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Quantifying Learned Non-Use after Stroke using Unilateral and Bilateral Steering Tasks

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Abstract— **Learned non-use (LNU) is common after stroke and manifests when persons with stroke spontaneously use their stronger less-impaired arm despite residual functional abilities in the impaired arm. This tendency of under utilizing the impaired arm slows down the re-acquisition of bilateral coordination on activities of daily living. We wanted to examine whether this behavior could be studied and quantified using the TheraDrive system, a low-cost, mechatronic/robotic stroke rehabilitation system which uses a commercial force-feedback steering wheel along with custom games and unilateral and bilateral steering tasks for therapy and assessment. We attempt to quantify the role of the impaired arm in bilateral tracking with one and two-wheeled modes of the TheraDrive. Our results indicate that impaired arm use, arm bias and learned non-use behaviors may best be detected in decoupled bilateral tracking tasks.**

Keywords-bilateral coordination; robot-assisted therapy; stroke rehabilitation; upper arm;

I. Introduction

After an ischemic or hemorrhagic cerebrovascular incident resulting in brain damage, stroke survivors typically present with significant residual physical, cognitive, and psychological impairments. Hemiparesis is the most common motor disability after stroke [1], which involves varying degrees of weakness in the limbs contralateral to the side of the brain injury [2]. Often in the upper limb, stroke results in decreased ability to perform smooth coordinated bilateral movements leading to decrease ability to perform many bilateral daily living tasks such as eating with a knife and fork. To adapt to their motor disability, many stroke survivors develop compensatory behaviors characterized by decreased use of their impaired arm and an increased use of their less-impaired arm despite existing functional recovery in the impaired arm [3-5]. The behavior of not using their impaired side even in the presence of latent functional capacity is learned non-use [4]. Learned non-use can also be described as the "gap" between impairment and functional ability or real arm use.

Researchers have attempted subjective and objective quantification of this phenomenon. Sterr and colleagues used the Motor Activity Log and the Actual Amount of Use clinical measures to describe the phenomenon [4]. Uswatte and colleagues have used accelerometers to quantify real arm use on daily living tasks before and after intense stroke rehabilitation therapy called constraint-induced movement therapy (CIMT) [5,6]. CIMT focuses on promoting impaired arm use by inhibiting the use of the less-impaired arm through binding and practice of daily activities. This therapy is credited for being able to decrease learned non-use behavior. The relative differences between accelerometer levels pre and post therapy indicated a change in impaired arm-use activity due to intervention. Brewer and colleagues developed a virtual environment that distorts the perception of the visual feedback and can quantify learned non-use [7]. Subjects were encouraged by the distortion to apply effort beyond their initial capacity. Johnson and colleagues [8] used Driver's SEAT, a custom steering environment with a split-steering wheel, to measure torques exerted by the dominant and non-dominant arm of subjects during bilateral and unilateral steering. They compared % effort for non-dominant arm in the unilateral and bilateral tasks. Differences in these torques for stroke survivors indicated the presence of learned non-use. These studies have a common goal of measuring changes in the impaired arm's actual and spontaneous use for subjects with low, moderate, and severe hemiparetic dysfunction. How can robot therapy systems assist in the understanding of this phenomenon? Can common metrics used in the assessment of motor impairment and arm use shed light on this behavior? This study examined whether this behavior could be studied and quantified using the TheraDrive system. The TheraDrive system was developed as one of several devices in a suite of devices aimed at the delivery of affordable robot/computer-assisted motivating rehabilitation [9-12]. The premise of TheraDrive is to use gaming technologies and force-feedback to deliver effective stroke therapy in under-supervised conditions and to use one or multiple wheels in a variety of orientations or configurations during steering tasks. [8, 9, 10, 11, 12, 13].

Our goal was to determine if impaired arm use, arm use bias and learned non-use behaviors can be effectively detected by examining the use of the impaired arm and the less-impaired arm during unilateral and bilateral steering on the TheraDrive system in one or two wheel modes. We utilized accuracy metrics as our method of quantifying arm use and report on our findings after two experiments were completed.

A. Hypothesis

First, we hypothesized that tracking errors will be higher for the impaired arm (ND) as compared to the tracking errors for the less-impaired (D) and that these errors will be more pronounced in low functioning subjects. Second, we attempt to determine whether we can detect arm bias and impaired arm use during bilateral tracking by comparing it with the unilateral tracking with the impaired/non-dominant arm (ND) to unilateral tracking with the less-impaired arm/dominant (D). We hypothesized that if arm bias exists and the impaired arm is not used during bilateral steering, the errors for the less-affected arm steering (D) will be no different from errors made in both bilateral tracking (BI), but both will be less than unilateral tracking with the impaired arm (ND). We suggest that the differences we expect to observe in the single and coordinated use of both the arms after stroke is possibly a consequence of leaned non-use and decreased awareness of the less-impaired arm due to the brain injury.

II. One-wheeled Experiment Investigation

A. TheraDrive

The TheraDrive system depicted in figure 1 is used as the experimental apparatus for the study [9-12]. The system consists of **one** Logitech force-reflecting wheel mounted on a height adjustable metal frame. The wheel is connected to the UniTherapy software platform [12], which records the angular movement of the wheel as subjects complete the custom and commercial tracking tasks displayed on the screen. Subjects are seated at a comfortable distance from the wheel. In the one–wheeled steering mode, the wheel is tilted through 20 degrees from the vertical to create a real driving experience. The steering wheel height is adjusted to ensure a comfortable interaction with the steering wheel. The maximum angle through which the wheel can rotate is 270 degrees. To standardize the group, subjects are made to hold on to a Vertical-gripper to complete the unilateral as well as bilateral steering tasks.

The UniTherapy software was developed by colleagues to provide therapy delivery and assessment tool for neurologically impaired subjects with accessible and accessibility features [10, 12]. The framework supports force-feedback joysticks, force-feedback driving wheels, various pointing devices (e.g. mouse; trackball), and windows keyboards. Using the software's task design manager we designed different tasks with different types of forces associated with virtual mechanical elements (e.g., spring, damper, and inertia), different force profiles related ("assist" or "resist") to different intensity levels (1 to 5 ascending order).

B. Tasks

A continuous and a discrete tracking task were used. Since the wheel has one degree of freedom, the UniTherapy software automatically updates y-axis on the screen and the subject's steering moves the cursor in x-direction. The continuous tracking task is pseudorandom sine tracking, where subjects move the cursor horizontally to keep pace with a downward moving vertical pseudorandom sine wave of three frequencies (1 Hz, 2 Hz, and 3 Hz). Subjects were asked to move the cursor to the square box as the target moves in the x-direction. In discrete target acquisition, the target jumps to different predefined positions on the y-axis. As the target jumps to a new position, the UniTherapy software moves the cursor in y-direction and then subject tracks the target in x-direction. Subjects performed these tasks with their impaired arm or non-dominant arm only (ND), less-impaired arm or dominant arm only (D), and with both the arms together (BI). Subjects were asked to perform 3 trials of each task. The sequence of the tasks was randomized each day.

Figure 1. TheraDrive System: The wheel can be used in front and side driving, For this study, the wheel will be used in front driving mode.

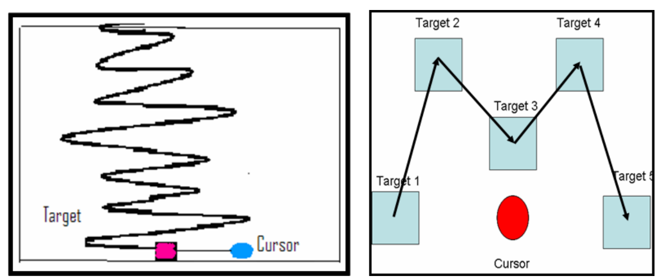

Figure 2. Tracking Tasks: a) A pseudo random sine tracking task is shown where subjects are asked to move the cursor to the target in the x-direction. The wave is generated vertically with three different amplitudes at frequencies (1 Hz, 2Hz and 3Hz) b) Discrete target acquisition target number suggests the sequential position of the target during the task.

C. Subjects

Chronic stroke survivors with hemiparesis who were at least six months post-stroke and have stable, low-to-medium impairment, and functional levels are recruited for the study. Seven stroke survivors (55-62 years) gave informed consent to participate in this study (see Table 1). Motor impairment levels are measured in the impaired arm using the upper extremity as per the Fugl-Meyer (UE-FM) scale [14, 15] a reliable measure of motor function (scores: 0-66), and functional disability levels were measured by the functional hand evaluation (UE-FT score scale- level 0 to level 7) [16]. Subjects were classified as high functioning if UE-FT >level 5 and as low-to-

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medium functioning if UE-FT ≤ level 5. Out of the seven subjects participants, three were low-to-medium functioning and four were high functioning. Five able-bodied subjects also participated with informed consent. The study was approved by the Institutional Review Board (IRB) of the Clement J. Zablocki VA Medical Center, Milwaukee, (WI), Marquette University, and Carroll University.

Subjects were seated at the TheraDrive system, appropriately familiarized with the tasks and then asked to complete the continuous and discrete tracking tasks unilaterally (one arm at a time, impaired and less-impaired setting) or bilaterally (both arms together). Each steering mode was repeated three times.

TABLE I. SUBJECTS

Subject	Age	Impaired Arm (ND)	Dom Arm (D) (prestrike)	UE-FM	UE-FT
S(Low-Med)					
S3	62	L	R	56	4
S7	60	L	L	24	4
S11	55	L	R	56	5
S(High)					
S1	55	L	R	66	7
S5	58	L	L	66	7
S9	55	R	R	66	7
S10	58	R	R	66	7
Five S(Norm)	Range: 58-63	D: Right Arm			

D. Data Analysis

For this analysis, we assess errors made during a pseudorandom sine tracking task (fig. 2(a)) and a discrete target acquisition task (fig. 2(b)) in our three steering modes (ND, D, BI). The sampling of position data and the input of force were at 33Hz. The representative plots of the pseudorandom sine tracking and discrete target acquisition task are shown in figure 3 and 4 with an illustration of how the errors were calculated. Tasks were approximately 33 seconds long. For pseudorandom sine tracking, the desired movement of the cursor and the actual movement were plotted. The error between actual and desired position was calculated in terms of degrees of rotation of the wheel for pseudorandom sine tracking. The RMS error was calculated by taking the square root of the squared difference between the desired-position signal (track) and the actual-position signal (arm movement) at every time instance as shown in figure 3. For discrete target acquisition task, the settling error was calculated by taking the squared root difference between the actual cursor position and the desired cursor position at the end of each target position as shown fig 4. The three trials were averaged. The averaged RMS data were presented for each subject. These errors were calculated for low-to-medium functioning, high functioning, and normal subjects.

The mean averaged RMS error and Settling error were compared within and across the groups using a repeated measure Analysis of Variance (ANOVA) with an alpha significance level 0.05. Paired t-test were used to establish significant differences between data pairs.

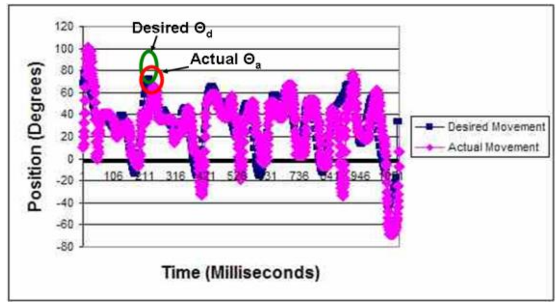

Figure 3. Desired and actual position of cursor during the pseudorandom sine tracking task. Accuracy (RMS Error) $= \sum_{n=1}^{N}\sqrt{\frac{(\theta_d-\theta_a)^2}{N}}$

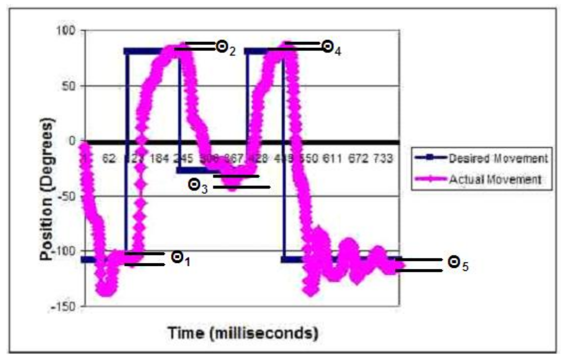

Figure 4. Desired and actual position of cursor during the discrete tracking task. Accuracy (SETTLING Error) = $\frac{\sqrt{(\theta_1^2+\theta_2^2+\theta_3^2+\theta_4^2+\theta_5^2)}}{5}$.

E. Results

We hypothesized that there will be greater errors during ND steering than D steering for all subjects. Greater ND steering errors will be more pronounced in low-to-medium level stroke subjects than high functioning stroke subjects and able bodied subjects. We anticipated that for low-functioning stroke survivors, D and BI lateral steering will be similar if in bilateral steering subjects primarily used their non-impaired arm to complete steering tasks. Bilateral errors would increase over D steering errors if the impaired arm was being used.

Figure 5 plots the comparative graph of RMS errors during ND unilateral, D unilateral, and BI bilateral steering pseudorandom sine tracking for all three subject groups. Table II shows the average RMS error (with standard error) of ND, unilateral, D unilateral, and BI bilateral steering for pseudorandom sine tracking (continuous). Overall, the repeated measure ANOVA indicated that there were significant differences across arm use (p=0.003) and there was a significant interaction effect (p=0.014) for arm-use and subject. The average errors made by low-to-medium functioning subjects in ND steering were significantly higher than the errors in ND steering by high functioning subjects (p=0.022) and were significantly higher than errors made in ND steering by able-bodied subjects (p=0.005). Within each subject group, ND tracking could not be consistently distinguished from D tracking and BI tracking, but D tracking was consistently similar to BI tracking. Table III shows Post-Hoc results across the ND unilateral, D unilateral and BI bilateral steering tasks. RMS errors for ND steering trended greater than RMS Errors for D steering and BI steering for low-to-medium functioning subjects (ND: 30.52º, BI:23.40º, and D:23.62º) and normal subjects (ND: 12.04º, BI:10.05º, and D:10.16º). The low-to-medium functional subjects trend was not significant (ND > D: p=0.213 and ND > BI: p=0.1). The differences were significant for normal subjects (ND > D: p=0.005 and ND > BI: 0.019).

We had hypothesized that if the impaired arm is significantly involved in the bilateral task then its performance should affect the bilateral tracking activity. It is reasonable to suggest that if its performance is poor, then the bilateral tracking performance should degrade (errors increase, variance increase etc.), if the performance is comparable to the D steering then we should see minimal to no effects on BI steering. For the low-functioning stroke survivors, we were not able to clearly distinguish this trend. Despite trends for poor ND performance, the BI steering is not significantly. The trends suggest that ND was not involved in BI tracking for the low-functioning stroke survivors. The less-impaired arm (D) had similar errors to the BI tracking (L-M: p=0.95) (BI) as compared to the impaired arm (ND) and bilateral tracking (L-M: p=0.1). Low subjects numbers and high variance may be obscuring results.

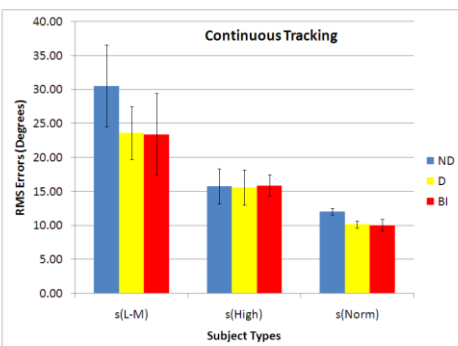

Figure 5. RMS Error (Mean and Standard Error) comparison across all groups during pseudorandom sine tracking. Subjects participated in the study during unilateral non dominant (ND) unilateral dominant (D) and bilateral (BI) pseudorandom sine tracking task.

Figure 6 plots the comparative graph of Settling errors during ND unilateral, D unilateral, and BI bilateral steering task for all three subject groups together. Table II shows the average Settling error comparison of unilateral less-impaired (D) steering, unilateral impaired (ND) steering and bilateral (BI) steering for discrete target acquisition. Overall, the repeated measure ANOVA indicated that there were significant differences across arm use (p=0.056) and there was non-significant interaction effect (p=0.389) for arm-use and subject. Settling errors for ND steering (11.97º) was greater than Settling Errors for D steering (6.12º) for low-to-medium functioning subjects with greater variance. These errors in ND steering tended to be greater than D steering for all subjects, but none were significant. Some aspects of the tracking accuracy pattern seen in continuous tracking is also seen here in discrete tracking, however larger variances in subject performances across the groups decreased the ability to determine significant differences.

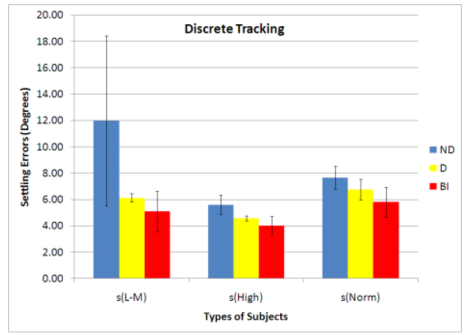

Figure 6. Settling errors (Mean and Standard Error) comparison across all groups during discrete target acquisition task. Subjects participated in the study during unilateral non dominant (ND) unilateral dominant (D) and bilateral (BI) in discrete target acquisition task.

TABLE II. TRACKING RESULTS : MEAN (STANDARD ERROR)

	Pseudo Random Sine(RMS)		
Subject	ND	D	BI
S(Low-Med)	30.52(6.03)	23.62(3.92)	23.40(6.03)
S(High)	15.77(2.58)	15.61(2.61)	15.87(1.60)
S(Norm)	12.05(0.48)	10.16(0.52)	10.05(0.83)
	Discrete Target (Settling Error)		
Subject	ND	D	BI
S(Low-Med)	11.97(6.46)	6.12(0.32)	5.10(1.55)
S(High)	5.61(0.75)	4.56(0.19)	4.01(0.72)
S(Norm)	7.66(0.87)	6.76(0.79)	5.81(1.15)

TABLE III. POST-HOC ANALYSIS ACROSS TRACKING (*SIGNIFICANT)

Modes	Normal	Stroke (High)	Stroke (L-M)
Continuous			
ND, D	P=0.005*	P=0.808	P=0.213
ND, BI	P=0.019*	P=0.942	P=0.1
D, BI	P=0.824	P=0.829	P=0.95
Discrete			
ND, D	P=0.6	P=0.225	P=0.457
ND, BI	P=0.268	P=0.303	P=0.349
D, BI	P=0.539	P=0.469	P=0.507

F. Detection of arm use bias and possible learned non-use

For stroke survivors, especially those with lower function, we expected to see RMS error not significantly different for D and BI steering, but significantly higher errors in ND steering than D steering and BI steering. Due to the presence of learned bias, in bilateral mode, the stroke survivors might rely on less impaired arm to do most of the work despite ability of the ND to participate as shown by ND unilateral. We were not able to identify the clear role of the impaired arm in bilateral tracking and the presence or absence of learned non-use. We hypothesize that this inability was may be due to the high variability in subject tracking performance as well as by the fact that bilateral tracking took place with only one wheel. In order to further investigate the impaired arm use in bilateral tracking and to parse out what was being observed in the one-wheeled bilateral tracking, a special mode was created that allowed the TheraDrive system to be used with two wheels that were fully decoupled mechanically but coupled via the software (Fig. 7).

III. Two-wheeled Experiment Investigation

A. Bi-TheraDrive

This bilateral mode consisted of two Logitech force-feedback steering wheels. A custom MATLAB (with Simulink) was written to allow the each wheel to independently contribute to a single tracking task. The new software is capable of transferring different types of forces (e.g., vibration, spring) to the wheel system in the bilateral mode.

A new unidirectional target acquisition task, shown in figure 8, was developed to evaluate bilateral tracking during the Bi-TheraDrive mode. Subjects were asked to move a single cursor to a target using one wheel or both the wheels as per the mode of tracking (with ND, D or Bi). A graphical representation of the movement is shown on the monitor in Figure 8. The target is shown as a red circle and cursor is shown as a green circle. The cursor has to move 75 pixels (202 degrees) to achieve the target. If the cursor moves and stays within the error window, the success condition is triggered. Subjects must complete each tracking acquisition task in 4 seconds. Subjects were required to complete 30 trials of the task with the impaired/non-dominant arm (ND), the less-impaired/dominant arm (D), and with both arms (BI). Bilateral steering required the subjects to rotate the wheels from top-dead center to bottom dead center in a counter symmetrical mode. Right wheel moved clockwise and the left wheel counterclockwise. In bilateral steering although both arms were involved in completing the tasks, it was still possible for the subject to use only one arm to complete the task successfully. The angular position of each wheel affected the cursor, $w_l\theta_l + w_r\theta_r = \theta_t$. The weighting factors were 1.

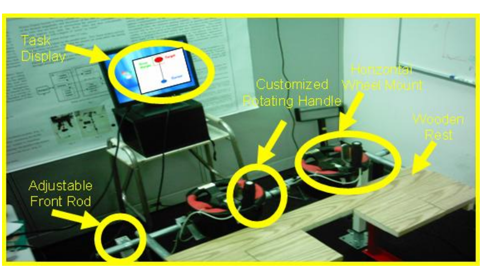

Figure 7. Bilateral mode with a de-coupled wheel setting. Two wheels were used for tracking.

Additional 5 chronic stroke survivors with hemiparesis who are at least six months post-stroke and have stable, low-to-medium impairment and functional levels were recruited for this portion of the study along with eight able-bodied subjects (Table IV). Average age of the normal population was 62 years (range: 54 to 81 years). Average age of stroke population was 62 years (range: 52 to 82 years). This portion of the study was approved by the Institutional Review Board (IRB) of the Clement J. Zablocki VA Medical Center, Milwaukee, WI and IRB of Marquette University. Seven stroke survivors with pre-morbid right hand dominance gave informed consent to participate in this study. After familiarization, each subject was able to complete the task.

TABLE IV. Subjects - BiTheraDrive

Subject	Age	Impaired Arm (ND)	Dom Arm (D)	UE-FM	UE-FT
S(Med-High)					
S1	62	R	R	21	5
S2	60	R	R	55	4
S3	55	R	R	50	6
S4	55	R	R	55	6
S5	58	R	R	66	7
Eight S(Norm)	Range: 54-81	D: Right Arm			

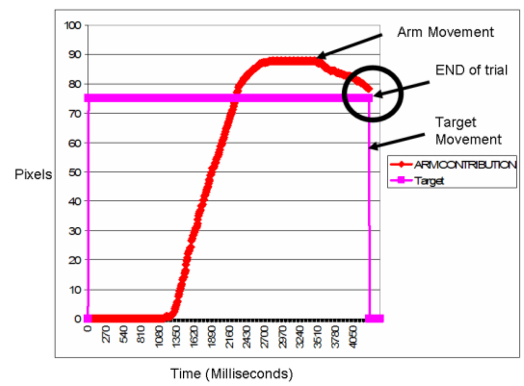

Figure 8. Settling error calculation for de-coupled wheels tracking task.

$$\text{Accuracy (Settling Error)} = \sqrt{\frac{\left(\theta_1^2+\theta_2^2+\theta_3^2+\theta_4^2+\theta_5^2 \ldots\ldots\ldots +\theta_N^2\right)}{N}}.$$

For the unidirectional target acquisition task the settling error was calculated as illustrated in figure 8. The error was calculated by taking the square root of the squared difference between the desired movement (track) and the actual-movement signal (arm movement) at the end of the trial. The thirty trials were averaged. The averaged settling error data were presented for each subject. These errors were calculated for stroke survivors and normal subjects for ND, D and Bi steering modes. Figure 9 shows the comparative results across subjects and across steering modes. Tables V and VI show the tracking errors and the significance detected across modes. Statistical analyses across different steering tasks and across subject groups were completed. Repeated measures Anova were completed along with Post-Hoc analysis across steering modes using paired t-tests.

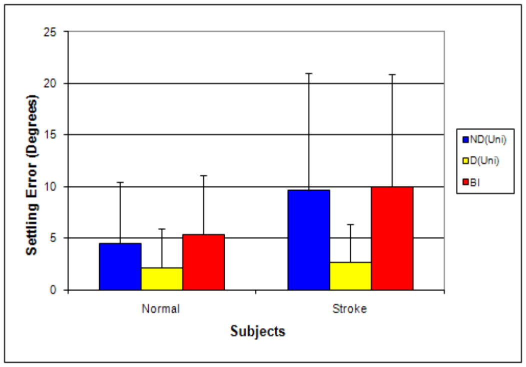

Figure 9. Subjects performance during unimanual ND, unimanual D and bimanual BI steering for the two-wheeled system.

TABLE V. TRACKING RESULTS: MEAN (STANDARD ERROR)

Subject	UE-FT	ND	D	BI
S1	5	17.21	2.54	8.44
S2	4	10.7	1.89	11.01
S3	6	9.14	3.69	17.66
S4	6	4.9	3.06	5.18
S5	7	6.13	2.14	7.67
Mean		9.61(2.16)	2.66(0.32)	9.99(2.13)
Eight S(Norm)	N/A	4.54(0.67)	2.2(0.62)	5.39(1.29)

TABLE VI. POST-HOC ANALYSIS (*SIGNIFICANT P<0.05)

Modes	Normal	Stroke
ND, D	P=0.006*	P=0.036*
D, BI	P=0.021*	P=0.021*
ND, BI	P=0.464	P=0.89

ND unilateral steering errors (stroke=9.61 normal=4.54) are higher than D (stroke=2.6 normal=2.2) unilateral steering. Repeated measure ANOVA results showed significant differences across subject groups (p=0.023) and across arm-use (p=0.0). There were no interaction significant effects (p=0.057). ANOVA (Post-hoc: paired t-test) results indicate that ND steering errors are significantly different for stroke survivors than their D steering error (p=0.036). ND steering errors are significantly different for able bodied subjects as well (p=0.006). For both able-bodied and stroke survivors ND tracking errors were significantly different than D tracking errors, but not significantly different from BI indicating that for both groups bilateral tracking errors were affected by non-dominant or impaired arm errors. Stroke survivors ND tracking errors were significantly greater than normal tracking errors (p=0.020). Their Bilateral tracking errors were also significantly greater than normal subject Bilateral tracking errors (p=0.074). Their less-affected arm tracking errors were not significantly different from dominant arm tracking errors for normal subjects (p=0.588). This suggests that for stroke survivors impaired arm usage was significant in the decoupled bilateral tracking.

IV. DISCUSSION AND CONCLUSIONS

The general hypothesis of the study was that differences observed in the single and coordinated use of both the arms after stroke could be useful for detecting impaired or non-dominant arm involvement in a bilateral tracking task and more specifically leaned non-use due decreased awareness and use of the contralateral side of the brain injury despite functional ability [17-20]. We hypothesized that first we would be able to detect the decreased motor control in the impaired arm over the less-impaired arm for stroke survivors. We also hypothesized that if the impaired arm was not being used in the bilateral tracking its impact on performance would be minimized and errors seen in Dominant/less-impaired arm (D) tracking would be most similar to errors seen in bilateral tracking (BI).

For stroke survivors we saw higher average errors for the impaired arm tracking than non-dominant arm tracking confirming that it is not as efficient in performing the tracking task when compared to the D arm. This trend is supported by other studies. It has been seen that weakness and lack of coordination are factors which limit motor performance of the contralateral side after stroke [2, 16, 17, 18, 19]. The error metrics used here were effective in capturing the impairment and in spite of the small sample population shows the trend towards significance. Errors made during continuous tracking task in the one-wheel experiment were more distinguishable across steering modes than those made in the discrete tracking task.

Learned non-use may be revealed by considering the extent of less-impaired arm use in a task despite functional ability in the impaired arm. The ability to detect impaired arm use in the bilateral task was clearly affected by variability in tracking performance across subjects within the group, by the type of tasks being used, and by whether the errors made by each arm could independently affect performance. It is clear that in the unimpaired brain, the right and left arms have a significant degree of independent functioning. The effective level of independence is task dependent and is known to diminish in the face of symmetric and fast rhythmic movements. The results show that ideally impaired arm performance should affect bilateral performance and the magnitude of the effect would be increased with the level of involvement of the impaired arm in the task. The results also indicated that these effects could be better distinguished when the mechanical structure of the system allowed for independent arm performance despite a shared tracking goal.

The results indicate that it is possible to examine impaired arm contribution to a bilateral task using a steering wheel environment as TheraDrive. When bilateral steering is done with one wheel individual arm contribution cannot be captured clearly during the activity. The results were in line with research indicating that, in bilateral steering with no force-feedback, if an arm use bias exists, the impaired arm will most likely be under-used during bilateral steering than unilateral steering [8]. Detection of learned bias and arm use specifically was easier with two wheels and these results echoed results seen in Johnson et al with a split-steering wheel as in Driver's SEAT. When the impaired arm is highly involved, the performance of the bilateral tracking tasks will be affected and bilateral tracking errors will be similar to unilateral tracking errors with the impaired arm. If the arm is not involved the errors would reflect more of the unilateral tracking with the dominant arm.

These results can impact strategies for robot-assisted therapy and the evaluation of bilateral coordination and learned non-use after stroke. We anticipate that impaired arm use and learned non-use during bilateral coordination tasks can be quantified using error performance at the beginning, end and during unilateral and bilateral therapy if the training and assessment robot/mechatronic system permits the de-coupled but coordinated use of the impaired and less-impaired arms. Over time progress could be assessed by comparing and tracking performance trends in ND, D and Bilateral activity on the system. As we demonstrated, the decoupled wheel environment exposed the real use of impaired arm. Further studies examining the role of the impaired arm in bilateral steering tasks are needed.

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