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Robotic Training and Kinematic Analysis of Arm and Hand after Incomplete Spinal Cord Injury: A Case Study.

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Abstract—**Regaining upper extremity function is the primary concern of persons with tetraplegia caused by spinal cord injury (SCI). Robotic rehabilitation has been inadequately tested and underutilized in rehabilitation of the upper extremity in the SCI population. Given the acceptance of robotic training in stroke rehabilitation and SCI gait training, coupled with recent evidence that the spinal cord, like the brain, demonstrates plasticity that can be catalyzed by repetitive movement training such as that available with robotic devices, it is probable that robotic upper-extremity training of persons with SCI could be clinically beneficial. The primary goal of this pilot study was to test the feasibility of using a novel robotic device for the upper extremity (RiceWrist) and to evaluate robotic rehabilitation using the RiceWrist in a tetraplegic person with incomplete SCI. A 24-year-old male with incomplete SCI participated in 10 sessions of robot-assisted therapy involving intensive upper limb training. The subject successfully completed all training sessions and showed improvements in movement smoothness, as well as in the hand function. Results from this study provide valuable information for further developments of robotic devices for upper limb rehabilitation in persons with SCI.**

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

I. INTRODUCTION

According to the national spinal cord Injury statistical center, the annual incidence of spinal cord injury (SCI), not including those who die at the scene of injury, is approximately 12000 new cases each year. Furthermore according to this source incomplete tetraplegia which is caused by spinal cord injury at the cervical level has been the most frequent neurologic category in the U.S.A. since the year 2000. Weakness of the upper and lower limbs, loss of bladder and bowl control and sexual dysfunction are the primary impairments for individuals with incomplete teraplegia, yet loss of the upper limb function is considered the most significant impairment [1], and as the main factor that could improve quality of life [2]. Given that arm and hand function has a great impact on the level of independence in most daily living activities such as self care, and social and work related tasks [3], increase in arm and hand function can lead to increase in independence, engagement in social activities, decrease in caregiver burden, and can therefore impact the overall health related quality of life for this population.

It is believed that small improvements in hand function in patients with incomplete tetraplegia contribute substantially to their ability to use their hands [4, 5]. Despite the evidence that repetitive practice can result in upper limb improvement in this population [6] and that it can induce practice-dependent brain and spinal plasticity [7, 8] the majority of current research has been on improving leg strength and retraining gait after SCI. Robotic devices can serve those with SCI for rehabilitation purposes and help therapists deliver repeated practice in a more efficient and effective way. Robitc devices could potentially automate labor-intensive therapy procedures and lower therapy costs. Additional potential advantages of robotics include bringing therapy to new venues including the home, new sensing capabilities for monitoring progress, and increased therapy efficiency with the possibility of group therapy.

A significant research effort has been the design of novel therapeutic robots or devices for stroke rehabilitation. Early examples of these robots include the MIT-MANUS [9] and MIME [10, 11], both of which were designed for rehabilitation of the proximal upper extremity joints (shoulder and elbow). Robotic devices for rehabilitation of distal joints of the upper extremity have also been developed, such as the MAHI

Exoskeleton [12], the wrist module of the MIT-MANUS [13, 14] and wrist devices developed by Anderson et al [4]. To our knowledge no study has been carried out to measure the feasibility of robotic training of hand function in SCI. A review of the current literature revealed no publication on robotic training of the upper extremities after SCI. This is in contrast to a growing literature on robotic upper-extremity training in stroke rehabilitation [15-17]. The current study is a novel first attempt to use robotic upper-extremity training for SCI patients.

The goal of this study was to demonstrate that it is effective and safe for a person with tetraplegia caused by incomplete SCI to use robotic training to gain better control of his arms and hands. We hypothesized that this individual could successfully complete 10 sessions of robot assisted training using the RiceWrist robotic device and that he could gain better control of his arms and hands indicated by robotic measure of smoothness after completing the training. Findings can help encourage further administrations of robotic devices for SCI patients with different levels of injury and disability.

II. METHODS

A. 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 training over 2 weeks. Minimum voluntary movements were preserved on the right upper extremity whereas on the left side he had moderate level of voluntary movement. The subject signed consent form approved by the Institutional Review Boards of all affiliated institutions.

B. Apparatus

RiceWrist an electrically actuated upper-extremity and wrist haptic (force feedback) exoskeleton device, was designed for rehabilitation applications in the Mechatronics and Haptic Interfaces laboratory at Rice University (Fig. 1). The device design extends from prior work, details of which can be found in [12]. The unique kinematic design of the RiceWrist allows for reproduction of most of the natural human wrist and forearm workspace. 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 control feedback to a specific human joint, for example to constrain the forearm rotation during wrist rehabilitation, without affecting other joints. The RiceWrist has three therapeutic modes, which enable treatment to be tailored to persons' abilities: passive, active-constraint, and triggered modes. In the passive mode, movement is provided by the robot and the subject is passive; in the active-constraint mode the RiceWrist opposes the subject's movement by adding a degree of force throughout the entire movement. With constraint set to zero the subject can move freely with no resistance or assistance from the robot. In the triggered mode the RiceWrist facilitates movement once the subject overcomes a pre-determined threshold. For the purpose of this study, the active-constraint mode-with zero constraint- was used for evaluation. All three modes were incorporated into the training protocol.

C. Procedure

Robotic training was provided with the RiceWrist for three hours per day on 10 consecutive weekdays for the right and left upper limbs. Each session included robotic evaluations followed by training practices. During each session the subject was seated behind a low table, centered in front of a computer monitor and placed his hand inside the robotic device holding the cylindrical end of the device. A bandage was used to wrap the subject's hand due to his inability to maintain his grasp throughout the training (Fig.1). During the first session, evaluation and training trials were completed for the left hand (stronger hand) followed by the opposite hand. This order alternated at each successive session.

The evaluation trial involved a series of target hitting tasks through a visual display carried out by flexion/extension, radial/ulnar deviation or forearm supination/pronation. The visual display included a center target, located between two other targets (Fig. 2) all 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 based on the subject's maximum range of motion that was captured with the RiceWrist while the subject moved to the maximum range in each plane of movement. During evaluation, targets became highlighted one at a time. The subject moved the circular cursor to the highlighted target and returned to the center before the next target was highlighted. Movements from the center target to the highlighted target were considered a hit. The subject performed 20 target hits for each plane of movement in the active-constraint mode with zero constraint during evaluations.

Training followed evaluation and involved target hitting and distortion tasks each tailored individually based on the subject's movement capabilities. The target-hitting task was the same the evaluation with the exception that all three

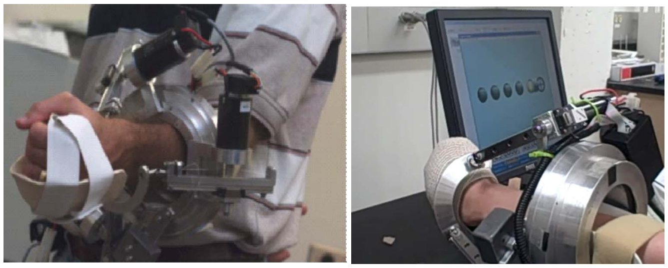
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Figure 1. (A) RiceWrist modeled on a healthy individual (B) The left hand of the participating subject with spinal cord injury wrapped in RiceWrist, during training.

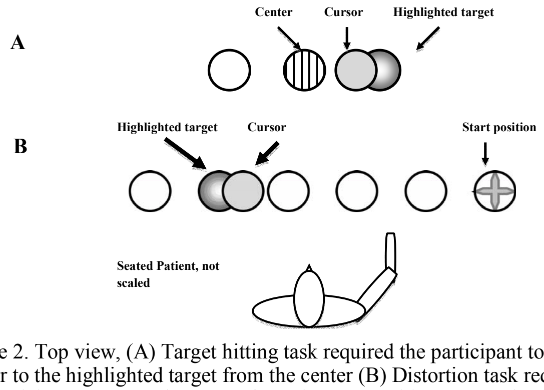

Figure 2. Top view, (A) Target hitting task required the participant to move cursor to the highlighted target from the center (B) Distortion task required the participant to move the cursor from the start position. For each task the participant was provided with visual display similar to that in the figure.

operating modes (passive, active-constraint and triggered) and more repetitions were administered. In addition the number of repetitions and speed of movement were given to the subject 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. The distortion task was administered at later training sessions to enhance use of the somatosensory feedback [18]. The visual display of the distortion task involved 5 targets aligned horizontally for wrist flexion-extension, forearm supination-pronation, and vertically for radial-ulnar deviation (see Fig. 2). Targets were equally spaced across 44-80% of the subject's maximum range of motion. The training was divided into blocks of visible and invisible cursor conditions where each target was randomly highlighted twice during each condition. For the visible condition the subject 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 subject 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% increase in the ROM distributed equally across target distances without the subject's knowledge (distortion). The number of completed blocks gradually increased across practice sessions to challenge the subject throughout training. The subject was given sufficient breaks throughout each training sessions. No other therapeutic interventions for upper limbs were provided during the study period.

D. Measure of interest

Angular position data were collected at 100 Hz for all evaluation trials. The smoothness factor (F_s) was selected as the primary measures of interest. This measure is a modified form of a more commonly used smoothness metric, the correlation coefficient (rho) [15, 19], which describes the correlation between the subject's velocity profile and the corresponding minimum jerk velocity profile. The minimum jerk profile is a function of the actual distance travelled by the subject's hand between two target hits, as well as the total time of that motion, and represents the velocity profile of an ideally-smooth movement over the specified distance in the specified amount of time. The minimum jerk speed profile was calculated by (1)

$$v_{mj}(t) = \Delta \quad \frac{30t^4}{T^5} - \frac{60t^3}{T^4} + \frac{30t^2}{T^3} \qquad (1)$$

where t is time, Δ is the movement distance and T is the time elapsed between two target hits. Subject's speed profiles were time shifted to match the initiation of the actual and the minimum jerk profile. Similar to previous work the amount of this shift was based on the temporal distance between the previous target hit instance and the minimum value in the first half of the actual speed profile [19].

The rho (ρ) value was calculated by (2)

$$\rho = \frac{\left(V_{subj} - \bar{V}_{subj}\right)\left(V_{mj} - \bar{V}_{mj}\right)}{\sqrt{\left(V_{subj} - \bar{V}_{subj}\right)^2 \quad \left(V_{mj} - \bar{V}_{mj}\right)^2}} \qquad (2)$$

where V_{subj} is the movement speed of the subject, $\overline{V}_{\text{subj}}$ is the mean movement speed of the subject, V_{mj} is the minimum jerk speed profile, $\overline{V}_{mj}$ *i*s the mean minimum jerk speed, following the formulation given in [19].

The smoothness factor is the product of rho and the coefficient of determination (r^2) between the subject's velocity profile and a fourth-order best-fit curve all of which were calculated by MATLAB. Thus, the smoothness factor reflects not only how similar the subject's velocity profile is to the minimum jerk profile, but also how closely it can be represented by a general fourth-order, bell-shaped curve. A smoothness factor of 1 indicates a perfect correlation to the minimum jerk profile. During data processing, negative F_S values occasionally calculated for individual movements, which implied negative correlation, were set to zero. For the given data set, the smoothness factor offers more insight into the shape of the subject's velocity profile than rho alone can provide.

Jebsen Taylor Hand Function Test (JT) which is a measure of function rather than movement was selected as the clinical measure of interest. This test has been used extensively and successfully in the spinal cord injury populations [6] and includes various functional tasks such as turning cards, feeding using a teaspoon, lifting small, large and heavy objects and stacking cards. These tasks are designed to mimic functions used during activities of daily living. The time to complete each task is recorded and compared. A physical therapist administered JT before and after the training to assess functional improvements in upper limbs. For a detailed description of JT administration and other clinical assessments performed for the participant of this study refer to [20].

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 participating individual was unable to voluntarily perform forearm supination and pronation with the right limb due to severe weakness. Hence, no evaluation trails were completed for these movement directions (Table 1) and training was only operated in the assistive mode. For the same reason the subject was unable to perform several tasks of the JT assessment test with the right upper limb during initial assessments that took place before training.

TABLE 1. AVERAGE SMOOTHENSS FACTOR VALUES BEFORE AND AFTER TRAINING [a]

Average Smoothness Factor (F_s)	**Pre-training**		**Post-training**	
	Right	***Left***	***Right***	***Left***
Forearm supination	n/a	0.26	n/a	0.56
Forearm pronation	n/a	0.17	n/a	0.46
Wrist flexion	0.00	0.01	0.03	0.30
Wrist extension	0.10	0.10	0.09	0.58
Wrist radial deviation	0.00	0.44	0.07	0.48
Wrist ulnar deviation	0.00	0.06	0.00	0.26

a. Increased values indicated improvement in performance. n/a: subject could not perform the task; Pre: before training; Post: after training.

TABLE 2. JEBSEN TALOR HAND FUNCTION TEST BEFORE AND AFTER TRAINING [a]

Subtest	**Pre-training**		**Post-training**	
	Right	***Left***	***Right***	***Left***
Simulated page turning (5 cards)	n/a	11.82	150(5)	7.09
Lifting small common objects (2 paper clips, bottle cap, pennies, cup)	n/a	20.88	180(2)	20.44
Simulated feeding (5 kidney beans)	n/a	17.53	n/a	15.25
Stacking checkers (4 checkers)	n/a	44.13	180(2)	20.03
Lifting large light objects (5 cans)	n/a	6.87	n/a	5.87
Lifting large heavy objects (5 cans)	180(2)	6.85	180(4)	6.28

a. Test was ended at 180 sec.; Number in () represents completed items; n/a: subject could not perform the task; Pre: before training; Post: after training. Decreased time indicated improvement in performance.

In order to compare movement smoothness before and after training, evaluation data from sessions 2 and 10 were used for comparison. Data collected in the first training session were discarded due to the subject's unfamiliarity with the task and his inability to adhere to the provided instructions during this session. As presented in Table 1 comparison of average F_S values for the left upper limb before and after training indicated a considerable increase for the all movements. The smallest improvement in F_S was observed for the wrist radial deviation. Changes in movement smoothness were accompanied by a great progress in the subject's ability to perform JT assessment test with the left upper limb (Table 2). Figure 3 shows the subject's

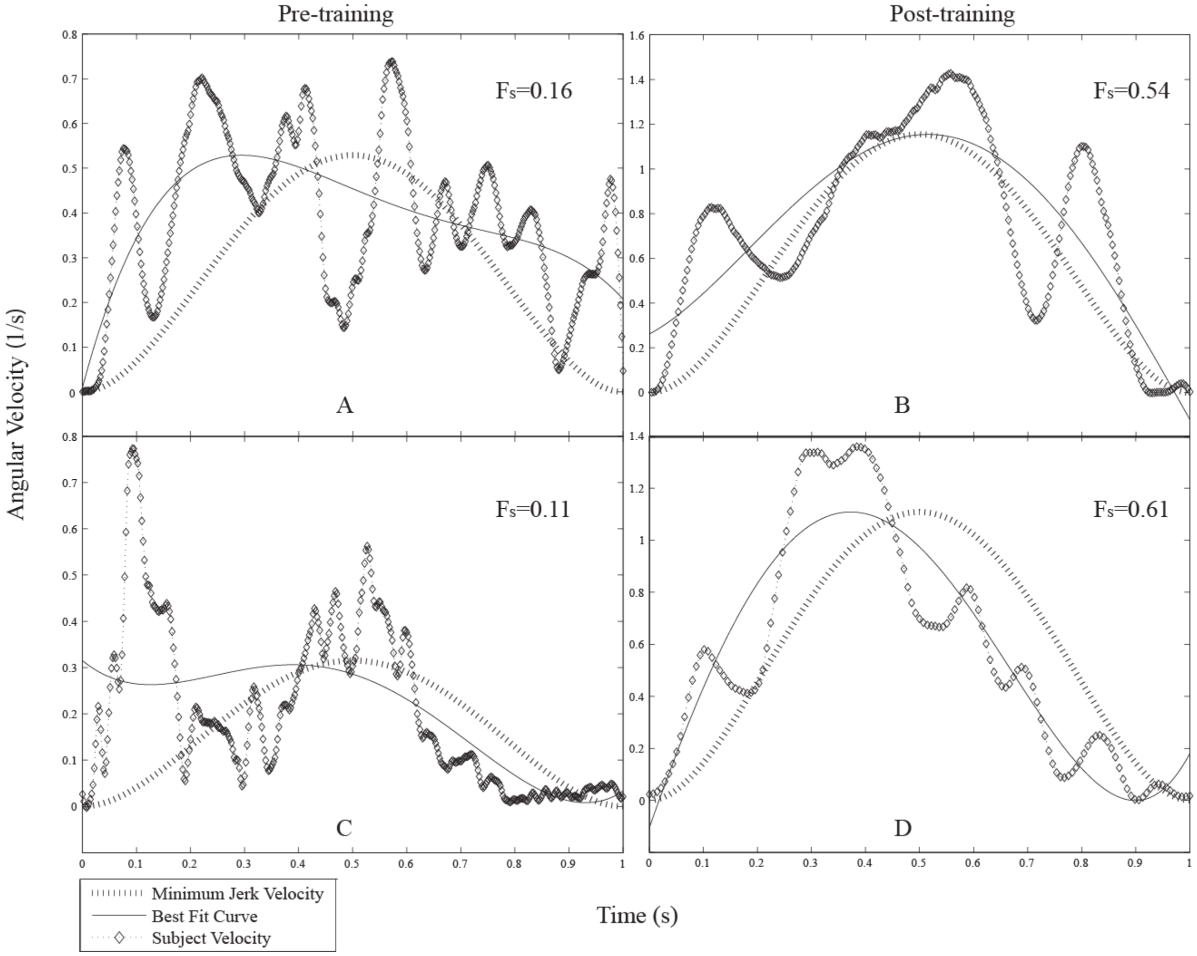

Figure 3. Angular velocity profiles of a single target hit for forearm pronation (A,B) and wrist extension (C,D) before (left panel-A,C) and after (right panel-B,D) robotic training for the left upper limb. Corresponding smoothness factor values (F_s), minimum jerk velocity profiles and the best fit curves are also presented. Pre: before training; post: after training; F_s: smoothness factor.

angular velocity profile during a single target hit for the left upper limb for forearm pronation and wrist extension with the corresponding F_S values. A sample of angular velocity for radial deviation is presented in Figure 4.

Training resulted in smaller changes in F_S for the wrist movements performed with the right upper limb when compared to the left. Improvements were observed in the subject's performance of JT for the right limb (Table 2).

Overall, results indicated that while robot assisted therapy was beneficial for regaining upper limb function for the SCI patient; the level of impairment impacted the degree of motor progress.

IV. DISCUSSION

The smoothness factor provides a value that is sensitive to movement fluctuations from an ideally-smooth profile. While healthy individuals demonstrate an optimally smooth speed profiles for unconstrained wrist [21] and for forearm [22] movements, persons with spinal cord injury exhibit highly intermittent movements [23]. The underlying mechanisms for movement intermittency are not clear. It has been suggested that disrupted commands from the central nervous system affect voluntary movements due to abnormal muscle recruitment, weakness and spasticity [24, 25]. Hence it is reasonable to assume that improvements indicated by the F_S represent enhanced motor control abilities.

In the present study the SCI patient who completed 10 sessions of robot-assisted therapy made considerable motor progress in his left upper limb evident by the gains in the movement smoothness for the wrist and forearm (Table 1) and functional improvements indicated by the JT assessment tool (Table 2). This did not hold true for the right upper limb that had minimum movement capabilities when compared to the left prior to training (see JT results in Table 2). The smaller improvements in movement smoothness for the right upper limb after training indicate that the current protocol is more effective for moderate levels of disability. Given that the recommended rehabilitation period for a SCI tetraplegic patient is greater than 3 weeks [26] and that refining the movement occurs at later stages of skill learning (after a certain level of success in completing the task is achieved) [27] we suggest longer or more intensive trainings when working with severely impaired upper limb/s in persons with SCI.

Several mechanisms of recovery can explain sensori-motor improvements after incomplete SCI. These mechanisms emphasize on the plasticity of the central nervous system and include; reorganization of remaining circuits and formation of new circuits at cortical and sub-cortical regions and in the spinal cord below the lesion [28]. These forms of recovery can continue several years after injury but are more evident during the first 9 months post SCI [29]. Spontaneous recovery cannot be ruled out in case of our participant who was only 6 months post injury. However given the evidence of enhancements in plasticity with massed practice [7] the positive role of the administered robotic training cannot be ignored.

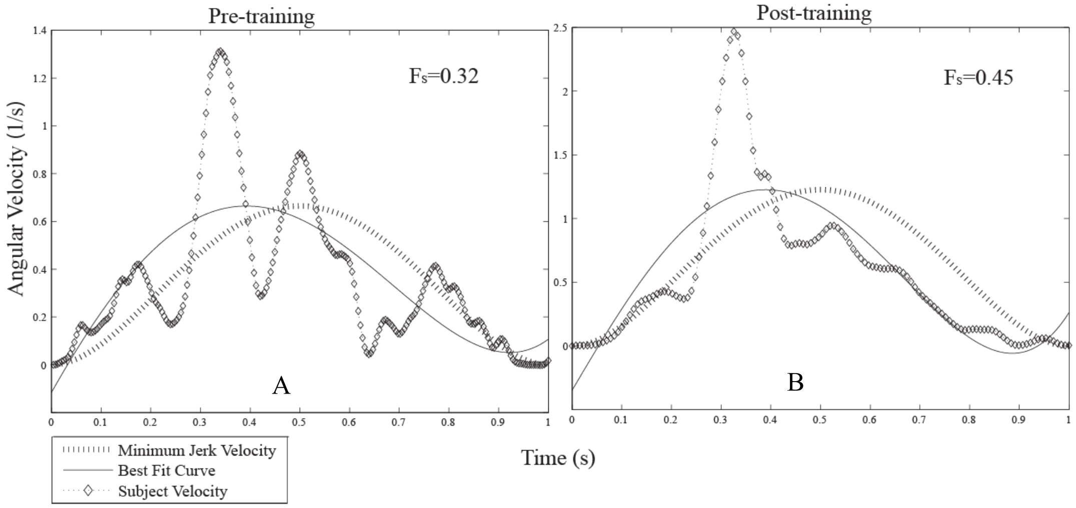

Figure 4. Angular velocity profiles of a single target hit for wrist radial deviation before (left panel-A) and after (right panel-B) robotic training for the left upper limb. Corresponding smoothness factor values (F_S), minimum jerk velocity profiles and the best fit curves are also presented. Pre: before training; post: after training; F_s: smoothness factor

Overall current results indicate that robotic devices can potentially play a critical role in the motor recovery of upper limbs for individuals with SCI. In addition robotic devices can serve as assessment tools that can generate valuable measures that quantify upper limb movement. These robotic measures can help therapists customize therapeutic strategies and can further enhance development of successful upper limb interventions.

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