Spatial and Temporal Movement Characteristics after Robotic Training of Arm and Hand: A Case Study of a Person with Incomplete Spinal Cord Injury

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Abstract— **Background: Upper limb weakness is the primary concern of tetraplegic individuals who have sustained incomplete spinal cord injury (SCI), to an extent that it is considered more important than standing abilities. Recent evidence of the plasticity of the brain and the spinal cord that can be enhanced by repeated practice- such as that available with robotic devices- suggest that robotic training of upper limbs can be beneficial to persons with SCI. The goal of this pilot study was to evaluate an innovative rehabilitation technique using the RiceWrist, a newly developed robotic device, for a person with tetraplegia. A 24-year-old male with incomplete SCI at the C4 level, 6.5 months post-injury participated in 10 sessions of robotic training over 2 weeks. Variability of movement trajectory (spatial) and the time to complete (temporal) simple point-to-point wrist and forearm were collected before and after training completion to determine skill acquisition. The participant successfully completed 10 sessions of robotic training. While there were minimal changes in variability of movement trajectory, great improvements were observed for the average movement time for the majority of wrist and forearm movements. Overall, results suggest that the RiceWrist robotic device could be used for upper-limb rehabilitation and can potentially serve as an assessment tool for the SCI population.**

Keywords-rehabilitation robotics; spinal cord injury; upper limbs.

I. INTRODUCTION

In persons with tetraplegia who have suffered incomplete spinal cord injury (SCI), upper limb (UL) impairment is the key component limiting independence [1]. After initial discharge and surpassing the acute phase, persons with tetraplegia must continue UL therapy, especially rehabilitation, to gain ultimate functional recovery [2-4]. Given the extent of impairments tetraplegic persons with incomplete SCI experience, and the number of limitations in ADL that they face after inpatient discharge, it is important to establish a treatment plan that would best help these patients reach ultimate recovery. A recent survey reported that more than 70% of tetraplegic individuals with SCI regarded UL function as an important or very important factor in their quality of life, exceeding concerns for sexual dysfunction (<50%), pain (<50%), and standing abilities (<45%) [1]. Only bowl and bladder problems were rated as equally or more important than UL function [1]. Given that overall level of function in the upper extremities has great impact on the level of independence in most daily living activities such as self care, and social and work related tasks [5], increase in arm and hand function can lead to increased independence, engagement in social activities, decrease in caregiver burden, and can therefore impact the overall health related quality of life for this population.

Small improvements in hand function can greatly impact the ability of patients with incomplete tetraplegia to use their hands [6, 7]. There is evidence that intensive training through repeated practice can result in upper limb improvement in tetraplegic patients [8]. Furthermore repeated practice can influence sensori-motor recovery by enhancing mechanisms of recovery in the brain and the spinal cord [9, 10]. Robotic devices are efficient and effective options for administering repeated practice to persons with SCI. Furthermore robotic devices can potentially automate labor-intensive therapy procedures and lower therapy costs. Additional advantages of robotics include potential use for at-home therapy, monitoring progress, and increased efficiency in therapy, with the possibility of group therapy. Despite the potential advantages of robotic devices and the greater concerns of those with SCI for the upper and not the lower limbs, the majority of current research has been on improving leg function and retraining gait after SCI.

Numerous therapeutic robotic devices have been designed and developed for rehabilitation of motor impairments caused by stroke. Early examples of these robots include the MIT-MANUS [11] and MIME [12, 13]. These devices were administered for rehabilitation of the proximal upper extremity joints (shoulder and elbow) after stroke. Robotic devices for the rehabilitation of distal joints of the upper extremity have also been developed, such as the MAHI Exoskeleton [14], the wrist module of the MIT-MANUS [15, 16] and wrist devices developed by Hesse *et al.* (2003) and Andreasen (2005). To our knowledge, no study has been carried out to administer robotic training for upper limbs in persons with SCI. A review of the current literature yielded no publications on robotic training of the upper extremities after SCI. However there is growing body of literature on robotic upper-extremity training in stroke rehabilitation [17-19]. This study is unique in using robotic upper-extremity training to improve upper-limb movement capabilities a person with SCI.

The end goal of the study was to demonstrate effectiveness of robot assisted for a person affected by tetraplegia caused by incomplete SCI in order to gain better control of his arms and hands. We used temporal and spatial measures of movement to detect upper limb movement characteristics before and after robot-assisted training. The findings from this study should encourage further administrations of robotic devices for SCI patients with different levels of injury and disability.

II. METHODS

Subject. A 24-year-old male with incomplete SCI at the C4 level (American Spinal Injury Association (ASIA) D according to American Spinal Injury Association Impairment Scale), 6.5 months post-injury participated in 10 sessions of robotic therapy over 2 weeks. Minimum voluntary movements were preserved on the right upper extremity whereas on the left side he had moderate to normal voluntary movements. The subject signed consent form approved by the Institutional Review Board of all institutes involved in the study.

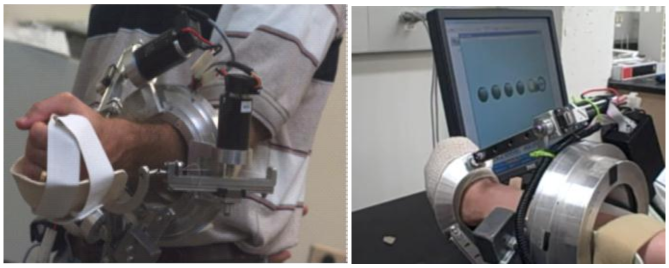

Figure 1. (A) RiceWrist modeled on a healthy individual (B) The left hand of the participating subject with spinal cord injury wrapped in RiceWrist, during training.

Apparatus. The Rice-Wrist, a wrist haptic (force feedback) and electrically actuated upper- extremity exoskeleton device was designed for rehabilitation applications in the Mechatronics and Haptic Interfaces laboratory at Rice University (see Figure 1). The device design extends from prior work, the details of which can be found in [14]. The unique kinematic design of the Rice-Wrist allows for reproduction of most of the natural human wrist and forearm workspace, while further permitting a limited range of elbow flexion-extension. The device features force isotropy and high torque output levels such as would be required during robot-aided training and/or rehabilitation. Another important feature of the design is the alignment of the axes of rotation of human joints with the controlled degrees of freedom of the exoskeleton. The problem of measurement of arm position is thus reduced to the solution of the exoskeleton kinematics, with no further transformations required. This makes it possible to actuate the robot to tailor feedback to a specific human joint, for example to constrain the forearm rotation during wrist rehabilitation, without affecting other joints. The Rice-Wrist has three unique therapeutic modes, which enable treatment to be tailored to persons' abilities: passive, active-constraint, and triggered modes.

In the passive mode, the subject is passive and the robot carries the movement. In the active-constraint mode, resistance is given to the subject. When resistance is set to zero the subject can move freely as used for initial training sessions and all evaluation trials.

In the triggered mode the subject overcomes a threshold before the robot takes over the movement. In this study, the active-constraint mode-with zero constraint- was used for evaluation while all three modes were incorporated into the training protocol.

Procedure. The subject underwent robotic training with the Rice-Wrist for three hours per day on 10 consecutive weekdays for left and right upper extremities. Each session began first with robotic evaluations and then followed by training practices. In each session, the participant was seated in front of a low table, centered in front of a computer

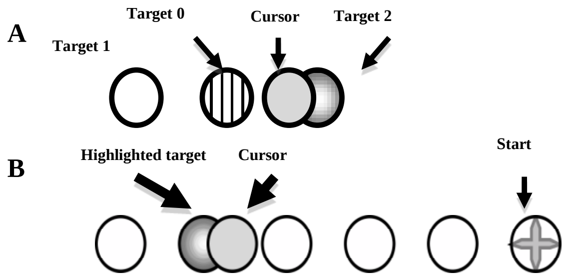

Figure 2. Top view, (A) Target hitting task required the participant to move the cursor to highlighted Target 2 from the center and return to the center before the next target was highlighted (B) Distortion task required the participant to move the cursor to highlighted target from the start position and return to the start position before the next target was highlighted. Note that during invisible curser condition the participant was not able to see the cursor thought the movement. For each task the participant was provided with visual display similar to that in the figure.

monitor. The subject then placed his hand inside the robotic device holding the cylindrical end of the device. Due to the subjects' inability to maintain his grasp throughout the training, a bandage was used to wrap the participant's hand around the cylindrical end of the device (Fig 2). During the first session, trials were first completed for the left hand (stronger hand) and then followed by the opposite hand. This order alternated for each successive session.

The evaluation trials involved a series of target hitting trials presented through visual display on the computer monitor carried out by wrist flexion/extension, radial/ulnar deviation or forearm supination/pronation. The visual display included a center target which served as the starting and end location, centered between two targets that aligned horizontally for wrist flexion-extension and forearm supination-pronation, and vertically for radial-ulnar deviation The distance of the two targets from the center was calibrated based on the participant's maximum range of motion. This range was captured with Rice-Wrist while the subject moved to the maximum range in each plane of movement. During evaluation, targets were highlighted one at a time. The participant moved the circular cursor to the highlighted target and returned to the center target before the next target became activated. Movements from the center target to the active target were considered a hit. The subject was asked to performed at least five trials for each plane of movement in the active-constraint mode during evaluations.

Training followed evaluation and involved target hitting and distortion tasks each tailored individually based on the participant's movement capabilities. The target-hitting task was similar to evaluation differing in that all three operating modes (passive, assistive and resistive) and more repetitions were administered. In addition, the number of repetitions and speed of movement were given to the participant as visual feedback throughout his performance. Task difficulty was increased by gradually adding to the number repetitions and the amount of applied resistance of the resistive mode and by avoiding use of the assistive mode. The distortion task was administered at later training sessions to enhance use of the somatosensory feedback [20]. Visual display of the distortion task involved 5 targets aligned horizontally for wrist flexion-extension and forearm supination-pronation, while vertically for radial-ulnar deviation (see Figure 2). Targets were equally spaced across 44-80% of the participant's maximum range of motion. Training was divided into blocks of visible and invisible cursor conditions where each target was randomly highlighted twice for each condition. For the visible condition the participant moved the circular cursor-visible at all times-to the highlighted target and returned to the starting location before the next target was highlighted. For the invisible condition the curser was only visible before movement initiation, and after the participant made a complete stop on where he assumed to be the correct location of the cursor relevant to the highlighted target. At each subsequent block there was 10.4% degrees of increase in the ROM distributed equally across target distances without the participant's knowledge (distortion). The number of completed blocks gradually increased across practice sessions to challenge the participant throughout training. The participant was given sufficient breaks throughout each training sessions. No other therapeutic interventions for upper extremity were provided during the study period.

A 30 year-old healthy female participant performed 5 trials of forearm supination/pronation, wrist flexion/extension and radial/ulnar deviation with her non-dominant arm to serve as a comparison basis with the SCI participant. Movements were performed the same as evaluation trials used for the SCI participant.

Measures of interest. Angular position data was collected at 100 Hz for all evaluation trials. It was found through the course of evaluation that the subject did not stop at the central target as expected, instead moving straight to the next target, which required the same movement. Therefore, instead of considering the movement from Target 1 to Target 0, and separately considering the movement from Target 0 to Target 2, the movement from Target 1 to Target 2 is considered directly. In addition to this, it was found that although targets 1 and 2 were displayed as boundaries for the subject's movements, the subject often overshot the targets. For this study, the subject's overall movements were of greater interest than the subject's movements within the target space only.

Average movement time (T_A)*:* In order to measure time to completion, a movement was considered to start from the maximum displacement in one direction from target 0 to the maximum displacement in the opposite direction. For example, for flexion and extension, a full movement of extension began at the end of the previous flexion movement, and ended as soon as flexion began again. This is opposed to the other option of considering only the movement which took place within the space of the outermost targets. The time to complete the task was average across the five trials performed at each evaluation session. The standard deviation of T_A was also calculated across the five trials to serve as measure of time variability.

Trajectory variability envelope (Tj_V)*:* This measure was calculated across the five trials performed at each evaluation session. Data were normalized for time and distance to allow for valid comparisons across session. Data were normalized by linear interpolation across 500 points.

After normalizing each trial, the mean at each data point was taken, and the standard deviation of each data point was taken and added to the mean to form the upper bound magnitude m_{upper}, and subtracted from the mean to form the lower bound magnitude m_{lower} . The variability measure is the difference of these curves integrated over the normalized $t_{norm} \in [0,1]$, as follows:

$$var = \int_0^1 m_{upper} dt - \int_0^1 m_{lower} dt$$

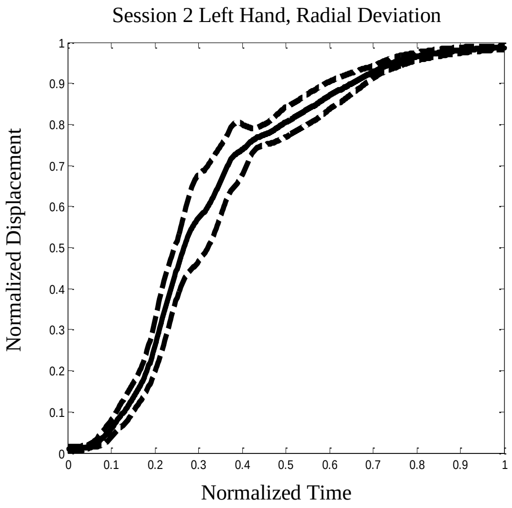
Session 2 Left Hand, Radial Deviation

Figure 3. Illustration of the variability envelope for radial deviation in the left hand, on the second day. The line in the middle is the mean, and the dashed lines represent the upper and lower bounds of the envelope.

Figure 3 provides a visual example of the measure of variability.

III. RESULTS

The subject was able to successfully complete 10 sessions of robot assisted training as predicted by the hypothesis. While evaluation trials were completed for all movements with the left upper limb this was not the case for the right. The participant was unable to perform forearm supination/pronation on the right side using the active-constraint mode of the Rice-Wrist device due to severe weakness. Hence, no evaluation trails were completed for these movement directions and training was only operated in the assistive mode.

In order to compare movement quality before and after training, evaluation data from sessions 2 (pre) and 10 (post) were used for comparison. This was primarily due to the participant’s inability to adhere to instructions during the first session. In case of the right hand radial/ulnar deviation, the subject was not able to complete the required number of target hits during sessions 1 and 2, and session 3 was used instead.

Comparison of Tj_V values before treatment with that of the healthy indicated that there was very little difference between the two for forearm and wrist movements (Table 1). As indicated in Table 1, Tj_V values made very little change with treatment. These findings were consistent for the right and the left upper limb movements.

T_A values are presented in Table 2. As it can be seen in this table there was a great difference between performance of the SCI participant and the healthy, where in some cases values were twice or three times longer than that for the right and left upper limbs of the SCI participant. Despite such differences improvements were observed for the left upper limb only where improvements approached that of the healthy and exceeded those values in some cases. Minimal changes were observed for the right upper limb.

The variability values of T_A were very similar to that of the healthy before training and showed no great levels gains or losses over the course of the training. Although Table 3 does reflect very little improvement between pre and post-treatment, this gain is very small given the similarity of values to that of the healthy.

TABLE 1. VARIABILITY ENVELOPE AREA

Variability Envelope Area	**Pre-Training**		**Post-Training**		
	Right	***Left***	***Right***	***Left***	***Healthy***
Forearm Supination	N/A	0.045	N/A	0.124	0.113
Forearm Pronation	N/A	0.061	N/A	0.101	0.089
Wrist Flexion	0.103	0.134	0.099	0.195	0.127
Wrist Extension	0.123	0.134	0.147	0.084	0.096
Wrist Radial Deviation	0.090	0.067	0.064	0.107	0.127
Wrist Ulnar Deviation	0.097	0.051	0.119	0.101	0.070

TABLE 2. TIME TO COMPLETION

Time to Completion (s)	**Pre-Training**		**Post-Training**		
	Right	***Left***	***Right***	***Left***	***Healthy***
Forearm Supination	N/A	4.87	N/A	2.904	2.322
Forearm Pronation	N/A	2.924	N/A	2.49	1.982
Wrist Flexion	6.132	3.66	5.084	1.724	1.462
Wrist Extension	4.042	3.474	6.054	1.482	1.408
Wrist Radial Deviation	7.93	2.98	10.37	2.182	1.592
Wrist Ulnar Deviation	5.22	2.476	5.606	1.48	1.504

TABLE 3. STANDARD DEVIATION OF COMPLETION

Standard Deviation of Time to Completion	**Pre-Training**		**Post-Training**		
	Right	***Left***	***Right***	***Left***	***Healthy***
Forearm Supination	N/A	0.480	N/A	0.240	0.554
Forearm Pronation	N/A	0.408	N/A	0.379	0.439
Wrist Flexion	1.567	0.363	1.164	0.436	0.197
Wrist Extension	0.252	0.417	0.888	0.185	0.169
Wrist Radial Deviation	1.598	0.228	2.133	0.146	0.255
Wrist Ulnar Deviation	2.260	0.164	0.474	0.118	0.205

IV. DISCUSSION

In the present study, average time in completing each target hitting task (T_A) and Trajectory variability (Tj_V) represented temporal and spatial aspects of the movement performed with the RiceWrist robotic device. Comparison of these values for the SCI participant to that of the healthy before training, indicated that while Tj_V values were very similar, this was not the case for T_A values where the SCI participant completed each task in a longer duration (in some cases twice as long) than his healthy counterpart. Thus, lack of improvements in Tj_V values and greater improvements in T_A after robotic training were warranted and in line with previous findings of similar trajectories but slower movements during simple pointing tasks for C6 tetreplegic patients compared to the healty [21]. Kinematic analysis of upper limb movements in tetraplegic SCI patients, suggest that compensatory activation of muscles that are not normally involved in performance (e.g. abnormal activity of antagonist muscles) of a task accounts for their ability to maintain movement trajectories or to accomplishe spatial goals of the movement [21, 22]. However it appears that these compensatory mechanisms or the muscle weakness itself hinder temporal aspects of the movement performance. In addition, discrete spatial and temporal mechanisms of movement control explain improvements or deficits in one aspect and not the other [23].

In the present study the temporal progress observed for the SCI participant who completed 10 sessions of robot-assisted therapy, was limited to the left limb (Table 1), where T_A values decreased to a great extent and reached that of the healthy participant. The reductions in movement time on the left side, was accompanied with a temproal variability that was similar to that of the healthy, or improved to their level (Table 3), suggesting acquisition of the skill for this aspect of the movement [24]. Given the greater weakness of the right limb, it is possible that more or longer trainings were required to help the parcipant gain better progress. Furthermore it is possible that robotic training alone is not sufficient for severe levels of weakness and needs to be supplemented with other forms of treatment (e.g. functional electrical stimulation).

Overall current results indicate that robotic devices can serve for upper-limb training and assessment of patients who have suffered SCI. Robotic measures can help therapists determine spatial and temporal aspects of the movement and help them adjust their treatment plans to address deficiencies for all aspects of the movement.

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