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Comparison of Tone compensation and Spring assistance for hand rehabilitation in HEXORR

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Abstract—**Robotic rehabilitation techniques have the capacity to provide high dosage therapy without the labor burden of conventional methods. The most effective means of using robots to retrain function is not yet known, though many studies now support providing assistance to movement while the user actively participates in that movement. In this study, we compare, in three chronic stroke subjects, a novel Tone assistance mode to a Spring assistance method commonly used in other robots. The Tone mode provides assistance comparable to the subject's own resistance to extension while Spring mode provides a spring-like force to pull the subject to the target. All three subjects produced larger finger movements with robotic assistance, but they also produced much more positive work with the Tone assistance compared to the Spring assistance. This demonstrates that subjects were actively driving the movements in Tone mode to a greater extent than in Spring mode. Two out of three subjects showed similar results in the thumb. In the third subject, work was comparable across all modes. With Tone assistance, subjects produced movement and torque profiles more similar to that of Unassisted movement than Spring-assisted movement for both fingers and thumb. These results suggest that providing assistance tailored to the user's own tone profile may be an effective means of enhancing range of motion to ultimately enable gains in hand function.**

I. INTRODUCTION

PREVIOUS studies have shown that dosage has a positive effect on rehabilitation therapy [1-2]. The advent of rehabilitation robotics has enabled increased repetition while lessening the burden to the therapist and achieving comparable results to conventional therapy [3-4]. One of the questions still remaining is the best way of using robots to assist rehabilitation.

Robotic therapy can generally be categorized as passive, assisted, resistive, or bimanual exercises, or a combination of these [5]. Our study focuses on assisted exercises in which the user is actively engaged in moving the hand while the robot provides assistive forces. Many robots use an assistance algorithm that is similar to a linear spring approach in that the magnitude of the assistance increases with increasing distance from the target [6-9]. This Spring mode emulates attaching a physical spring (zero rest length) between one's limb and the target, with spring stiffness adjusted to modulate the level of assistance. The end of the spring attached to the target is fixed, so the limb is free to move with assistance force or torque that is proportional to one's distance from the target.

Our device, the Hand Exoskeleton Rehabilitation Robot (HEXORR), provides assistance based on the user's own physiology. The spasticity (reflexes and/or involuntary activation) and/or hypertonia (passive stiffness) that often accompany chronic stroke limit range of motion (ROM) [10]. To account for patient-specific resistance to extension, we developed a tone compensation algorithm (Tone). In this study, we show the results of a comparison between Tone and Spring assistance during a simple rehabilitation game. We then evaluate these methods by comparing them to an Unassisted trial of the same game. While both assistance modes adaptively adjust assistance levels to enable subjects to complete the movements in the game, we expected different levels of subject engagement in the tasks. This was evaluated by calculating the amount of positive work the subjects performed during the game. Higher levels of positive work are preferable because this indicates the subjects are actively driving the movements and not being passively moved by the robot.

TABLE I
SUBJECT DEMOGRAPHICS

Subject	Age	Years Post CVA	Sex	F-M (66)
S1	65	2.5	M	37
S2	33	4	F	40
S3	65	3.5	M	27

II. MATERIALS AND METHODS

A. Overall Study Design

This paper describes the results of a comparison study in which 3 chronic stroke subjects had a two-hour session of HEXORR training to compare two different, self-adapting types of robotic assistance. Each session consisted of three robotic modes: a passive stretch mode which was used to measure tone, a ROM evaluation with no robotic assistance, and a therapy game (Tone or Spring mode assistance).

A Fugl-Meyer score was collected on each subject to

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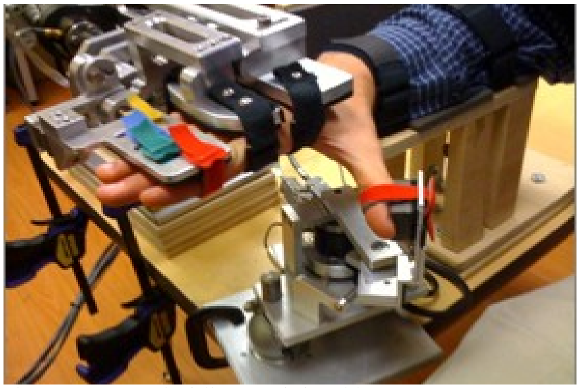

Fig. 1. HEXORR in fully extended position.

assess overall impairment level. Three chronic stroke subjects (S1, S2, and S3) were enrolled in this study, mean Fugl-Meyer was 34.7 (maximum=66, a higher score is less impaired); a profile of each subject can be found in Table 1.

B. *The Device*

HEXORR (Fig. 1) was used for robotic training, a full description of the device is available in [11]. It actuated the two proximal joints of the finger, the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints, while leaving the distal interphalangeal (DIP) joint free. The thumb was attached to the robot at the distal phalanx, resulting in coordinated movement of the three thumb joints (IP, MCP, and carpometacarpal, CMC). In both the ROM evaluation and therapy game modes, the HEXORR motors produced position and velocity dependent torque to compensate for the effects of gravity and friction, respectively. Both finger and thumb components include a digital optical encoder (resolution 0.0005° and 0.0002°, respectively) and a torque sensor (TRT-200, Transducer Techniques, Temecula, CA) with a max of 22.6 Nm of flexion/extension torque.

C. *Single-session Comparison Protocol*

Subjects operated under three different modes in the robot, two assessment measures and one game. First a stretch assessment mode slowly moved the subject's fingers and thumb (10 and 2.5°/s, respectively) through their full ROM five times. The stretch allowed us to measure the subject's tone by recording the motor output required to extend the digits. The second assessment recorded the subject's active ROM. The subject was asked to fully extend the fingers and thumb while the motors provided friction and gravity compensation for the HEXORR linkages. Each subject was given three one-minute attempts to reach maximal ROM before the robot completed the movement, if necessary. After each activity, subjects received the stretch again to relax the hand and ensure that tone was not increasing. If the tone had increased by more than 10%, the stretch was repeated to lower the tone to previous levels.

The subject then played a gate game starting in a flexed position and controlling two balls on the screen with finger and thumb movement. A wall with two open gates swept across the screen and the subject opened the fingers and thumb to pass each ball through its respective gate (see [12] for more details). As a baseline measure, subjects played 3 rounds of extension and flexion gates with only friction and gravity compensation (Unassisted mode). To test the assistance modes, each block was 30 rounds. The height of the gate was set at 200% active ROM, from the pre-test, or 85% of maximum possible ROM, whichever was lower.

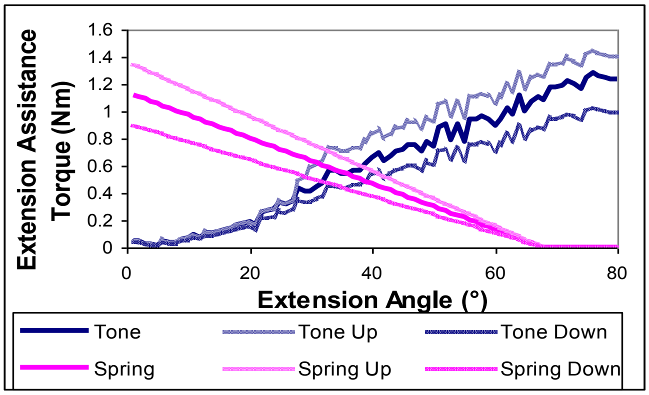

Fig. 2. Overlay of initial and self-adapted Tone and Spring assistance profiles for S1.

D. *Assistance Modes*

We tested two types of self-adapting assistance with two different adaptation scaling rates in the comparison study. S1 and S3 received Spring then Tone assistance, and S2 received Tone followed by Spring to reduce ordering effects. However, all subjects received the lower and then the higher adaptation rate (denoted by the number 1 or 2, respectively). For both Tone and Spring, assistance was provided only during the extension phase of the game.

All blocks were preceded by a passive stretch trial to confirm that tone levels were within 10% of that recorded at the start of the session. Tone assistance provided extension torque to balance the measured tone during the passive stretch. Spring assistance provided a linear, spring-like force dependent on the subject's distance from the target. Initial stiffness of the Spring mode was selected so that both modes produced the same assistance level midway to the target. Thus, the average level of assistance was similar between Tone and Spring modes at the start of each block of trials. Fig. 2 shows the Tone and Spring assistance profiles for S1. Note the Spring profile decreases assistance as the target is approached whereas the Tone profile increases assistance.

Both types of assistance employed a self-adapting algorithm to increase or decrease assistance based on performance. Tone assistance magnitude was scaled down upon success and offset up upon failure. When the subject fell short of the gate, the offset was added to the profile at the point which the subject stopped moving. This offset method allowed the assistance profile to be shaped to match the subject's tone profile while playing. Tone 1 decreased by 10% each time a subject successfully reached two out of two gates and was increased by an offset of 0.121 Nm as

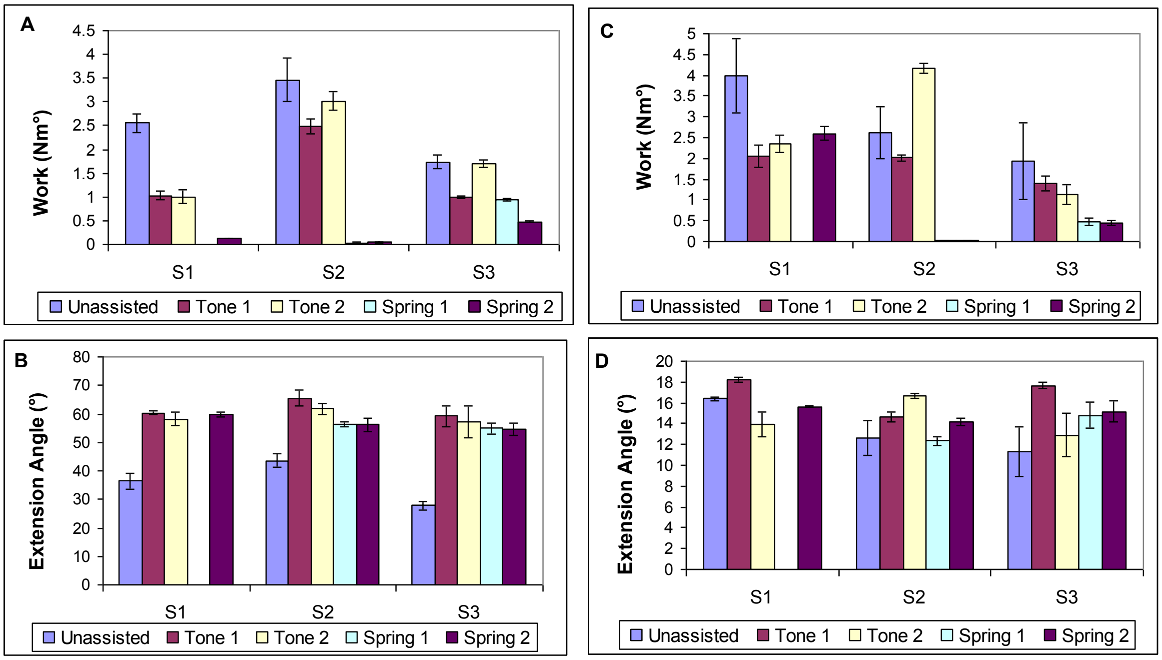

Fig. 3. Overview of finger (subplots A, B) and thumb (C, D) work and extension angle by subject and mode..

described above each time a subject failed at two out of two gates. The assistance was unchanged with one successful gate out of two. In Tone 2, assistance decreased by 20% and increased by an offset of 0.165 Nm. A similar algorithm was used to adapt Spring 1: per 2 gates, the assistance was decreased by 10% after two successes and increased by 10% after zero successes. Again, assistance was unchanged with only one success. In Spring 2, decrease and increase were both changed to 20%. A graph of the two types of assistance and how they are scaled at the high adaptation rate can be found in Fig. 2.

E. Data Analysis

The fingers and thumb were analyzed separately. To analyze the subject's performance, extension movements in the therapy game mode were isolated from flexion movements. Flexion movements were not analyzed because assistance was only provided in extension. Work for each sample period was calculated by multiplying the distance moved (in degrees) by the average torque (in Nm) measured within the sample period. The work done over the entire movement was calculated by summing the work done in all sample periods.

III. RESULTS AND DISCUSSION

All subjects tolerated HEXORR use and robotic assistance. Positive work is produced by the user while extending; negative work is produced by the robot but may also show active braking on the part of the subject. Extension angle of the fingers goes from 0° (flexion) to 90° (extension) and refers to both the MCP and PIP angles. For the thumb, the range is 0° (flexion) to 20° (extension) and refers to the CMC angle; the corresponding thumb IP ROM is 90°. Fig. 3 shows average positive work and displacement values for the three Unassisted gates and the last ten gates of the Tone and Spring modes. The last ten gates were chosen to allow the adapting algorithm to optimize the assistance provided and thus promote maximal positive work from the subject. Due to a technical error, data is unavailable for S1 for Spring 1.

For the fingers, positive work values during the gate game were much higher for all subjects with Tone assistance compared to Spring assistance; however, they were highest for the Unassisted trials (Fig. 3A). ROM was comparable between assistance modes and clearly larger than Unassisted trials (Fig. 3B). The thumb data showed a similar pattern in S2 and S3 (Fig 3C-3D). S1 showed little difference in thumb work between assistance modes. This was likely due to S1 having an Unassisted ROM (82% of max) close to the target (85%), and thus needing minimal assistance. ROM increase in the thumb was less dramatic than that of the fingers likely due to starting ROM: finger ROM in Unassisted was 35-55% of maximum while thumb ROM was 56-82% of maximum.

All subjects showed higher positive finger work in the Unassisted trial than the assisted trials; however, they were unable to achieve as large ROM. This result may be influenced by the small number of gates included in the Unassisted trial. Though we only tested three gates to reduce the possibility of fatigue, S1 completed one Unassisted trial of 30 gates. S1 had an average positive work value of 2.6 Nm° in the three-gate Unassisted trial and 1.6 Nm° in the 30-gate Unassisted trial, a decrease of 37.6%. This finding suggests a trend of fatigue or reduced engagement over the course of 30 Unassisted trials. The assistance modes help reduce fatigue by providing self-adapting assistance, while still allowing the subject to successfully reach the target and maintain motivation.

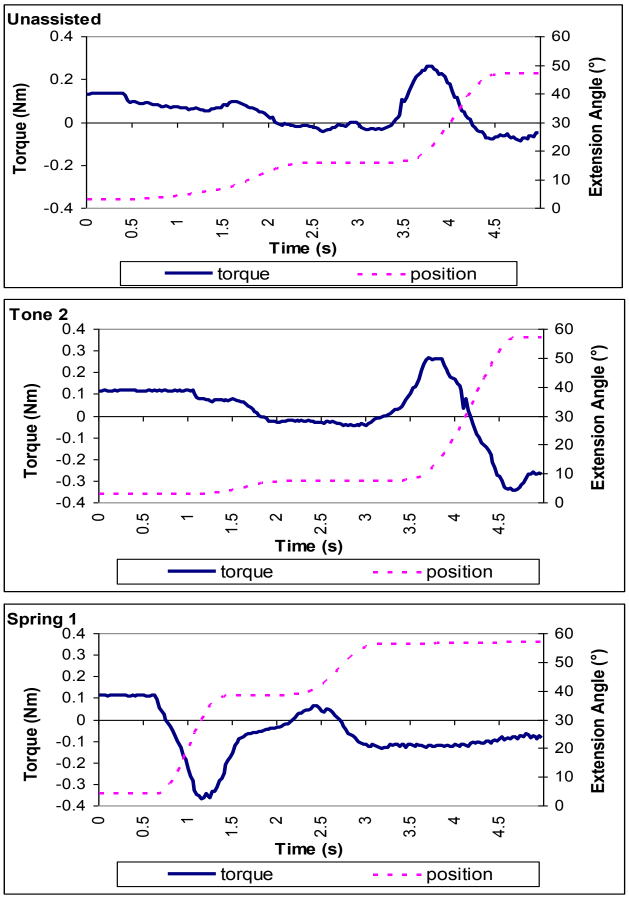

Fig. 4. Torque and extension angle plots for sample movements from each Unassisted, Tone 2, and Spring 1 for S2. Extension produces positive torque while flexion produces negative.

To better understand the difference in positive work between the three modes, a sample extension movement from S2 in each mode was further examined. (Each sample movement was chosen because it had the largest positive work value for that mode.) Fig. 4 shows three plots overlaying displacement and torque for each sample finger movement. While both Tone and Spring modes allow S2 to achieve a larger ROM, in Tone mode the subject creates a torque profile more similar to that with the Unassisted mode. The pattern of movement is also more comparable between the Unassisted and Tone modes than the Spring mode. These data suggest that while the Spring mode encourages a large ROM, it does so in a way that does not match the subject's innate movement and thus limits the subject's active participation. Note the large burst in negative torque at the onset of movement in Spring mode, indicating the subject was being pulled along by the robot. In contrast, movements in Tone mode are initiated by positive torque on the part of the subject indicating the subject is driving the movements. This analysis was performed in the same manner for the thumb and similar results were found (not shown).

IV. CONCLUSIONS

Subjects had much larger positive finger work with Tone assistance compared to Spring assistance while maintaining similar displacement. (Statistical analysis was not performed due to small n.) Two of the three subjects showed the same pattern in the thumb. Similar to conventional therapy strategies in which a therapist actively assists a patient, training a larger ROM with robotic assistance may enable subjects to ultimately access that ROM outside of the robot in daily life. While both types of assistance enabled subjects to access a higher ROM, Tone assistance also enabled them to produce more work. These data suggest customizing robotic assistance to a subject's own tone profile allows subjects with hypertonia to train a wider range of motion while encouraging them to actively engage in training. We acknowledge that in cases where hypertonia is not present, Tone and Spring assistance may be comparable methods for increasing ROM while encouraging user work. This study included subjects with flexor spasticity/hypertonia but could be adapted to those with extensor spasticity/hypertonia. In the future, we intend to expand this comparison study to include subjects with a wider variety of baseline impairment and tone.

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