Impact of Gravity Compensation on Upper Extremity Movements in Harmony Exoskeleton

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Abstract— **Robots have been used to offset the limb weight through gravity compensation in upper body rehabilitation to delineate the effects of loss of strength and loss of dexterity, which are two common forms of post-stroke impairments. In this paper, we explored the impact of this anti-gravity support on the quality of movement during reaching and coordinated arm movements in a pilot study with two participants with chronic stroke. The subjects donned the Harmony exoskeleton which supported proper shoulder coordination in addition to providing gravity compensation. Participants had previously taken part in seven one-hour sessions with the Harmony exoskeleton, performing six sets of passive-stretching and active exercises. Pre- and post-training sessions included assessments of two separate tasks, planar reaching and a set of six coordinated arm movements, in two conditions, outside of and supported by the exoskeleton. The movements were recorded using an optical motion capture system and analyzed using spectral arc length (SPARC) and straight line deviation to quantify movement smoothness and quality. We observed that gravity compensation resulted in an increased smoothness for the subject with high level of impairment whereas compensation resulted in a reduction in smoothness for the subject with low level of impairment in the reaching task. Both participants demonstrated better coordination of the shoulder-arm joint with gravity compensation. This result motivates further studies into the role of gravity compensation during coordinated movement training and rehabilitation interventions.**

I. INTRODUCTION

Individuals affected by stroke and other neurological injuries can have profound upper extremity impairment marked by loss of strength, lack of dexterity, and emergence of unwanted synergies [1, 2]. In several large studies, robot-assisted therapy has achieved parity with dosage-matched conventional therapies [3–6]. While these recent studies have placed an emphasis on acute stroke participants to measure high-impact interventions [3, 7], chronic stroke remains an important population in terms of sheer size as well as in terms of their role in exploratory studies on intervention and assessment designs. In particular, studies in chronic stroke populations which use robotic devices such as Harmony exoskeleton (Fig. 1) to create or mediate experimental conditions [8] can be valuable for investigations into new therapeutic interventions or the fundamental neuromuscular function behind stroke impairment [9].

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Fig. 1. Harmony exoskeleton, a bimanual, 14-DOF upper body exoskeleton was used to provide gravity compensation of arm weight during reaching and coordinated arm movements with two participants with chronic stroke.

One area of interest has been the relationship between neuromuscular control strategies available to individuals after a stroke for motions that require strength and/or dexterity. It has been shown that reducing upper extremity torque requirements through gravity compensation of limb weight can reveal motor function obscured by weakness or abnormal joint coordination patterns [10]. Previous studies have suggested that the partial loss of corticospinal pathways leads to increased reliance on remaining neural pathways, resulting in abnormal joint coordinations and reductions in workspace [2, 11]. When strength output requirements are high, the body may rely on less coordinated pathways to perform tasks as a maladaptive strategy caused by a focus on task completion (and away from movement quality) [3]. As shoulder torque output requirements increase, abnormal joint coordination patterns between the joints of the upper extremity increase, reducing workspace [10, 12]. Similar coordinations have also been seen in isometric joint torque generation tasks [13]. Offloading limb weight can allow for improved performance and control [14], seen as increased range of motion, accuracy, and potentially improved movement quality, as measured by different smoothness metrics [15].

To further examine the effects of robot-mediated training, a pilot study of five participants with chronic stroke was performed. Initial presentation of this study [13] focused on changes in traditional clinical outcome measures (range of motion (ROM), Fugl-Meyer, and ARAT), and joint-space coordination seen after training. In this paper, we are exploring the effect of gravity compensation of arm weight implemented using the Harmony exoskeleton on 3D upper extremity motion. While the pilot study involved a total of five participants with chronic stroke, we are focusing on data from two participants: one with highest level of impairment and the other with lowest level of impairment among the five participants who completed the study.Here we present new results focused on kinematic parameters of movement quality (Cartesian-space straightness and smoothness) measured with motion capture. We hypothesize that differences in movement quality will be recognizable in both reaching and coordination tasks due to the introduction of gravity compensation. In Section II, we describe the experimental protocol and study participants. We then present the results in Section III, which show a difference between smoothness increases in task-oriented reaching movements and coordination movements. Potential interpretations of this difference is presented in in Section IV before a discussion future work and conclusions in Section V.

II. METHODS

The goal of this analysis was to investigate changes in movement quality in gravity compensated reaching and coordination movements. The protocol, first presented by de Oliveira *et al.* [13], was approved by the Institutional Review Boards of The University of Texas at Austin (2017-10-0033) with further data analysis approved by Auburn University (#20-601 EX 2012).

A. Harmony Exoskeleton

The Harmony exoskeleton is a bi-manual upper-extremity exoskeleton with position and force control capabilities through series-elastic actuation [16]. The shoulder girdle supports five degrees of freedom, and the robot controller [17] ensures the scapulohumeral rhythm (SHR) [18], which is often impaired after a stroke [19, 20]. The robot is thus designed to support the study of rehabilitation in people who have suffered loss of upper-limb coordination post stroke.

B. Gravity Compensation Implementation

Harmony uses a multi-level control structure to ensure high performance and safe operation. At the lowest level, Harmony uses joint-level torque measurement and control in each of the seven DOF of the arm (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). This joint-level control has a bandwidth of 7 Hz, within the desired range for human-robot interaction [21], and with feedforward partial cancellation of friction and viscous damping, has a resistive torque of between 0.1 Nm and 0.2 Nm for the velocities experienced in the experiments [16]. At the next level, the controller provides gravity compensation to offload the weight of Harmony and the wearer's arm while maintaining the correct SHR. Specifically, an inverse dynamics algorithm [22] consisting of a forward kinematics recursion and a backward recursion to calculate the compensatory torques was implemented to reduce the gravitational pull of a wearer's arm weight. The training sessions involved adaptive assist-as-needed control [13, 23] on the passive and triggered active motions to provide assistance for task completion. However, the assessment movements used in this study only relied on gravity compensation where arm weight was initially estimated through the total body weight and arm dimensions [24]. Each participant had their arm's dynamics model fine-tuned in the first session eliminating stationary drift to properly implement the desired torque control [16].

C. Participants

The population for this study were individuals post-stroke with body dimensions that would fit comfortably into Harmony with a Modified Rankin Score (MRS) less than or equal to four. Six participants were recruited with five completing the entire protocol (S3 did not meet inclusion/exclusion criteria). Descriptions of S5 and S6, the most and least impaired participants are presented in Table I.

TABLE I
DEMOGRAPHIC DATA OF PARTICIPANTS

	S5	**S6**
Age	55	63
Months post onset	30	10
Mod. Rankin Score	2	2
Affected/Dominant Side	L/R	L/R
Post-Study [13] FM-UE Score (Δ)	24 (+10)	49 (-2)

D. Training Protocol

During robotic training and assessment, participants' arms were attached to the robot using elastic cuffs at the humerus and wrist, and the eminence grip at the hand [25]. Robotic training consisted of seven one-hour sessions, two per week. During the training sessions, participants performed sets of passive stretching and assisted movements. In both sets, participants performed six coordinated joint movement tasks, three of which are pictured in Fig. 2.

Shoulder Rotation Scapular Elevation Inward Diagonal

Fig. 2. Participants performed a set of six coordinated motions during training [13], and in this manuscript we analyzed the impact of gravity compensation on a subset of three movements, pictured here, which involve different levels of effort and shoulder coordination. Specifically, a shoulder rotation, scapular elevation, and an across-the-body inward diagonal motion.

During this training, the only feedback provided to participants were demonstrations of the motions by the occupational therapist and kinesthetic feedback during the motions, in that the robot provided restorative torques in the forms of an impedance around the joint trajectories. These six movements were designed by collaborating physical and occupational therapists, with a focus on creating motions that explored multi-joint coordination and were outside of a task context. Each participant completed around 1130 exercise repetitions tasks throughout three and a half weeks of training [13].

E. Assessment Tasks

In occupational therapist-supervised sessions before and after the seven training sessions, participants were assessed through two tasks: a Cartesian space reaching task and the trained joint coordination tasks.

1) Reaching Task: Reaching tasks, shown in Fig. 3 were designed to investigate the effects of gravity compensation in Harmony exoskeleton on visually guided tasks, similar to previously studied assessments [7] and functional tasks. The task involved reaching three targets, placed to require different levels of shoulder abduction. To this end, contralateral and ipsilateral targets were placed 10 inches away from the center target placed in-plane with the shoulder. Target heights were aligned with participants' hands when the elbow is flexed 90° and were placed such that the participant could touch the target with their wrist, which is approximately 75% of their reachable distance [26, 27]. Participants were asked to reach each target five times in pseudo-random order. The reaching tasks were performed first without any assistance and then followed with gravity compensation active provided by Harmony exoskeleton, with a rest period between to reduce potential fatigue effects. A reduction of the workspace was expected as a result of this strength requirement [10, 12]. We hypothesized that the changes in workspace brought on by increased shoulder abduction torque requirements would also affect movement quality.

Fig. 3. Reaching targets were set up in a line in front of the seated participant at elbow height (left) and set at a distance requiring 75% of reachable distance (right). Three targets were presented in a pseudo-random order to the participant: ipsilateral (orange), contralateral (purple), and the center target aligned with the shoulder (green).

2) Coordinated Movement Task: Participants performed sets of three repetitions of each coordinated movement [13], presented in a different pseudo-randomized order for the robotic gravity compensation (RGC) and no gravity compensation (NGC). Prior to evaluation, each movement was demonstrated by the attending occupational therapist. Unlike the reaching task, which provided visual feedback, the only feedback modality provided to the participant during the coordinated movements tasks were demonstrations at the start of each subset by the attending occupational therapist. We investigated three of these motions: shoulder rotation, scapular elevation, and an inward diagonal motion, shown in Fig. 2. Out of the six coordination tasks in the intervention, these tasks range from the simplest to most difficult in terms of strength and coordination required. The shoulder rotation task required control of a single joint, moving largely in a plane perpendicular to gravity, resulting in minimal difficulty. Scapular elevation requires some strength and SHR coordination, but as much as the inward diagonal motion, which had the most complex joint coordination pattern and shoulder torque outputs.

F. Data Processing

All movements were captured via a 10-camera optical motion capture system (Optitrack Prime 17W, NaturalPoint Inc., Corvallis, OR, USA) at 100 Hz. Markers were grouped into rigid bodies and placed on the upper extremity (top of the sternum, acromion process, humerus, forearm, and the hand, as previously described [28]) to track body segment motion. Trajectories of these rigid bodies were manually checked for labeling errors and the requisite point corrections for each of the tasks were made in Motive:Body. To reduce marker position measurement noise, a low pass Butterworth filter with a cutoff of 6 Hz was applied minimally for error correction native inside Motive:Body software. Post processing included a fifth order Savitzky-Golay filter with 21-sample window for all marker positions and tasks before analyzing and quantifying movement positions and velocities [29]. Reaching movements were segmented with a 5% velocity threshold [30].

G. Movement Quality Measures

Several assessments have been proposed to assess upper extremity function, ranging from functional task-based metrics to high resolution robotic measures [15]. In this manuscript we focus on two measures of movement quality, spectral arc length (SPARC) [31] to quantify smoothness and the deviation from the most efficient straight line path in Cartesian space, similar to previously presented measures [29, 30], to quantify movement efficiency. The maximum distance from the initial point by a straight line integrated against the absolute value of the movement path was defined as straight line deviation $\mathrm{SLD} = \int_0^{t_f} \frac{(|X_{pos}(t) - X_{SL}|)}{\|X_{SL}\|} dt$. SPARC, a movement smoothness measure with clinical relevance and robust performance to changes to time domain aspects of velocity trajectories (e.g., segmentation) was used to quantify movement quality through the utilization of peak velocities standardized by a relative velocity profile utilized in both reaching and coordination tasks.

III. Results

The impact of gravity compensation applied by Harmony from the post-training evaluations is analyzed and grouped below by task, unless stated otherwise. Note that 'robot gravity compensated' condition refers to results from movements performed by participants while wearing the exoskeleton that provided gravity compensation of the robot and wearer limb weight, while the 'no gravity compensation' condition refers to results from movements performed without the robot.

A. Pre- and Post-Assessment

Fig. 4 compares the movement smoothness of the reaching and coordination tasks, separated by condition, between the pre- and post-training assessment sessions. Potential improvements in movement quality in the robot gravity compensated condition suggest that experience with Harmony exoskeleton and gravity compensation may have increased participants' ability to move smoothly. To reduce the influence of experience with Harmony (potentially explaining changes seen in Fig. 4), only the post-study assessment after the three and a half weeks of training has been analyzed.

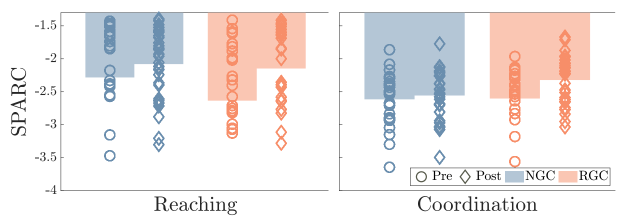

Fig. 4. Pre and Post assessment of movement quality (SPARC) separated by condition (robot gravity compensation (RGC) and no gravity compensation (NGC)) and task (reaching/coordination). Increase in reaching (All targets) and coordination tasks (SR, SE, and ID combined) in the gravity compensation condition could suggest improvements in performance due to training. To avoid improvement biases, post-assessment data was analyzed.

B. Reaching

Movement quality (SPARC and SLD) of the reaching motions, separated by target and participant is shown in Fig. 5. While gravity compensated reaching movements were smoother for S5, gravity compensation seemed to have limited or slightly negative impact on S6. To determine if compensatory strategies, such as trunk rotation, contributed to the unexpected decrease in smoothness, the maximum distance the hand rigid body and sternum rigid body were compared, with the results in Fig. 6 suggesting that trunk rotation was only slightly reduced by Harmony exoskeleton.

C. Coordinated Movements

The movement smoothness of the three coordination tasks, shown in Fig. 2 were quantified through SPARC alone, as these joint-space motions did not follow a straight line path in Cartesian space. In general, both S5 and S6 generated smoother movements when the weight of their arms was reduced via gravity compensation (robot gravity compensation), with the largest gains occurring in the inward diagonal motion (Fig. 7). Also of note, the coordinated tasks were in general less smooth than the reaching tasks. This trend seems to be independent of impairment levels for S5 and S6.

IV. Discussion

We investigated changes in movement quality in upper-limb movement of participants with chronic stroke resulting from gravity compensation implemented by an exoskeleton. We hypothesized that both task-oriented [32] and movement quality focused tasks would see improvements in movement quality with gravity compensation. The results were mixed

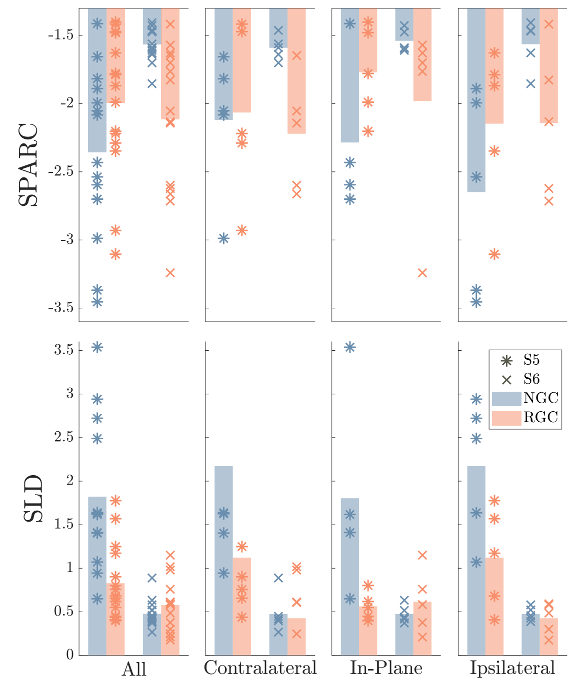

Fig. 5. Movement quality for S5 and S6 in the reaching task. Top: Movement smoothness (SPARC) for reaching tasks separated by target and participant condition (robot gravity compensation (RGC) and no gravity compensation (NGC)). SPARC was calculated on hand trajectories in Cartesian space, suggesting that in general, NGC conditions were smoother for the less impaired participant (S6) and comparable for the most impaired participant (S5). Bottom: (SLD) for reaching tasks separated by target, condition (RGC/NGC), and participant. SLD was calculated on hand trajectories in Cartesian space, with similar results to movement smoothness, where participant S6's change was minimal, and S5 saw a reduction in curvature.

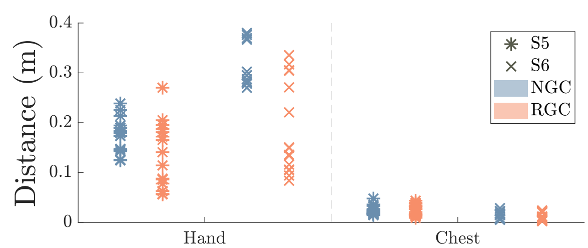

Fig. 6. Motion of the hand and the chest was examined to determine if compensatory strategies contributed to differences in movement quality between robot gravity compensation (RGC) and no gravity compensation (NGC) conditions. Maximum distance of the hand (left) and the chest (right) suggests compensation strategies were minor.

in the case of reaching task while we observed improvement for both participants in the coordinated movement tasks. A further examination of the tasks suggests potential interpretations of this result and its implications for robot gravity compensated training and assessment.

A. Reaching Tasks

In the post-study assessment of the reaching task (Fig. 5), gravity compensation provided by Harmony exoskeleton resulted in an increased smoothness for the most impaired participant (S5) and a reduction in smoothness for the least impaired (S6). This follows previous results [10, 13] which suggests that impairment may result in an over-reliance on

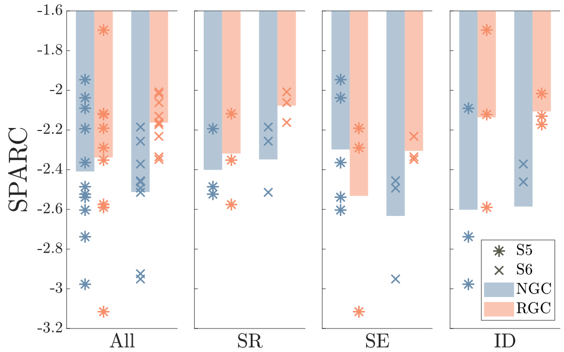

Fig. 7. Movement smoothness (SPARC) of three different coordinated tasks: Shoulder Rotation (SR), Scapular Elevation (SE), Inward Diagonal (ID) motions separated by participant and condition. For the simplest (SR) and most difficult (ID) motion, gravity compensation increased smoothness, with mixed results for scapular elevation(SE).

suboptimal neural pathways. While it is possible that the reduction in smoothness for S6 was due to a robot-imposed reduction in compensatory strategies, the minimal changes in SLD (Fig. 5) and lack of trunk movement (Fig. 6) suggest other causes. Another potential interpretation would be that Harmony exoskeleton and gravity compensation perturbed the motion of S6, either due to control strategy or kinematic overconstraint, which might have provided miniscule elasticity between the robot and human joints [33]. Gravity compensation, as implemented in this study, is not able to completely remove the dynamic impact of the friction and inertia inherent to the robot, potentially adding some mechanical filtering or disturbances. However, the joint-level torque control performance and high backdrivability [16] due to the low impedance from the series elastic actuators, combined with the relatively slow speeds at which the participants moved in this study reduces the impact of both friction and robot inertia. The increases in smoothness in the shoulder rotation coordination task for both participants (Fig. 7) suggests that the limitations of the gravity compensation implementation did not perturb motion. The task-oriented nature of reaching may be the cause of this reduction in smoothness. Visual feedback, coupled with the reduction in effort due to gravity compensation might have enabled additional, corrective motions to improve target reaching accuracy at the cost of movement smoothness. Also, it is possible that only participants with low levels of impairment could make these additional corrective motions.

B. Coordination Tasks

In the coordinated movements, S5 and S6 improved in their SPARC values across all three tasks with the exception of the scapular elevation task, where S5 had a slight downward trend (Fig. 7). Each task required varying levels of shoulder torques to overcome gravity, along with differing levels of joint coordination. There were two factors which may have resulted in gravity compensation causing greater changes during the coordination movements than in the reaching tasks. First, when comparing the reaching and coordination tasks, movement quality in differing levels of ‘refinement’ in participants’ internal models must be considered. Realizing functional improvements or changes in movement quality may be easier in novel coordination tasks than familiar reaching tasks. Second, improvements in movement quality seen across pre- and post-study assessments (Fig. 4), may not be the sole result of experience with Harmony. These improvements may be the result of achieved gains in function [13] and suggest further potential gains. By eliminating instantaneous visual and kinesthetic feedback, these movements tasked subjects to focus on learning the motion itself. This learning goal could result in a more effective improvement of movement quality [3], as opposed to the completion and accuracy focus of the reaching task.

C. Limitations

However, this pilot study has some limitation which may impact the clarity of results. Changes in feedback modality (visual vs. none) varied between task type and condition, potentially limiting the comparison of reaching and coordination tasks. The differences between the tasks and the relative gravitational effort required by Harmony exoskeleton may contribute to the differences in result for reaching and coordination tasks. The reaching task, even with the ipsilateral and contralateral targets, required less shoulder torque than some of the coordinated tasks (SR), which might potentially complicate interpretations of task orientation vs. exploratory movements. Lastly, a small sample size prevents a robust analysis for confirmation of our hypothesis. However, anecdotal evidence is supported by prior work utilizing gravity compensated training and suggests directions for future study.

D. Future Work

The differences seen between task-oriented reaching motions and coordination movements focused on quality support further investigation into gravity-compensated upper-extremity rehabilitation interventions. The next study building on these anecdotal results should seek to further explore the effects of feedback and increased training focus on movement quality over task completion without changes in feedback modality. Our next investigative study will be formed around gravity control with consistent feedback levels and new improvements and tweaks for assisted therapy methods. Additionally, investigations into the effects of perturbations on coordinated arm movements, such as prior investigations on arm kinematics [28] and wrist dynamics [29], could better quantify the impact of the robot on the motion and resulting smoothness measures.

V. CONCLUSIONS

Results from movement quality focused training, instead of task completion or strength motivated studies, can target neural pathways associated with dexterous control and can be aided by gravity compensation. Here, we sought to determine effects of gravity compensation on the movement quality of reaching and coordinated movement tasks. We hypothesized that these movements would show improvements in quality for both participants with chronic stroke enrolled in the study. However, gravity compensation seemed to matter less, in particular for the less impaired participant, for the planar reaching tasks than the coordinated movements. These results, while anecdotal, motivate further study to better understand the role feedback and the focus on task completion or movement quality play on the restoration of motor function.

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