATLAB program as described and the adjusted forward kinematic positions were used to calculate dominant/less-impaired and non-dominant/impaired wrist position. The corresponding velocities traces were obtained using Eq. 7.

$$V_{\text{inst}} = 0.002\left(\sqrt{(X_{i+1}-X_i)^2+(Y_{i+1}-Y_i)^2+(Z_{i+1}-Z_i)^2}\right). \qquad (7)$$

Movement initiation for each arm was defined as the time when the velocity of the wrist exceeded than 5% of its maximum velocity. Movement termination for each wrist corresponded to the time when the velocity falls below the 5% threshold and remained there. Movement initiation for the task is the earliest of this time while movement termination for the bilateral task was the latest of the two times.

We used several metrics from the literature to assess interlimb coordination; these were phase difference (PD), movement overlap (%MO), and task completion time (TCT) [33, 10, 12, 29, 30]. The literature indicates that the relative phase metric (the lag between right and left limbs) is often used to assess interlimb coordination in symmetrical tasks such as synchronized reaching and continuous tasks such as circle tracking. The functional studies such as those conducted to examine how the drawer opening task is performed are fewer and tend to assess interlimb coordination with temporal measures of goal synchronization, %MO, and TCT [12]. The phase of each limb was calculated in degrees by the arc tangent of the instantaneous velocity divided by the displacement. PD was found by subtracting the non-dominant phase from the dominant phase (Eq. 8). For stroke subjects, the non-dominant limb is the impaired limb and the dominant limb is the less-impaired limb. The TCT was defined as the time from movement initiation to when both hands returned to the rest position and the velocity of the slowest limb was less than 5% of its peak velocity. Finally %MO was defined as the task time when both hands were in motion as a percentage of total TCT; a limb was not at rest if its instantaneous velocity, V_{inst}, was above 5% of its peak velocity.

$$\mathrm{PD} = a\tan\left(\frac{V_{\text{inst\_D}}}{\sqrt{(X_{i\_\mathrm{ND}})^2 + (Y_{i\_\mathrm{ND}})^2 + (Z_{i\_\mathrm{ND}})^2}}\right) - a\tan\left(\frac{V_{\text{inst\_ND}}}{\sqrt{(X_{i\_\mathrm{D}})^2 + (Y_{i\_\mathrm{D}})^2 + (Z_{i\_\mathrm{D}})^2}}\right). \tag{8}$$

For *study 1*, the interlimb coordination metrics, %MO, TCT, and PD were calculated for each subject and were averaged across three trials. Despite expectations, using analysis of variance (ANOVAs) at an alpha level of 0.05, we tested the null hypothesis that there will be no differences between task and across subject types [26]. Post-hoc analyses were performed using one-way ANOVAs. For *study 2*, the interlimb coordination metrics, %MO, TCT, and PD were also derived and averaged across the three trials for pre- and post-therapy. Since, there were not enough subjects in the intervention group, only descriptive statistics were used. We examine individual subject trends across time (pre- and post-therapy) and across task (drink and pour).

2.5 Hypotheses

In *study 1*, we hypothesized that the bilateral drink task would require higher %MO, smaller PD, and shorter completion times (TCT) than the bilateral pour task and that stroke subjects as compared with healthy ones would perform with lower %MO, longer TCT, and larger PD. In *study 2*, we hypothesized that if bilateral coordination improved after the robot therapy, there would be a normalization of each subject's performance for both tasks. On the symmetric drinking and pouring tasks, the subjects would have increased MO, decreased PD between the two arms, and decreased time to complete them.

3 Results

Figure 3a–d show example BiAS trajectories for the *XY* (in the table plane) and *XZ* (in the torso) plane for the dominant (D) and non-dominant (ND) arms of a healthy subject (N24) and a stroke subject (S27) for the drink and pour tasks. The symmetry inherent in the bi-drink task as well as the asymmetry of the bi-pour task is clearly observed. These trajectories tended to be curved and not straight-lined trajectories typically observed in point-to-point reaching movements [36]. Figure 4a–d shows typical BiAS velocity profiles for the D and ND arms of a healthy subject (N24) with the key events highlighted [see left traces Figs. 4a (top), c (bottom)]. Velocity traces for the less-impaired (D) and impaired (ND) arms of stroke subject (S27) for drink and pour tasks [see right traces Fig. 4b (top), d (bottom)] are also shown. The *drink task* has reach and transport events, reach and back for the cup and transport cup to and from the mouth. The movements between the arms were highly symmetric (Fig. 3, top) with corresponding velocity profiles (Fig. 4a, top) showing four distinct bell-shaped movements for D and ND for the healthy subject. Unlike the healthy subject, the impaired arm stroke subject did not remain in sync with less-impaired arm on the return to rest portion of the task. The impaired arm velocity traces tended to be less smooth suggesting more stops and starts in the movement [8].

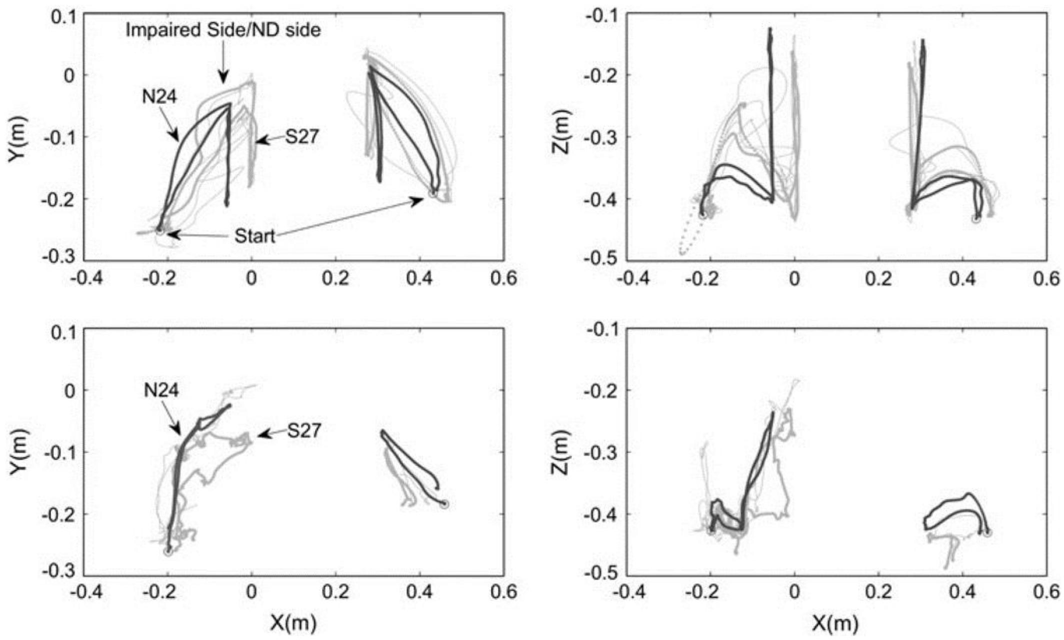

Fig. 3 a, b Kinematic position traces [*XY*: in plane of table and *XZ* (in plane of torso) of both limbs during the bilateral drink task (*top*: a, b) and bilateral pour (*bottom*: c, d)]. Subjects S27 is contrasted with healthy subject (N24) (Table 2). Three trials were processed for S27. *Y*-axis was inverted to allow for easier understanding of graph. Dominant hand (D) and non-dominant hand (ND) are shown. Notice in pour task the D is stabilizing the cup and the ND hand is moving pouring

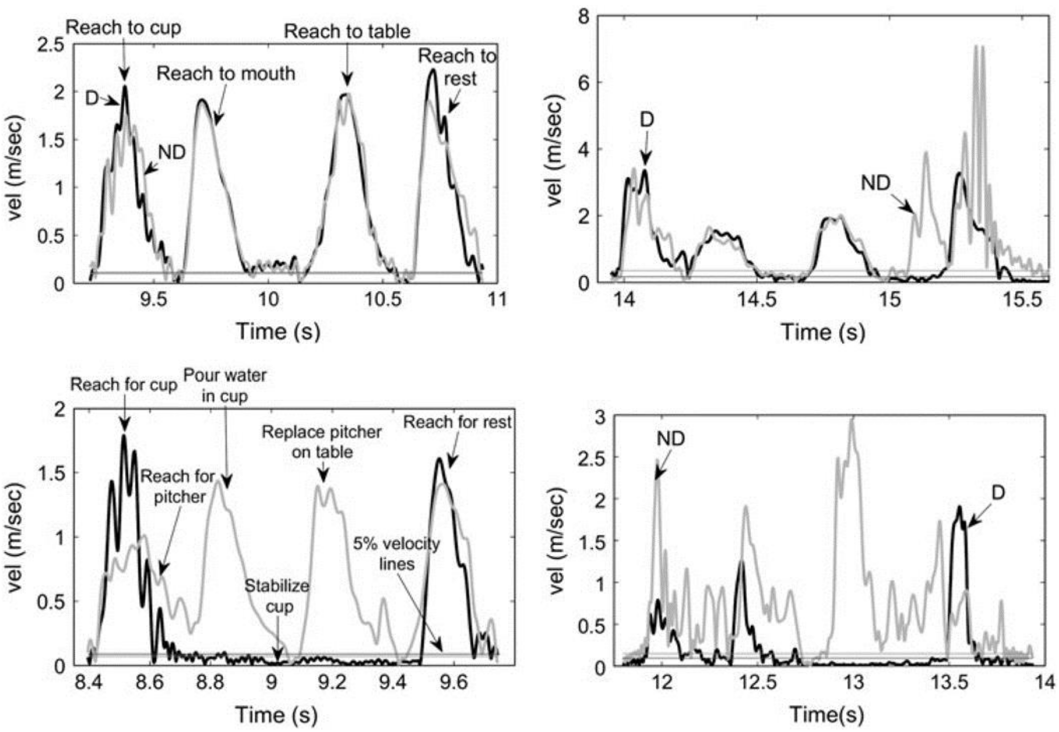

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Fig. 4 (*Left traces*: **a, c**) Velocity traces of both limbs during the bilateral drink task (*top*) and pour task (*bottom*) for N4 (*ND* non-dominant velocity, *D* dominant velocity). (*Right traces*: **b, d**) Velocity traces of both limbs during the bilateral drink task (*top*) and pour task (*bottom*) for S27. Note S27 had tendencies to complete tasks with more time and more sequential movements of limbs.

The *pour task* has reach and transport events for the non-dominant/impaired arm, reach to and from the pitcher, pour water and return pitcher, and primarily reach event for the dominant/less-impaired arm, reach to and from cup. The movements between the arms showed symmetry for reach to cup and pitcher (Fig. 3, bottom) with corresponding velocity profiles (Fig. 4c, bottom) showing two distinct bell-shaped movements for D and four for the ND of the healthy subject. Unlike the healthy subject, the impaired arm (ND) movement of the stroke subject was not so distinctive. The stroke subject was less smooth and more likely to take more time to grasp and release the pitcher.

3.1 Normal versus stroke interlimb coordination

The averaged interlimb coordination results for bilateral drink and pour tasks are shown in Table 2. In *study 1*, the ANOVA reported significant differences between subject groups and between tasks (P < 0.05). For the drink task, the average TCT for stroke subjects (1.80 ± 0.86 s) increased significantly over able-bodied subjects (1.37 ± 0.35 s) (P = 0.006). The average %MO decreased significantly for stroke subjects (61.79 ± 22.38%) when compared to able-bodied subjects (80.44 ± 4.53%) (P = 0.00). Differences in averaged PD did not reach significance across groups (healthy: 4.47 ± 1.55° vs. stroke: 4.20 ± 6.20) (P = 0.975). For the pour task, the average overall TCT for stroke subjects (2.50 ± 1.54 s) increased significantly over able-bodied subjects (1.37 ± 0.35 s) (P < 0.001). The average %MO decreased for stroke subjects (26.29 ± 13.06%) compared to able-bodied subjects (34.44 ± 4.24%), but not significantly (P < 0.097). Differences in average PD did not reach significance between the groups (healthy: 5.03 ± 29.53° vs. stroke: 7.95 ± 24.69°) (P = 0.75).

Subjects	**Drink TCT (s)**	**Pour TCT (s)**	**Drink %MO**	**Pour %MO**	**Drink PD (deg)**	**Pour PD (deg)**
N4	1.07	0.98	78.56	39.92	4.98	36.51
N11	1.91	1.74	80.74	29.71	6.32	37.18
N21	1.19	1.22	83.69	30.01	3.66	31.23
N24	1.85	1.55	86.66	39.78	6.56	28.99
N25	1.08	0.98	76.72	36.14	4.08	−26.03
N26	1.37	1.16	79.89	33.46	5.76	30.43
N28	1.74	1.89	83.49	32.77	2.29	−18.59
N29	1.32	1.44	78.38	32.93	4.88	−20.08
N31	0.91	0.98	84.93	39.92	2.03	−27.7
N32	1.3	1.74	71.29	29.71	4.16	−21.61
Average normal (SD)	1.37 (0.35)	1.37 (0.35)	80.44 (4.53)	34.44 (4.24)	4.47 (1.55)	5.03 (29.53)
S14	2.54	3.56	63	25.44	−2.54	−12.64
S18	1.77	4.52	70.04	9.00	12.2	32.76
S28	1.81	2.21	64.17	36.72	−3.56	24.72
S27	1.45	2.5	68.2	33.95	3.93	38.03
S20	2.04	2.19	55.29	32.6	13.58	−15.38
S22	2.00	1.59	73.23	38.61	5.48	22.09
S4	3.33	4.99	67.76	18.17	2.69	−23.05
Average stroke (SD)	1.80 (0.86)	2.50 (1.54)	61.79 (22.38)	26.29 (13.06)	4.20 (6.20)	7.95 (24.69)

Table 2 Bilateral drink and pour results for healthy and strokes

TCT task completion time (s); *MO %* movement overlap; and *PD* phase difference (degrees)

Average and standard deviations of the interlimb metrics are reported for subjects in Table 1

As we expected, the analysis of BiAS kinematic data using the three metrics showed that the bilateral drink task compared to the bi-pour task required significantly higher movement overlap (%MO: drink: 80.44 ± 4.53% vs. pour: 32.44 ± 4.24%; $P = 0.00$) and stroke survivors tended to perform both tasks with less than desired movement overlap (%MO: drink: 61.79 ± 22.38% vs. pour: 26.29 ± 13.0%). Time needed to perform the bi-pour and bi-drink tasks was the same for healthy subjects, but stroke subjects tended to take longer to perform the bi-pour task (TCT: pour: 2.50 ± 1.54 s vs. drink: 1.80 ± 0.86 s; $P = 0.493$); most had difficulty with grasping and pouring. Regardless of task, stroke survivors were slower and were more likely to move limbs sequentially. These results indicate that kinematic measurements of the wrist using the BiAS are sensitive to impaired and unimpaired movement. The most sensitive metrics seemed to be time and %MO. PD was more reliable for bi-drink task than for bi-pour suggesting that the pour task had higher performance variability.

3.2 Interlimb coordination after robot therapy

The interlimb coordination results for bilateral drink and pour tasks pre- and post-robot therapy are shown in Table 3. In *study 2*, three stroke survivors (S1, S2, and S8) were low functioning having less motor control and ADL function than stroke subjects in study 1, and as a result, before therapy, had longer TCTs and less %MO with similar PD variability. Pre-therapy TCTs should in fact be longer because these subjects were not able to complete each task. S6, a moderate functioning subject, was similar to stroke subjects in study 1 having similar movement patterns prior to therapy; subject 6 was able to complete all tasks. As a result of robot training, subjects S1 and S2 experienced functional changes (they moved from level 2 to 3 on the

UE-FT), but were essentially still low functioning according to the UE-FM scores. Subject S8 had improvements on UE-FM score from 19 to 22 post-therapy and saw some gains in ADL function with UE-FT changes from level 2 to 3. Subject S6 had improvements on UE-FM score from 44 to 47 post-therapy, but no change on ADL function with UE-FT remaining at level 5. The therapy was most effective for S6 who already had some hand function.

		UE-FM/UE-FT	TCT	%MO	PD
Bi-drink					
S1-Low	Pre	8/Level 2	4.64 (0.7)	7.3 (4.04)	−9.93 (3.32)
	Post	8/Level 3	2.75 (0.14)	53.81 (7.11)	−1.14 (0.81)
S2-Low	Pre	8/Level 2	5.23 (1.13)	35.32 (6.62)	7.82 (5.93)
	Post	8/Level 3	3.37 (0.03)	41.95 (2.79)	21.22 (2.83)
S8-Low	Pre	19/Level 2	4.06 (1.33)	18.66 (10.36)	−20.98 (6.66)
	Post	22/Level 3	5.02 (0.24)	43.12 (5.01)	−6.57 (1.52)
S6-Med	Pre	44/Level 5	2.39 (0.31)	68.4 (1.49)	3.65 (2.42)
	Post	47/Level 5	2.38 (0.18)	74.88 (5.03)	1.59 (1.24)
Avg. stroke		56.5/Level 6	1.80 (0.86)	61.79 (22.38)	4.20 (6.20)
Avg. normal		N/A	1.37 (0.35)	80.44 (4.53)	4.47 (1.55)
Bi-pour					
S1-Low	Pre	8/Level 2	5.8 (1.23)	26.37 (6.69)	−4.22 (2.12)
	Post	8/Level 3	3.19 (0.15)	20.9 (6.82)	−1 (2.53)
S2-Low	Pre	8/Level 2	4.93 (0.42)	16.11 (4.74)	−17.81 (2.57)
	Post	8/Level 3	4.28 (0.29)	9.26 (3.45)	−4.21 (5.84)
S8-Low	Pre	19/Level 2	3.63 (0.66)	27.38 (11.44)	−28.32 (3.47)
	Post	22/Level 3	6.84 (1.45)	18.53 (5.64)	−6.00 (3.04)
S6-Med		44/Level 5	4.85 (0.32)	48.81 (7.3)	−10.7 (2.96)
		47/Level 5	3.56 (0.34)	69.99 (5.03)	−14.77 (4.51)
Avg. stroke		56.5/Level 6	2.50 (1.54)	26.29 (13.06)	7.95 (24.69)
Avg. normal		N/A	1.37 (0.35)	34.44 (4.24)	5.03 (29.53)

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Table 3 Bilateral drink and pour summary of metrics for stroke subjects (pre- and post-robot therapy)

We had hypothesized that if bilateral coordination improved after the robot therapy, there would be a normalization of each subject's performance for both tasks. Recall that for the bi-drink task, healthy subjects tended to have at least 80% overlap in movement between the limbs and the dominant arm tended to lead the non-dominant hand (Table 2). In addition, the healthy subjects were able to complete the task in less than 1.4 s. High functioning stroke survivors had close to 62% overlap between limbs with similar lead-lag relationship between the limbs. They were able to complete the task in less than 2 s. We expected that post-therapy, all stroke survivors would move closer to the performance of high-level stroke survivors. They would complete the bilateral drink task faster with improved symmetry, and with a decreased tendency to move limbs sequentially and out of phase. The post-therapy trajectories for the impaired arm of all subjects tended to be smoother than pre-therapy ones [17, 28] indicating some reduction in motor impairment.

In Table 3 the three low-functioning subjects were able to complete the bi-drink task post-therapy by coupling the impaired arm to the cup; on some trials they were able to hook onto the cup handle with a thumb or a finger and then relied on the less-impaired arm to move the impaired arm to the mouth. They were not able to do this before therapy indicating some functional gain in the hand (full grasp was not achieved); however, this "successful" strategy did mask the true ability of the impaired limb. In contrast, the moderate functioning subject S6 was able to complete the task pre- and post-therapy.

Figure 5a–d shows the pre- and post-therapy position trial 3 results for bi-drink for subject 6 and subject S8 contrasted them with healthy subject N24. Figure 5e shows the pre- and post-therapy velocity trial 3 results for bi-drink for S6 and contrasted them with subject N24. Post-therapy kinematic results indicate that S6 more so than S8 improved use of the impaired limb in the task. The stroke subjects still do not move as smoothly as the healthy subject, but, especially for S6, increased their range of motion, smoothness, and the symmetry between limbs. For S6, the bi-drink task was completed in essentially the same time in the pre- and post-sessions, but the percent overlap between her limbs increased from 68.4 to 74.88% and the PD indicating less-impaired hand leading the movement decreased from 3.65° to 1.59°. For S8, the bi-drink task was completed only in the post-therapy; an increase in TCT is seen from an average of 4.06–5.02 s. The percent overlap between her limbs decreased from 18.66 to 43.12% and the PD which favored her impaired limb decreased from 20.98° to 6.57°. Figure 5e illustrates these changes clearly in that we see the differences in the peaks of the velocity profiles for the impaired and less-impaired arm decreasing. The impaired arm moved smoother in that there were a decreased number or stops and starts during movement. The impaired arm was better synchronized with the less-impaired arm for the task in that the expected bell-shaped velocity curves for the four key task events (reaching and transporting of the cup to and from the mouth) emerged more clearly.

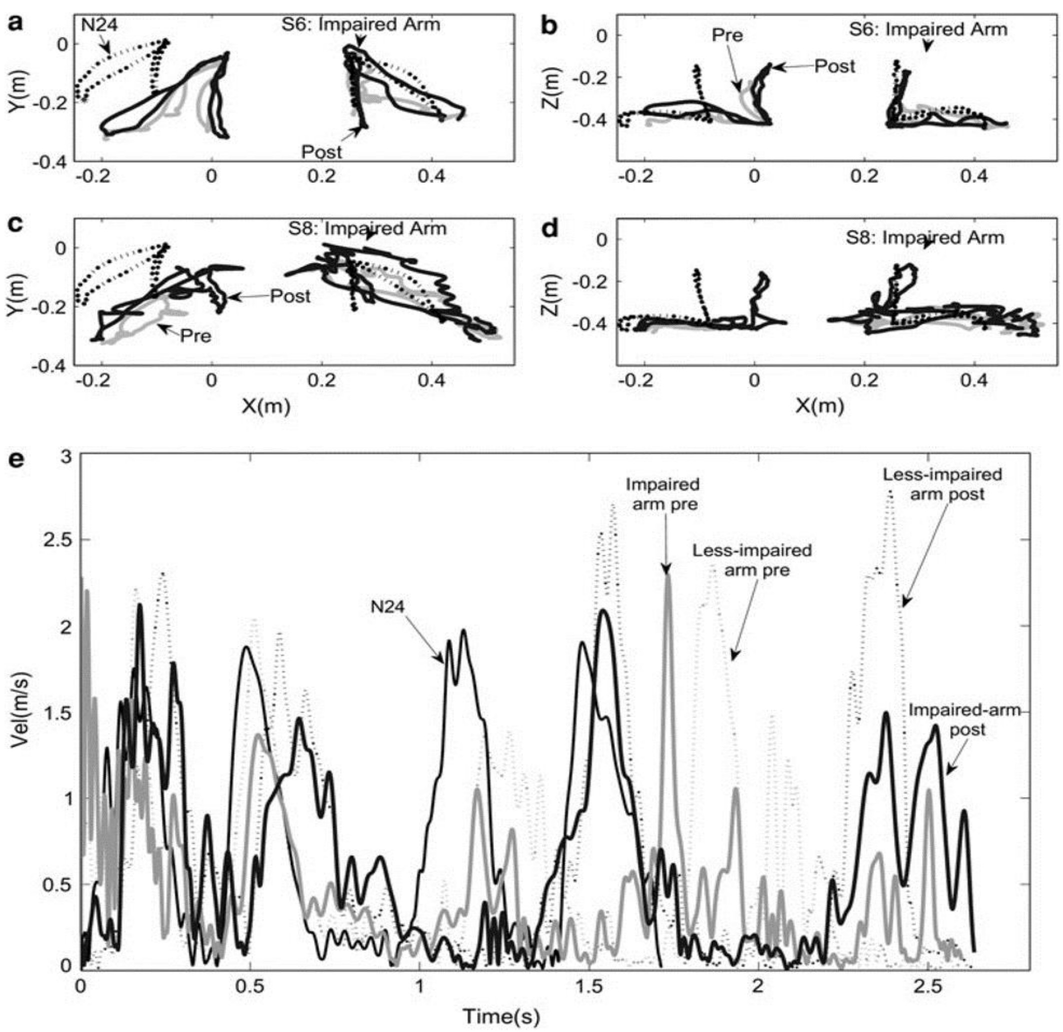

Fig. 5 Position (**a, b**: *top*) of S6 for both limbs during the bilateral drink task pre- (*light lines*) and post- (*dark lines*) therapy. Only third trial is shown and contrasted with S8 low movement (**c, d**) and N24 normal movement (*dotted lines*). **e** Velocity of S6 for both limbs during the bilateral drink task. Only third trial is shown and contrasted with N24 normal movement.

Recall that for the bi-pour task healthy subjects tended to have at least 34% overlap in movement between the limbs and high functioning stroke survivors had close to 27% overlap between limbs with similar lead-lag relationship between the limbs. We saw that healthy subjects were able to complete these tasks in less than 1.4 s while high-level stroke subjects in less than 2.5 s. Again, we expected that as stroke subjects saw motor impairment reduction post-therapy, they would complete the bilateral pour task faster with symmetry and phase relationships similar to high-level stroke survivors. Unlike the drink task, success on the pour task will require the impaired arm to stably grasp the pitcher and to move in and out of phase with the less-impaired arm. As a result, we saw that only S6 was able to complete the full bi-pour task and the low-functioning subjects (S1, S2, and S8) completed only the movements to the cup and the pitcher and were not able to grasp or manipulate the pitcher. Simply, the low-functioning subjects did gain sufficient hand function for this task. Their ability to complete the reaching sub-movements for this task suggest that the battery of functional tasks used for assessment using the BiAS system must include more tasks that are doable by lower functioning subjects and must define methods for analyzing sub-events within the task. Given this, the %MO and PD results in Table 3 give somewhat credible information about interlimb movement for these subjects, but the completion times were unreliable. Post-therapy results for S6 were most reliable. Figure 6a–d show the pre- and post-therapy position trial 3 results for bi-pour for S6 (Fig. 6a–b) and S8 (Fig. 6c–d) contrasted with subject N24. Figure 6e–f shows the pre- and post-therapy velocity trial 3 results for bi-pour for S6 only contrasted with subject N24.

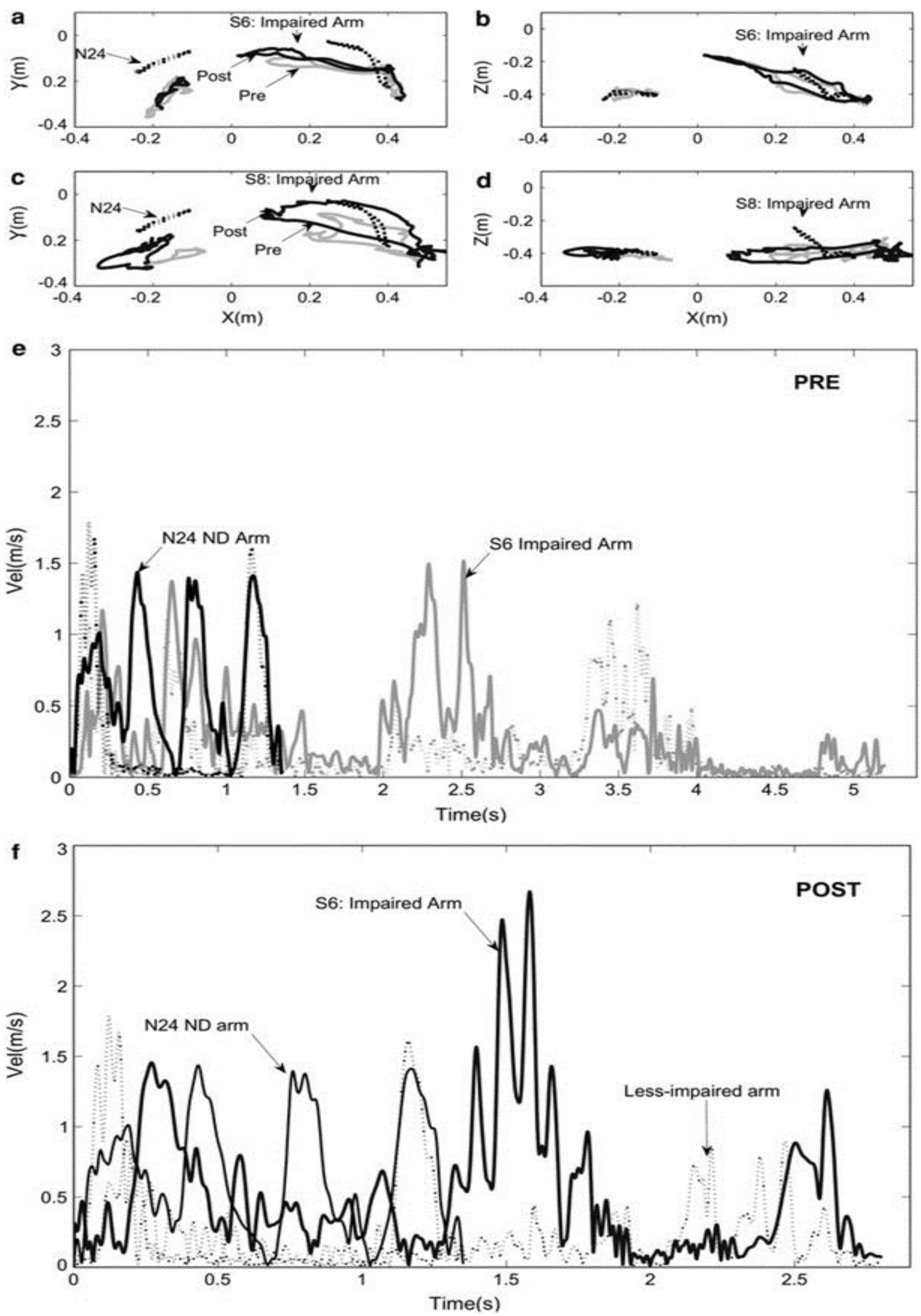

Fig. 6 Position (**a, b**: *top*) of S6 and of S8 (**c, d**) for both limbs during the bilateral drinkpour task pre- and post-therapy. Only third trial is shown and contrasted with

N24 normal movement. **e, f** Velocity of S6 for both limbs during bilateral pour task—pre- and post-therapy. Only third trial is shown and contrasted with N24 normal movement

Table 3 indicates that S6 completed the task with shorter times after therapy (TCT: 4.85 ± 0.32–3.56 ± 0.34 s). She had greater symmetry post-therapy with increased MO (%MO: 48.01 ± 7.3–69.99 ± 5.03 s). Her starting and ending %MO indicated greater symmetry than the task typically required, which indicated possible issues completing the task stably. S6 had difficulty with the lift and pour aspects of the task and had difficulty performing it pre-therapy with improvements post. The impaired arm moved smoother and was better coordinated with the less-impaired arm for the task in that the expected bell-shaped velocity curves for the impaired hand's key task events (reaching and pouring of the pitcher) emerged more clearly in post-therapy evaluations.

4 Discussion

This article presented novel methods to measure and evaluate bilateral coordination of arm function on ADL tasks before and after robot-assisted therapy. A low-cost system called the BiAS was described along with validation results. The average static accuracy was 1 mm and the average dynamic accuracy was 8.6 mm across tested speeds, although not as accurate as the Optotrak system (0.01 mm at 2.25 m distance) or the ADLER robot (1 mm), is sufficient to evaluate interlimb coordination in the ADLER workspace as the motions we typically study and practice are not fine quick-paced manipulation movements. The bilateral functional tasks used for evaluation (drink, reach, feed etc.) involve moderate to slow paced reaches that are at short paths such as the distance between the spoon and the bowl in the bilateral feed task (from dot 1 to dot 2 in Fig. 2b). The advantage of still using this system despite it not being as accurate is in the trade-off. We gain a low-cost system that is portable, non-magnetic, and highly compatible with our robot system.

BiAS was able to measure accurately right and left arm kinematics during typical functional tasks, a bilateral symmetric (bi-drink) task and a bilateral asymmetric (bi-pour) task. Three metrics, PD, %MO, and TCT, were used to assess bilateral coordination for these tasks. We examined data for a total 11 stroke survivors and 10 healthy subjects in two studies. In study 1, we analyzed arm movements of 7 stroke subjects and 10 healthy subjects using the BiAS system during a single visit. In study 2, we analyzed arm movements of 4 stroke subjects using the BiAS system pre- and post-robot therapy. Despite our small subject size were are able to provide insights into the functional tasks themselves and how performance of these tasks differs across subject types and due to the task-specific therapy.

Study 1 provided insights into the functional tasks themselves and how performance of these tasks differs across subject types. As previously reported in Wisneski and Johnson [36], for all subjects wrist trajectories in and out of the plane were curved and not straight-lined trajectories. As expected, the bilateral drink task compared to the bi-pour task required significantly higher MO and with tendencies toward smaller PDs and smaller execution times. Regardless of task, stroke survivors were significantly slower and were less likely to move limbs simultaneously (decreased %MO). In the drink task, healthy subjects were most likely to lead with their dominant hand, but PDs between groups were essentially the same. In the pour task, subjects accomplished the task in a variety of ways resulting in large variability in PD. These findings are similar to past studies investigating interlimb coordination utilizing the asymmetrical drawer paradigm. In a study by Serrien and Wiesendanger, cerebellar subjects showed de-synchronization of the hands and decomposition of movement at the onset and termination of the task through prolonged offsets at the initiation and termination of the hand movements [29]. Another study by Hung, Charles, and Gordon who investigated these metrics with children with hemiplegic cerebral palsy also found significant increases in TCT and %MO for the overall asymmetrical drawer paradigm [12]. Overall, we verified that the BiAS system can accurately quantify movements of the wrist during functional tasks and detect differences between the tasks and between impaired and unimpaired limb movements.

Study 2 showed that kinematic data resulting from the BiAS system were sensitive to changes in bilateral coordination after robot therapy, whether or not clinically significant changes were identified. Four stroke subjects (S1, S2, S8, and S6) were assessed pre- and post-task-oriented therapy with ADLER. The moderately functioning subject, S6, had the best clinical results and the most reliable kinematic outcomes. Subject 6 experienced improved symmetry in and interlimb coordination in both bi-pour and bi-drink tasks and hand improved completion times for the more complicated bi-pour task. The lower functioning subjects tended to have smaller changes on clinical outcomes and their kinematics results were more difficult to interpret; interpretation must be examined in combination with videos. We expected that all low-functioning stroke survivors to have some gains in motor control and improvements in reach and grasp. This result may suggest that the task-specific therapy may be most suited for subjects with some existing hand function. On the other hand, since other therapy interventions with robots and/or with FES grasp systems have resulted in 20% or more changes in UE-FM along with improvements in grasp [2, 6, 7, 11, 20], we suggest that another reason for our study results may the lower intensity of the training provided for reaching and grasping. Compared to other studies which provided 12 to as much as 60 total hours of training, subjects completed about 12 h of therapy with only about 2 h of these involving reaching with FES assisted grasp. Future implementation of the robot therapy should involve increasing the total hours spent in training for both reaching and grasping (the best therapies seem to average 36 total hours) and the use of FES assisted grasp or another grasp-assisting modality for all of those hours.

Results from studies 1 and 2 suggest that while the BiAS system can accurately measure the kinematic wrist positions of all subjects regardless of impairment levels, grasping changes should to be measured to provide additional insight into manipulation components of the task. The results also suggest that there were limitations in the tasks used to evaluate bilateral function and the metrics used to measure changes. The metrics used were limited in measuring change regardless of impairment level. Of the three metrics, %MO and task completion seem most consistent. For the functional tasks used, these metrics were better able to detect changes for moderate to high functioning subjects who were able to complete all aspects of the bilateral tasks and were less sensitive to low-functioning stroke movements especially when the tasks were partially completed. There is the possibility that the metrics were appropriate, but the tasks used were not sufficiently constrained to evaluate the low-functioning subjects' coordination. For example, the bilateral drink task required both arms to move to and grasp the cup to bring the cup to the mouth and back. Ideally, task success depended on a successful stable grasp of the cup and movement of the cup to the mouth. Low-functioning subjects were unable to grasp the cup pre-therapy, but post-therapy had some gains that allowed them to "hook" their impaired hand to cup handle to allow the less-impaired hand to provide help to compete the task. Although a realistic strategy, this masked the ability of the impaired arm. This issue revealed the need to use a variety of evaluative bilateral functional tasks including those that can be performed without manipulation of objects, e.g., a bilateral reach or point-to-point versions of the bi-pour and bi-drink tasks. In addition, the issue also revealed the need to critically examine the sub-events within each task with the metrics.

Additional kinematic metrics such as ratio of impaired and unimpaired arm smoothness [7, 28], impaired and less-impaired arm difference velocities [2, 21, 22] could also be used in combination with the ones proposed to offer additional insight into bilateral coordination post-robot therapy. Studies suggest that unilateral impaired arm deficits also affect the less-impaired hand by altering its kinematics to preserve symmetry and goal invariance. In symmetrical reaching studies, almost always subject will slow down their less-impaired hand to the level of the impaired hand such that the deficit of the impaired hand had re-established the spatial and temporal demands of the task [10, 12, 32]. In the asymmetrical bimanual drawer involving opening a drawer with one hand while the other hand had to pick up a peg which was inserted in the drawer's recess with the other hand, neurological impaired patients and healthy subjects, there was an initial de-synchronization of the limbs indicated by an increase offset for initiating hand movements at the start when compared to normal control. At the goal, the magnitude of temporal offset was smaller than at initial movement onset preserving goal invariance [30]. This phenomenon could be examined using the BiAS system along with an appropriate battery of tasks and metrics.

We anticipate that bilateral coordination changes with the BiAS would be more clearly seen with bilateral interventional strategies in general [32] and technology-assisted ones such as MIME [2, 22] and BATRAC [32, 34]. Bilateral interventions will have differing effects on improving coordination on symmetric functional tasks and asymmetric discrete functional tasks, the more complex of the two. For example, the BATRAC and MIME interventions may be more likely to improve interlimb coordination on symmetric tasks. In BATRAC subject practice simple temporally synchronized and spatially similar reaching movements and in the MIME they practice more complex (3D) bilateral reaching movements via mirror symmetry. Currently, there are no bilateral robotic intervention strategies that have been shown to adequately improve bilateral coordination on functional tasks types. This suggests a need to include bilateral training within the ADLER training system.

In conclusion, we showed that the portable, low-cost measurement system of two 3DOF passive joints can quantify movements of the wrist during functional tasks pre- and post-robot therapy. Results of impaired and unimpaired arm kinematics analysis using BiAS are in agreement with the literature and indicate that stroke subjects tend to move slower and are less likely to use their arm simultaneously even when the functional task requires simultaneous movement.

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Appendix

The coefficients of the six voltage conversion Eqs. 1 and 2 are given in Table 4.

Dynamic accuracy details

The trackers were attached to the robot end-effector and moved along eight trajectories; the adjusted forward kinematics equations were used to calculate corresponding position trajectories. The difference between the measured and reference trajectories were calculated over the constant velocity segments within the trajectory and then averaged across all samples; there were approximately 250 samples. Table 5 shows that the best accuracy was seen in the *X* coordinate for all speeds. The differences in positions were not significant ($P = 0.62$).

Speed	Tracker	*X* (mm)	*Y* (mm)	*Z* (mm)
Slow	1	−0.8 ± 6.4	22.4 ± 5.6	2.8 ± 5.4
	2	0.3 ± 7.2	25.6 ± 9.0	0.6 ± 5.6
Medium	1	0.4 ± 5.6	21.4 ± 6.3	3.8 ± 4.9
	2	−1.5 ± 10.5	24.9 ± 10.7	1.6 ± 6.4
Fast	1	1.2 ± 5.4	18.7 ± 8.1	7.4 ± 5.6

Table 5 Position differences are described between robot and tracker position for three speeds

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