Exploring the Capabilities of Harmony for Upper-Limb Stroke Therapy

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***Abstract*— Harmony is a bimanual upper-limb exoskeleton designed for post-stroke rehabilitation. It moves the subject's shoulders and arms through their entire ranges of motion while maintaining natural coordination, is capable of force/torque control of each joint, and is equipped with sensors to measure motions and interaction forces. With these capabilities Harmony has the potential to assess motor function and create individualized therapy regimens. As a first step, five stroke survivors underwent rehabilitation sessions practicing multi-joint movements with the device. Each participant performed a total of 1130 motions over seven hours of therapy with no adverse effects reported by participants or the attending therapist, supporting the suitability of Harmony for use in a clinical setting. Donning and doffing time averaged 3.5 minutes and decreased with therapist experience. Reported levels of stress, anxiety, and pain indicate that the Harmony safely assisted in the completion of the trained movements and has great potential to motivate and engage patients. We developed a novel methodology for assessing coordination capability and results from the study indicate that Harmony can enable therapists to identify neuromuscular weakness and maladaptive coordination patterns and develop targeted interventions to address these aspects of upper-limb function. The results suggest Harmony's feasibility and show promising improvements, motivating future study to gain statistical support.**

I. Introduction

Stroke is a leading cause of long-term disability, which leaves a substantial portion of the US population with permanent impairments that limit their ability to perform activities of daily living (ADLs) [1]. Previous studies have reported that robotic-assisted rehabilitation can improve motor recovery after stroke and that robotic devices are safe and feasible in delivering rehabilitation [2], and others have shown that their outcomes are better or equivalent compared to conventional therapy with regard to improvements in ADLs and arm function [3–5].

Developing interventions for post-stroke motor rehabilitation is complicated by the complex biomechanics of the upper-limb. In particular, every arm movement is achieved by a kinematic coordination in the shoulder girdle joints known as the scapulohumeral rhythm (SHR) [6]. Post-stroke, most individuals with hemiparesis experience flaccid paralysis of the shoulder and spasticity, resulting in limited range of motion (ROM) , shoulder pain, and an abnormal SHR [7–9]. Additionally, some stroke survivors with moderate to severe impairment exhibit abnormal torque coupling patterns during isometric tasks [10]. These abnormal interjoint patterns can be caused by various reasons like exaggerated stretch reflexes, increased muscle tone, and abnormal neural activity [11]. However, other stroke survivors exhibit neuromuscular weakness that largely limit workspace ROM and force outputs, which might lead to impaired motor behaviors. Post-stroke therapeutic interventions must be able to apply biomechanically-consistent forces in sync with the SHR to prevent serious negative effects [12, 13] and provide information to discern whether impaired motor function originates from neuromuscular weakness or maladaptive couplings.

Despite the promise of robotic rehabilitation and the importance of supporting the SHR, there has been limited development of interventions that support the coordinated movements in the shoulder complex. A variety of robotic exoskeletons have been developed to match shoulder movements [15–21] , but they are not capable of retraining biomechanically-sound motion supporting all significant DOF in the shoulder complex. Harmony (Fig. 1) is an exoskeleton designed for post-stroke interventions capable of supporting the natural arm movements for a wide range of body dimensions [22] due to its shoulder mechanism that actively supports SHR with a baseline control algorithm that elevates the shoulder girdle following a predefined SHR ratio of scapular and humeral motion (for more information, see [23]).

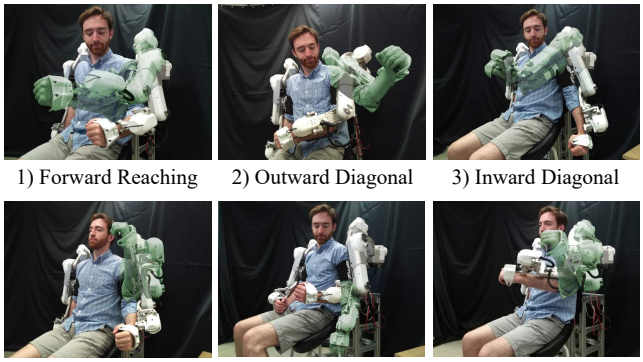

Fig. 1: Harmony, a bimanual upper-limb exoskeleton, powered six key movements for the participants: 1) forward reaching; 2) proprioceptive neuromuscular facilitation (PNF) D2 pattern [14] ("outward diagonal"); 3) PNF D1 pattern ("inward diagonal"); 4) scapular elevation; 5) elbow extension with forearm pronation; and 6) internal-external humeral rotation near the open packed position of the GH joint ("shoulder rotation"). The green semi-transparent portion represents the motion's final position.

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Beyond this novel mechanical design, Harmony's sensing and control provide therapists with higher-level information about the wearer's performance in important areas such as neuromuscular weakness or abnormal interjoint couplings. One way to discern the underlying nature of a person's impaired motor function is through isometric tasks with specific force output requirements [10]. This method can identify whether the impaired motion is originated by neuromuscular weakness or maladaptive couplings, and is helpful for participants who can initiate or provide some forces near the start of the motion, but are unable to complete it [24]. Furthermore, isometric joint torque generation exercises may be more effective for learning in the upper-limb [25]. For a given task, we herein hypothesize that if a person can generate sufficient force magnitude but still cannot complete the task, it is likely that they lack the proper interjoint coordination pattern. Clinicians can further use information from isometric tasks to design individualized interventions addressing either neuromuscular weakness through strengthening exercises, or maladaptive couplings with coordinated therapy.

Ultimately, Harmony will be used to compare the outcomes of robotic therapy that supports individualized and biomechanically-consistent force application and the outcomes of the conventional therapy. Before Harmony's capabilities at developing individualized regimens can be validated broadly, we establish its feasibility for use in therapy. This paper presents 1) results supporting the robot's capacity to safely work with a post-stroke individual for passive stretching and assisted training, 2) feedback from users and therapists, and 3) results supporting Harmony's potential to assess neuromuscular weakness and joint coordination.

II. Materials and methods

We developed and implemented a state-of-the-art interaction control paradigm in a multi-session experimental protocol and measured a wide range of aspects of these interactions and the impacts they had on the participants.

A. Harmony Interaction Control

Harmony is powered by Series Elastic Actuators (SEA) in each of its joints, which enables joint-level torque measurement and control. It can actively impart torques to seven DOF (elevation-depression and protraction-retraction of the shoulder girdle; abduction-adduction, flexion-extension, and medial-lateral rotation of the shoulder; flexion-extension of the elbow; and pronation-supination of the forearm) in both arms over a wide ROM. In addition to gravity compensation and support of the SHR in the baseline controller, passive stretching and active exercises have been implemented in Harmony. In passive stretching exercises, the baseline controller of Harmony was supplemented with an impedance controller to assist the user during the execution of preprogrammed trajectories. As a result, the robot drives the user along the path with some compliance to ensure safe human-robot interaction. The drawback of this strategy is that it might lead to slacking, since it does not use any measure of user's effort or performance to adapt the controller's output.

One way to require active participation is through the use of a triggered mode. In this mode, Harmony allows motion only after a wearer overcomes a force threshold in a specific direction, and can be further analyzed as an isometric task.

Similarly, assist-as-needed (AAN) strategies attempt to reduce slacking by adapting robotic assistance according to the user's performance via adjustment of either the controller [26, 27] or task parameters [28, 29] with a performance-based adaptive control law. In active exercises, Harmony uses an impedance-based AAN strategy detailed in [30]. The adaptation law consists of a forgetting factor, which is a proportion from 0 to 1 of the adaptation gain calculated in the previous iteration, and an error gain, which is a positive coefficient that multiplies an error metric. The error metric is calculated as the accumulated error in a given time window. The forgetting factor ensures that the controller does not get trapped in the maximum assistance level when the participant's effort decreases, thus discouraging slacking. The gain error will tune the adaptation to the current observed performance within a reasonable time period, which, in this case, is approximately the time to complete one repetition.

B. Experimental protocol

The protocol, approved by the Institutional Review Board of The University of Texas at Austin (2017-10-0033), consisted of seven one-hour training sessions over three and a half weeks (two per week), and evaluation sessions carried out before the first training session to set the baseline (pre-study), and after the last training session (post-study), with an occupational therapist (OT) present for all sessions.

1) Task Design: Trained movements were pre-programmed reference trajectories recommended by the clinicians to target the difficulty with voluntary extension and lateral movements often experienced by post-stroke patients (Fig. 1). In each training session, the participants underwent two groups of exercises: the first group consisted of six sets (one for each exercise) of five repetitions with full robotic assistance (passive stretching). The second group (assisted training) consisted of six blocks (one for each exercise), each including three sets of seven repetitions with robotic assistance being modulated by the position error in joint space. Each block starts with two repetitions with full robotic assistance, with the purpose to provide proprioceptive feedback of the movement and facilitate the movement initiation. After the two repetitions, the three sets of seven repetitions start, each preceded by an isometric triggering phase. To trigger the set, the participants were required to apply forces with magnitudes larger than specified thresholds and that lie within a 20°cone around the desired force directions determined for each exercise. The desired force magnitudes and directions were determined by the average force application of four healthy participants (three male and one female, with average age of 25 ± 2 years) performing each of the motions. The triggering period was programmed to time out after a predefined period of time (10 seconds), initiating the set of assisted training.

More details of the criteria used in the post-processing of triggering data are in Section II-D.

2) Donning and Doffing: The donning process was executed by the OT with the assistance of one researcher. Once seated on a stool, the participant's arm was attached to the robot, whose joints were locked in a convenient configuration, starting from proximal to distal points. Harmony was attached proximally to the wearer with an elastic strap around the upper arm, and distally with an elastic strap around the wrist along with custom grippers to the hand.

C. Participants

The target population for this study were post-stroke individuals that met the following criteria: (1) age between 18 and 85 years, (2) Modified Rankin Score (MRS) less or equal to four, (3) body dimensions within the limits of Harmony. They were excluded if they have: (1) recurrent stroke, (2) unstable cardiovascular, orthopedic, or neurological conditions, (3) history of seizure, (4) significant communication deficits, (5) severe upper-limb joint pain or limitations that would restrict their ability to complete the protocols.

Five male participants were enrolled in this study and underwent the entire protocol. One participant was recruited but not enrolled due to lack of compliance with the inclusion/exclusion criteria. Table I summarizes the demographics of the enrolled participants.

TABLE I
DEMOGRAPHIC DATA OF PARTICIPANTS

	S1	**S2**	**S4**	**S5**	**S6**
Age	52	76	51	55	63
Months post onset	12	35	5	30	10
Ischemic/Hemorrhagic	I	H	H	I	I
Mod. Rankin Score [31]	2	3	3	2	2
Affected Side	R	R	R	L	L
Handedness	R	R	R	R	R

D. Data acquisition and analysis

The upper-extremity portion of the Fugl-Meyer (FM-UE) and the Action Research Arm Test (ARAT) were adopted as outcome measures of motor function and activity, respectively, due to their reliability [32]. They were administered by the OT in the pre- and post-study evaluations along with passive ROM measured with a goniometer. Analysis of significance in the observed improvements of the FM-UE and ARAT outcome measures was performed with the Wilcoxon signed rank one-sided test.

To measure donning time, a stop-watch was started once participants were seated on the robot's stool and was stopped as soon as they confirmed they were comfortable. For doffing, a stop watch was started once the robot was locked and was stopped as the participants stood up from the stool.

Heart rate, blood pressure, and pain levels were measured at the start and end of each session, with the pain level assessed with the Wong Baker Faces Scale [33]. Participants also answered surveys in each session to assess their anxiety and perception of safety, with the questions "How safe do you expect to/did you feel using Harmony?" and "Do you feel anxious or stressed about the upcoming session?/ Did you feel anxious or stressed about the session?" on a scale of "not at all being 1 to very being 10".

Robot joint angles and torques were measured during the training sessions as well as interaction forces in the upper-arm and wrist attachment points. Joint angles were measured with high-resolution magnetic rotary encoders (Contelec AG Inc.), and joint torques were obtained from the displacements measured in the SEAs using the same encoders. Interaction forces and moments at the upper-arm and the wrist were measured with six-axis force/torque sensors (ATI Industrial Automation Inc.). Data was captured with a sampling rate of 50 Hz and smoothed with a second-order low-pass Butterworth filter with cut-off frequency of 5 Hz.

In the isometric exercises, a participant may not be able to "trigger" the motion if they lack the proper joint coordination in either magnitude or direction, which could be caused by conditions such as neuromuscular weakness or abnormal interjoint coordination patterns. We hypothesize that if participants had sufficient force outputs to trigger, it is likely that they lacked the proper interjoint coordination pattern. To separate these conditions, analysis of interjoint coordination was performed using estimated human joint torques during the isometric triggering exercise. The torques in the human arm joints were estimated using inverse dynamics based on a kinematic model of the human arm , which is represented by a 5 DOF kinematic chain (including the shoulder, elbow, and forearm) [34], and the measured wrenches at the attachment points. Dynamic parameters of the human arm were estimated based on the total body weight and arm dimensions of each participant [35]. As an attempt to mitigate effects of cuff tightness and hypertonia, average offset wrenches in each attachment point were obtained in a 250 ms time window immediately before the triggering phase started. To determine if participants' inability to trigger motion is related to neuromuscular weakness, each participant's strength capability was evaluated according to the number of force peaks they were able to generate and the average force magnitude of those peaks. A force peak was considered if it was separated from other peaks by at least 1 second and its magnitude was greater than the threshold magnitude, which varies for each exercise in a range of 10 to 20% of the average magnitude applied by healthy participants.

Force peaks were used to detect attempts to initiate motion. Each attempt was categorized for post-process analysis as "triggered", "almost-triggered", or "non-triggered", depending on the angle difference θ_{diff} between the direction of the force applied and the desired force at the attachment points. Each attempt was categorized into three groups : "triggered" if $\theta_{diff} < 20°$, "almost-triggered" if $30° < \theta_{diff} < 60°$, and "not-triggered" if $\theta_{diff} > 60°$. Here we chose the elbow extension movement to illustrate the capabilities of Harmony in examining interjoint coordination. Given the movement characteristics, only the wrist forces were taken into consideration in the group categorization. The torques generated by the participant in each trial were averaged over a 100 ms time window preceding and including the force

peak instant. Torque values were normalized for each participant according to the maximum voluntary torque recorded for each joint in each session.

III. Results

Each participant completed approximately 1130 repetitions over 7 hours of training. The impact these sessions had on the participants as well as Harmony's role in identifying therapeutic goals are discussed in the following section.

A. Changes in ROM and Clinical Scores

The results for FM-UE and ARAT are summarized in Table II. The mean improvement in FM-UE and ARAT scores were 5.2 $\pm$ 7.8 and 2.0 $\pm$ 4.6 points, respectively. While these are promising results, they were not statistically significant. The minimal clinically important difference (MCID), although not standardized for stroke patients, can be approximated as 10 percent of the full scale [36]. For the FM-UE and ARAT, the MCID is 6.6 and 5.7, respectively.

TABLE II
Comparison of Clinical Measures

	Pre	Post	Δ	p-value	MCID [36]
FM-UE	27.60	32.80	5.20	0.111	6.60
	(15.95)	(9.58)	(7.82)		
ARAT	13.00	15.00	2.00	0.139	5.70
	(16.39)	(9.58)	(4.58)		

Some of the participants have demonstrated improvements in FM-UE larger than the MCID, with the more impaired, chronic participants experiencing the largest increases (Fig. 2). Similarly, changes in ROM were small and skewed positive (Fig. 3).

B. Suitability of Harmony in Therapy Regimens

Donning and doffing times generally decreased over time for each participant (Fig. 4a), and across the study (Fig 4b). The overall average donning and doffing times are 3'26" $\pm$ 1'19" and 1'41" $\pm$ 0'29", respectively.

All participants reported high safety perception and low anxiety level as assessed by surveys, with average responses of 9.80 $\pm$ 0.41 and 1.17 $\pm$ 0.51 for the safety perception and anxiety or stress level, respectively. No moderate or severe pain related to the training protocol nor adverse events were reported. Heart rate averaged 71.7 $\pm$ 5.8 bpm and exhibited a low variation within session for all participants (average variation of 3.9 $\pm$ 2.8 bpm).

C. Harmony's Potential for Individualized Interventions

Table III summarizes the strength capabilities and success rate on movement initiation during the triggering phase of the elbow extension movement. The number of times the participants successfully triggered the elbow extension movement did not change significantly from session 1 to session 7 across participants (Fig. 5).

Torque values generated in the triggered, almost-triggered, and not-triggered trials are depicted in Fig. 6. Each axis

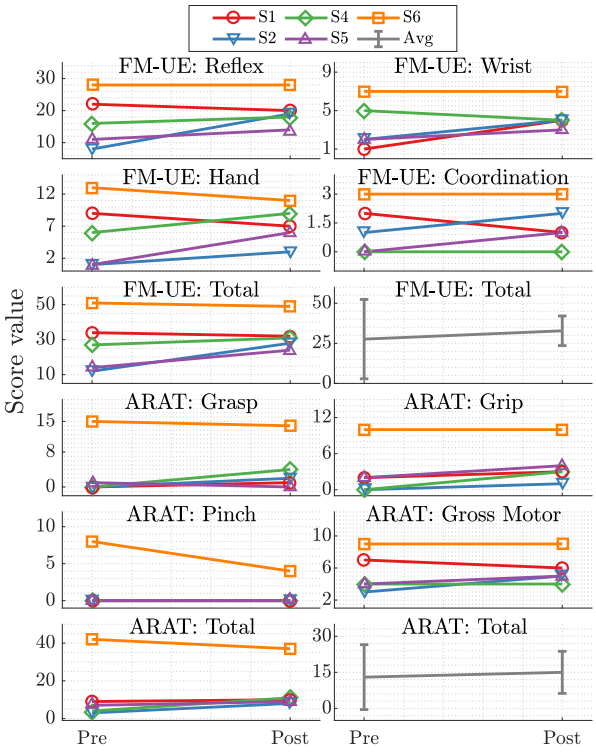


Fig. 2: The Fugl-Meyer upper-extremity (FM-UE) assessment and Action Research Arm Test (ARAT) were administered before and after participants completed their sessions. Some participants have demonstrated improvements in FM-UE larger than the MCID. Of particular interest is the response of the chronic and more impaired participants S2 and S5. However, some other (in particular S6) did not benefit from the sessions, perhaps as a result of their relatively high abilities.

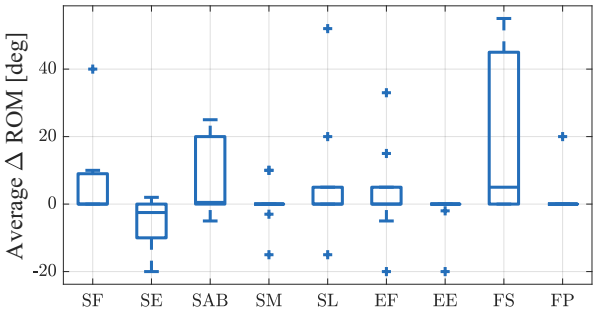
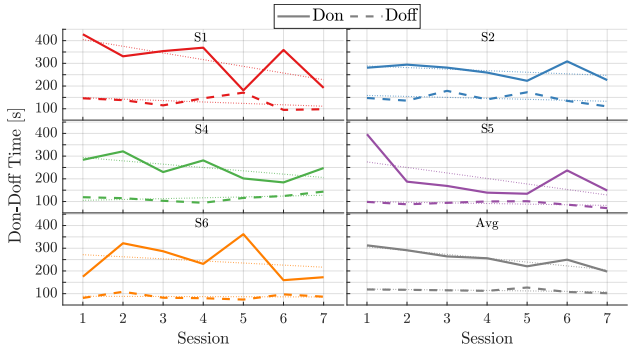


Fig. 3: Average changes in passive ROM across all participants suggests that some participants experienced increases, but the measurement modality (manual goniometry) has a high variability which may obscure the results.

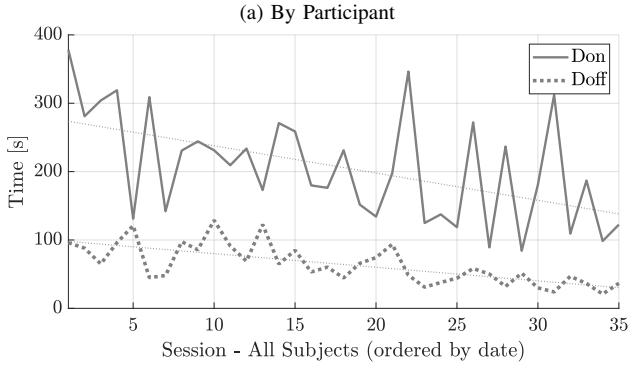
represent one DOF and its direction: Shoulder flexion (SF), shoulder extension (SE), shoulder adduction (SAD), shoulder abduction (SAB), shoulder medial rotation (SM), shoulder lateral rotation (SL), elbow flexion (EF), elbow extension (EE), forearm pronation (FP), and forearm supination (FS). Torque values calculated with force data recorded from healthy participants, used to determine the threshold forces, are also shown for comparison.

IV. Discussion

The results of this study provide useful insights into the impact of robotic training, which motivate future studies.



(a) By Participant



(b) Across trials

Fig. 4: Donning and doffing Harmony, when aided by a therapist, took on average three and a half minutes, with a trend in most participants' times decreasing over the study shown in subfigure (a). Overall, the times decreased as the study progressed, with subfigure (b) showing a quick learning curve for the therapist.

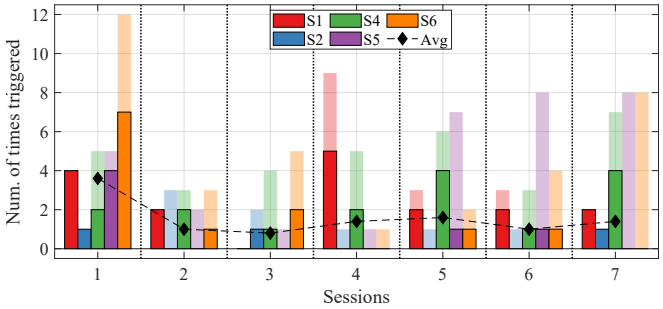


Fig. 5: The number of times elbow extension was successfully triggered per session did not change significantly, on average, from session 1 through 7. Average was calculated across all participants. Transparent bars indicate the total number of times subject attempted to trigger (if not visible, number of times triggered is the same as the total number of attempts).

TABLE III
PEAK FORCES DURING ISOMETRIC EXERCISE

	Num. Peaks	Average peak force (N)	Success rate
S1	23	33.55 ± 17.27	74%
S2	10	24.71 ± 10.71	30%
S4	33	46.07 ± 25.01	48%
S5	32	45.35 ± 16.14	19%
S6	35	56.27 ± 22.43	34%

We used FM-UE and ARAT as the indicators of recovery, and the overall results were positive but not statistically significant (Fig. 2 and Table II). The lack of significance was anticipated because of the low number of repetitions and participants. Improvements in ARAT were somewhat unexpected since this measure focuses on hand dexterity and the training protocol targeted proximal joint whole-arm movements. Clinical studies of the same category have reported length of intervention with a robotic device varying from 12 40-minute sessions [37] to 60 90-minute sessions [38], with total number of repetitions as high as 36000 repetitions [39]. The improvements in FM-UE reported in those high intensity regimen studies were still subtle, with a majority of the participants' improvements lower than the MCID. Despite the low number of repetitions, improvements greater than the MCID were observed in this study for participants S2 and S5, who had the lowest initial FM-UE scores. On the other hand, no significant improvements were observed for participant S6, which presented the highest initial FM-UE score. These results suggest that stroke patients with mild impairments will have to be further challenged to see benefits compared with moderate to severe impairments.

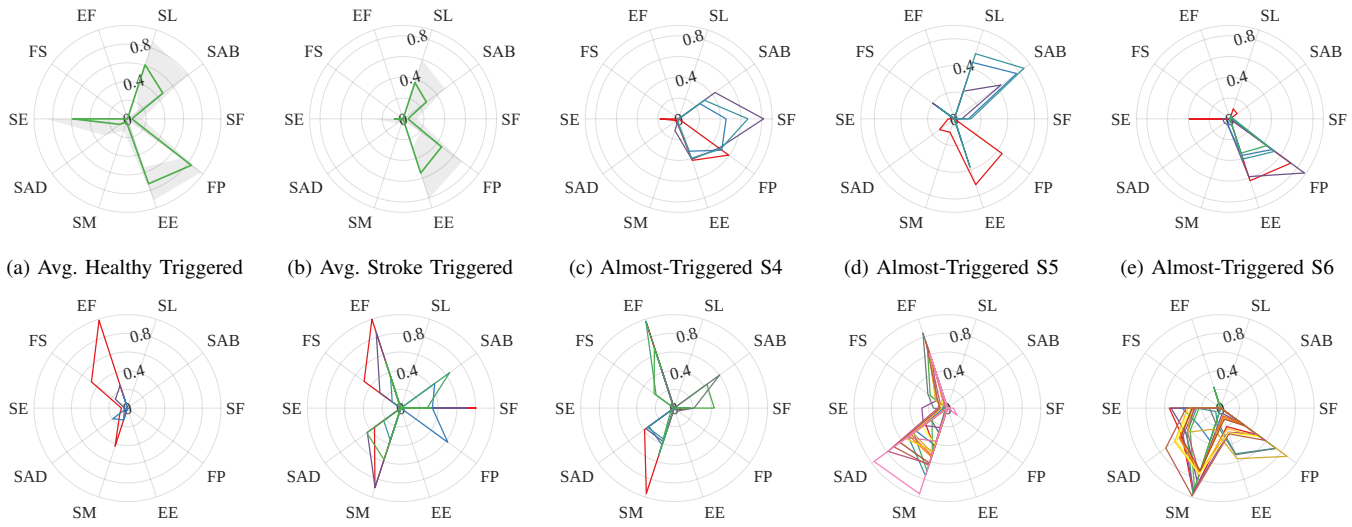
Results reported for passive ROM indicate mixed and subtle changes. While this might be, in fact, caused by high participant variability, it is more likely that it is related with the lack of robustness and consistency of the measurement procedure. Passive ROM was measured using a manual goniometer, which introduces inconsistencies in the measurement of joint angles. This motivates the use of devices like the Harmony exoskeleton as an assessment tool, because they can provide standardized measures with high resolution, robustness, and consistency.

Recorded donning and doffing times exhibited a learning pattern with a decreasing trend overtime. Anecdotal suggestions from clinical partners indicate that donning and doffing times for rehabilitation devices must be lower than 5 minutes, which was often and on average satisfied in this study protocol (Fig. 4). Isolated occurrences of donning times larger than 5 minutes occurred in the first training sessions, when initial adjustments were necessary.

The low average heart rate variation within session indicates that participants were not stressed, anxious, or exerted, and were comfortable using Harmony.

The strength capability results (Table III) indicate low success rate in initiating the elbow extension movement overall, which could be related with the lack of extrinsic feedback. Results for S2 show low number of force peaks and average peak force magnitude. This suggests that the low success rate in this particular case is likely related with neuromuscular weakness. Among all participants, S5 presented the lowest success rate, but differently from S2, without clear indication of neuromuscular weakness in the reported results. These observations suggest that some participants (S2) could benefit from strengthening exercises whereas others (S5) should improve their interjoint coordination.

The joint torque pattern that emerged in the successfully triggered trials is very similar with the pattern identified in the data collected from healthy participants, (Figs. 6a and 6b). It is worth recalling that the force magnitude requirements for stroke participants was 10-20% of the average magnitude recorded from healthy participants, and that might



(a) Avg. Healthy Triggered (b) Avg. Stroke Triggered (c) Almost-Triggered S4 (d) Almost-Triggered S5 (e) Almost-Triggered S6

(f) Not-Triggered (S1) (g) Not-Triggered (S2) (h) Not-Triggered (S4) (i) Not-Triggered (S5) (j) Not-Triggered (S6)

Fig. 6: Polar plots representing torque patterns identified in "triggered", "almost-triggered", and "not-triggered" trials. (a) indicates the average torques for healthy participants (green solid line) with the standard deviation (grey shade). (b) shows average torques during triggered trials across all stroke participants and the standard deviation. (c) through (e) show the torques recorded in all trials that were almost triggered. Participants S1 and S2 did not generate any force peaks categorized in this group. (f) through (j) show the torques recorded in all trials that were not triggered. Successful trials present a distinctive pattern of torques as observed in (a) and (b), which mainly consists of EE, FP, SL, and SAB. Components of this pattern can be found in trials that were almost triggered, but not in trials that were not triggered. Trials that were not triggered present different patterns across all the participants.

explain why the two patterns differ in total area. Also, we can observe in Fig. 6b lower shoulder extension (SE) torque, suggesting that stroke participants might have a limited ability to generate this torque component in this particular movement. All the patterns that emerged in the almost triggered trials (Figs. 6c, 6d, and 6e) seem to be incomplete versions with various components of the successful pattern (Fig. 6b). It is possible that with extrinsic feedback and guidance from Harmony, participants could improve coordination and correct for missing pieces in their performance. Contrarily, in Figs. 6f through 6j, the patterns present almost no components of the successful pattern, and in most cases, participants exhibit high EF, which is unexpected given that the target movement requires elbow extension. This might be caused by abnormal interjoint coordination or, again, by a lack of extrinsic feedback. However, the frequent coupling between the EF and SAB is particularly interesting as it indicates an abnormal synergy very often observed in stroke patients, also known as flexor synergy [40]. The patterns that emerged in the unsuccessful trials present some similarities among all participants, excluding the participant S6. This participant has the greatest initial FM-UE, and therefore exhibits good interjoint coordination. Interestingly, the patterns generated by this participant in the unsuccessful trials do not exhibit EF, and in fact, present many components of the successful pattern. However, the movement seems to be highly coupled with other joints, suggesting that improving this participant's coordination should be the focus of feedback and intervention design.

This study has a few limitations. First, the number of participants precludes drawing statistically significant conclusions. Second, the number of sessions was likely too low to facilitate motor recovery. However, these tests demonstrated feasibility and showed promising improvements, motivating future study to gain statistical support. These future studies should explore the differences between chronic and acute participants examined together in this study.

Another limitation is related with the methodology used to measure passive ROM using goniometry, which did not seem to be robust. Furthermore, the clinical tests were not blinded, such that the same therapist that participated in the training sessions performed the tests with the participants, and this can potentially influence the results. Finally, the lack of extrinsic feedback during the triggering phase might have delayed or even negatively affected the learning process.

We plan to expand this study in the future, increasing the number of recruited participants and the number of repetitions performed. One of our focuses will be in the validation of the Harmony exoskeleton as an assessment tool, such that future studies should rely on Harmony to perform accurate joint level measurement [41]. Finally, training protocols will be modified to explore different movements, and investigate the role of extrinsic feedback in generating initiation forces.

V. Conclusion

Harmony provides biomechanically-consistent support to shoulder-arm movement during post-stroke rehabilitation interventions. Results from this study suggest that Harmony can safely and comfortably assist in the completion of beneficial upper-limb interventions with reasonably short donning-and-doffing times. The observed increase in clinical scores and positive participant response along with the suggested ability to identify participant-specific aspects of motor impairments motivates future studies to test the efficacy of individualized interventions. Interventions with Harmony have great potential to motivate and engage participants in

high intensity, long duration therapy regimens for stroke rehabilitation as evidenced by the results of this study.

REFERENCES

[1] E. J. Benjamin *et al.*, "Heart disease and stroke statistics - 2017 update: A report from the american heart association," *Circulation*, vol. 135, no. 10, pp. e146–e603, 2017.

[2] C. D. Takahashi, L. Der-Yeghiaian, V. Le, R. R. Motiwala, and S. C. Cramer, "Robot-based hand motor therapy after stroke," *Brain*, vol. 131, no. 2, pp. 425–437, 2007.

[3] J. Mehrholz, T. Platz, J. Kugler, and M. Pohl, "Electromechanical and Robot-Assisted Arm Training for Improving Arm Function and Activities of Daily Living After Stroke," *Stroke*, vol. 40, no. 5, pp. e392–e393, 2009.

[4] G. Kwakkel, B. Kollen, and H. Krebs, "Effects of robot-assisted therapy on upper limb recovery after stroke: a systematic review," *Neurorehabilitation and Neural Repair*, vol. 22, no. 2, pp. 111–121, 2008.

[5] B. R. Brewer, S. K. McDowell, and L. C. Worthen-Chaudhari, "Post-stroke Upper Extremity Rehabilitation: A Review of Robotic Systems and Clinical Results," *Topics in Stroke Rehabilitation*, vol. 14, no. 6, pp. 22–44, 2007.

[6] V. T. Inman, J. B. d. M. Saunders, and L. C. Abbott, "Observations on the function of the shoulder joint," *The Journal of Bone and Joint Surgery*, vol. 26, no. 1, pp. 1–30, jan 1944.

[7] H. Moskowitz, C. R. Goodman, E. Smith, E. Balthazar, and H. Z. Mellins, "Hemiplegic Shoulder," *New York State Journal of Medicine*, vol. 69, no. 4, pp. 548–550, 1969.

[8] M. Johnstone, *Restoration of Motor Function in the Stroke Patient: a Physiotherapist's Approach*. Churchill Livingstone, 1987.

[9] J. Chaco and E. Wolf, "Subluxation of the glenohumeral joint in hemiplegia," *American Journal of Physical Medicine & Rehabilitation*, vol. 50, no. 3, pp. 139–143, 1971.

[10] J. P. Dewald, P. S. Pope, J. D. Given, T. S. Buchanan, and W. Z. Rymer, "Abnormal muscle coactivation patterns during isometric torque generation at the elbow and shoulder in hemiparetic subjects," *Brain*, vol. 118, no. 2, pp. 495–510, 1995.

[11] P. S. Lum, C. G. Burgar, D. E. Kenney, and H. F. Machiel Van der Loos, "Quantification of force abnormalities during passive and active-assisted upper-limb reaching movements in post-stroke hemiparesis," *IEEE Transactions on Biomedical Engineering*, vol. 46, no. 6, pp. 652–662, 1999.

[12] T. Najenson, E. Yacubovich, and S. S. Pikielni, "Rotator cuff injury in shoulder joints of hemiplegic patients," *Scandinavian Journal of Rehabilitation Medicine*, vol. 3, no. 3, pp. 131–137, 1971.

[13] P. E. Kaplan, J. Meridith, G. Taft, and H. B. Betts, "Stroke and brachial plexus injury: a difficult problem," *Archives of Physical Medicine and Rehabilitation*, vol. 58, no. 9, pp. 415–418, 1977.

[14] H. V. K. V. Langenberghe, C. J. Partridge, M. S. Edwards, and R. Mee, "Shoulder pain in hemiplegia - a literature review," *Physiotherapy Practice*, vol. 4, no. 3, pp. 155–162, 1988.

[15] P. Garrec, J. P. Friconneau, Y. Méasson, and Y. Perrot, "ABLE, an innovative transparent exoskeleton for the upper-limb," in *Intelligent Robots and Systems (IROS), Intl. Conf. on*. IEEE, 2008, pp. 1483–1488.

[16] J. C. Perry, J. Rosen, and S. Burns, "Upper-limb powered exoskeleton design," *IEEE/ASME Transactions on Mechatronics*, vol. 12, no. 4, pp. 408–417, 2007.

[17] T. Nef, M. Guidali, and R. Riener, "ARMin III - arm therapy exoskeleton with an ergonomic shoulder actuation," *Applied Bionics and Biomechanics*, vol. 6, no. 2, pp. 127–142, 2009.

[18] S. J. Ball, I. E. Brown, and S. H. Scott, "MEDARM: A rehabilitation robot with 5DOF at the shoulder complex," in *Advanced Intelligent Mechatronics (AIM), Intl. Conf. on*. IEEE/ASME, 2007.

[19] A. Zeiaee, R. Soltani-Zarrin, R. Langari, and R. Tafreshi, "Design and kinematic analysis of a novel upper limb exoskeleton for rehabilitation of stroke patients," in *Rehabilitation Robotics (ICORR), 2017 Intl. Conf. on*. IEEE, 2017, pp. 759–764.

[20] P. W. McClure, L. A. Michener, B. J. Sennett, and A. R. Karduna, "Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo," *Journal of Shoulder and Elbow Surgery*, vol. 10, no. 3, pp. 269–277, 2001.

[21] D. D. Ebaugh, P. W. McClure, and A. R. Karduna, "Three-dimensional scapulothoracic motion during active and passive arm elevation," *Clinical Biomechanics*, vol. 20, no. 7, pp. 700–709, 2005.

[22] B. Kim and A. D. Deshpande, "An upper-body rehabilitation exoskeleton Harmony with an anatomical shoulder mechanism: Design, modeling, control, and performance evaluation," *The International Journal of Robotics Research*, vol. 36, no. 4, pp. 414–435, 2017.

[23] ——, "Controls for the shoulder mechanism of an upper-body exoskeleton for promoting scapulohumeral rhythm," in *Rehabilitation Robotics (ICORR), Intl. Conf. on*. IEEE, 2015, pp. 538–542.

[24] A. A. Blank, J. A. French, A. U. Pehlivan, and M. K. OMalley, "Current trends in robot-assisted upper-limb stroke rehabilitation: promoting patient engagement in therapy," *Current Physical Medicine and Rehabilitation Reports*, vol. 2, no. 3, pp. 184–195, 2014.

[25] P. Agarwal and A. Deshpande, "A framework for adaptation of training task, assistance and feedback for optimizing motor (re)-learning with a robotic exoskeleton," *IEEE Robotics and Automation Letters*, vol. 4, no. 2, pp. 808–815, 2019.

[26] J. L. Emken, S. J. Harkema, J. A. Beres-Jones, C. K. Ferreira, and D. J. Reinkensmeyer, "Feasibility of manual teach-and-replay and continuous impedance shaping for robotic locomotor training following spinal cord injury," *IEEE Transactions on Biomedical Engineering*, vol. 55, no. 1, pp. 322–334, 2008.

[27] L. Marchal-Crespo and D. J. Reinkensmeyer, "Haptic guidance can enhance motor learning of a steering task," *Journal of Motor Behavior*, vol. 40, no. 6, pp. 545–56, 2008.

[28] J. von Zitzewitz, M. Bernhardt, and R. Riener, "A novel method for automatic treadmill speed adaptation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 15, no. 1, pp. 401–409, 2007.

[29] D. Erol and N. Sarkar, "Intelligent Control for Robotic Rehabilitation after Stroke," *Journal of Intelligent and Robotic Systems*, vol. 50, no. 4, pp. 341–360, 2007.

[30] L. Marchal-Crespo and D. J. Reinkensmeyer, "Review of control strategies for robotic movement training after neurologic injury," *Journal of NeuroEngineering and Rehabilitation*, vol. 6, no. 1, p. 20, 2009.

[31] J. L. Banks and C. A. Marotta, "Outcomes validity and reliability of the modified rankin scale: Implications for stroke clinical trials: A literature review and synthesis," *Stroke*, vol. 38 3, pp. 1091–6, 2007.

[32] M. A. Murphy, C. Resteghini, P. Feys, and I. Lamers, "An overview of systematic reviews on upper extremity outcome measures after stroke," *BMC Neurology*, vol. 15, no. 1, p. 29, 2015.

[33] Wong-Baker FACES Foundation, "Wong-Baker FACES® Pain Rating Scale," accessed 6.20.18 http://www.WongBakerFACES.org, 2016.

[34] H. A. Abdullah, C. Tarry, R. Datta, G. S. Mittal, and M. Abderrahim, "Dynamic biomechanical model for assessing and monitoring robot-assisted upper-limb therapy," *The Journal of Rehabilitation Research and Development*, vol. 44, no. 1, p. 43, 2007.

[35] R. H. Krishnan, V. Devanandh, A. K. Brahma, and S. Pugazhenthi, "Estimation of mass moment of inertia of human body, when bending forward, for the design of a self-transfer robotic facility," *Journal of Engineering Science and Technology*, vol. 11, no. 5, pp. 166–76, 2016.

[36] J. H. van der Lee, H. Beckerman, G. J. Lankhorst, and L. M. Bouter, "The responsiveness of the Action Research Arm test and the Fugl-Meyer Assessment scale in chronic stroke patients," *Journal of Rehabilitation Medicine*, vol. 33, no. 3, pp. 110–113, 2001.

[37] M. Rabadi, M. Galgano, D. Lynch, M. Akerman, M. Lesser, and B. Volpe, "A pilot study of activity-based therapy in the arm motor recovery post stroke: a randomized controlled trial." *Clinical Rehabilitation*, vol. 22, no. 12, pp. 1071–82, 2008.

[38] J. McCabe, M. Monkiewicz, J. Holcomb, S. Pundik, and J. J. Daly, "Comparison of robotics, functional electrical stimulation, and motor learning methods for treatment of persistent upper extremity dysfunction after stroke: A randomized controlled trial," *Archives of Physical Medicine and Rehabilitation*, vol. 96, no. 6, pp. 981–990, 2015.

[39] Y.-w. Hsieh, C.-y. Wu, W.-w. Liao, K.-c. Lin, K.-y. Wu, and C.-y. Lee, "Effects of treatment intensity in upper limb robot-assisted therapy for chronic stroke: a pilot randomized controlled trial," *Neurorehabilitation & Neural Repair*, vol. 25, pp. 503–511, 2011.

[40] J. P. Dewald and R. F. Beer, "Abnormal joint torque patterns in the paretic upper limb of subjects with hemiparesis," *Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine*, vol. 24, no. 2, pp. 273–283, 2001.

[41] C. G. Rose, E. Pezent, C. K. Kann, A. D. Deshpande, and M. K. O'Malley, "Assessing Wrist Movement With Robotic Devices," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 26, no. 8, pp. 1585–1595, 2018.