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

D.P. Eng
Dept of Mechanical Engineering and Materials Science
Houston, USA
dpe1@rice.edu

Dept of Mechanical Engineering and Materials Science
Houston, USA

Z. Kadivar
Dept of PM&R, Baylor College of Medicine
Houston, USA

G.E. Francisco, N.Yozbatiran
Dept of PM&R, University of Texas Medical School
Houston, USA

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 bowel 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.

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 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 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 cursor 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
came 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 extremities 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 (T_jv):** 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
tnorm, [0,1], as follows:

$$\text{var} = \int_0^1 m_{\text{upper}} dt - \int_0^1 m_{\text{lower}} dt$$
This was primarily due to the difference between performance of the subject with treatment 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.

### 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 trials 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 $T_{J_V}$ 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, $T_{J_V}$ 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.

### IV. DISCUSSION

In the present study, average time in completing each target hitting task ($T_{A}$) and Trajectory variability ($T_{J_V}$) 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 $T_{J_V}$ 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 $T_{J_V}$ values and greater improvements in $T_{A}$ after robotic training were warranted and in line with previous findings of similar trajectories but slower

![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.](image-url)
movements during simple pointing tasks for C6 tetraplegic patients compared to the healthy [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 accomplish 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 temporal 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 participant 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.

ACKNOWLEDGMENT

We acknowledge the generous support of Mission Connect, A Project of TIRR foundation.


