Measuring Torque Production with a Robotic Exoskeleton during Cervical Transcutaneous Spinal Stimulation

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***Abstract*— Spinal cord injury (SCI) affects a large number of individuals in the United States. Unfortunately, traditional neurorehabilitation therapy leaves out this clinical population with limited motor function, as they are incapable of engaging in movement therapy. To increase the numbers of individuals who may be able to participate in robotic therapy, our long-term goal is to combine two validated interventions, transcutaneous spinal stimulation (TSS) and robotics, to elicit upper limb movements during rehabilitation following SCI. To achieve this goal, it is necessary to quantify the contributions of each intervention to realizing arm movements. Electromyography is typically used to assess the response to TSS, but the robot itself offers an additional source of data since the available sensors on the robot can be used to directly assess resultant actions of the upper limb after stimulation. We explore this approach in this paper. We showed that the effects of cutaneous TSS can be observed by measuring the holding torque required by the exoskeleton to keep a user's arm in a neutral position. Further, we can identify differences in resultant action based on the location of the stimulation electrodes with respect to the dorsal roots of the spinal cord. In the future, we can use measurements from the robot to guide the action of the robot and TSS intervention.**

I. INTRODUCTION

There are roughly 300,000 individuals living with spinal cord injury (SCI) in the United States, with as many as 17,810 new diagnosed cases each year. In almost 60% of SCI cases, the cervical spine is affected [1], and ensuing paralysis of the hand and arm imposes significant limitations in most activities of daily living, affecting overall quality of life. In these individuals, restoration of hand and arm function is reported as being the highest treatment priority [2]. As a result, therapeutic interventions directed at recovery of upper limb function are a significant focus of post-SCI motor rehabilitation [3], and robotic rehabilitation, which can provide intensive therapy, is increasing in use [4], [5], [6]. Despite the promise of motor recovery with robotic rehabilitation, movement therapy may not be effective for users who have minimum motor function, since there is limited substrate upon which to build neuromotor improvement [7], [8].

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Transcutaneous spinal stimulation (TSS) is a non-invasive neuromodulation approach that has emerged as a viable rehabilitation intervention for people with paralysis due to spinal cord injury (SCI) [9]. TSS has been used for rehabilitation [10], [11], [12], [13] and has been demonstrated to be a safe method that allows one to selectively stimulate dorsal nerve roots of the spinal cord [14], [15], [16]. TSS is an attractive alternative therapeutic intervention for individuals for whom surgical implantation of epidural stimulators is infeasible. Despite this, our understanding of the therapeutic potential of TSS is still rudimentary. For instance, one of the more recent studies to demonstrate the positive effects of TSS in individuals with SCI focused primarily on strength and control of grip forces [11], while the neuromodulatory effects during other upper limb movements, including elbow and wrist flexion and extension, remain unexplored.

To use TSS in a rehabilitative or assistive scenario, it is important to quantitatively characterize the effect of neuromodulation on the joints of interest. Two ways to accomplish this include characterizing the muscle activity in response to stimulation, or characterizing resultant joint-level movement or torque directly. Electromyography (EMG) is used to evaluate the muscular effects from TSS [9], [15] by measuring the electrical activity in muscle that results in response to the nerve stimulation. EMG provides an indirect means to estimate motor torque, since researchers must rely on muscle models to compute resultant force or torque at a joint-level from the electrical activation potentials. Alternatively, torque outputs or joint movements can be measured directly using a robotic exoskeleton fitted to the arm while administering TSS. Both of these methods provide useful input in creating models of TSS, and so it would be ideal to combine these techniques to give a more complete characterization of the effects of TSS on muscle and limb action.

We propose this additional approach to quantifying the resultant action of neuromodulation, which uses an upper limb robotic exoskeleton as a measurement device to assess the effects of cervical level TSS on upper limb movements. Our long term goals are to merge the therapeutic effects of upper limb robotic exoskeleton movement assistance and spinal neuromodulation technologies within a single protocol, influenced by other combined neurorehabilitation interventions [17], [18], and to elucidate the underlying neuromodulatory effects of cervical TSS. As a first step towards these goals, this paper presents an exploratory study of the potential to use a robotic exoskeleton as a measurement tool for evaluating the effect of cervical TSS on upper limb muscle

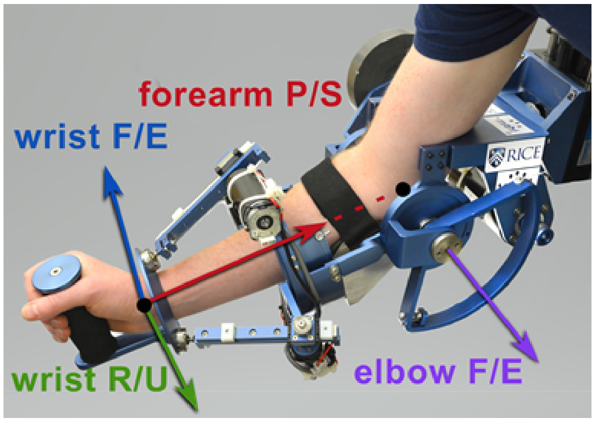

Fig. 1. The MAHI Exo-II robot provides measurement of the activity of the upper limb in response to TSS. The robot supports elbow flexion and extension (F/E), forearm pronation and supination (P/S), wrist F/E, and wrist radiul/ulnar (R/U) deviation.

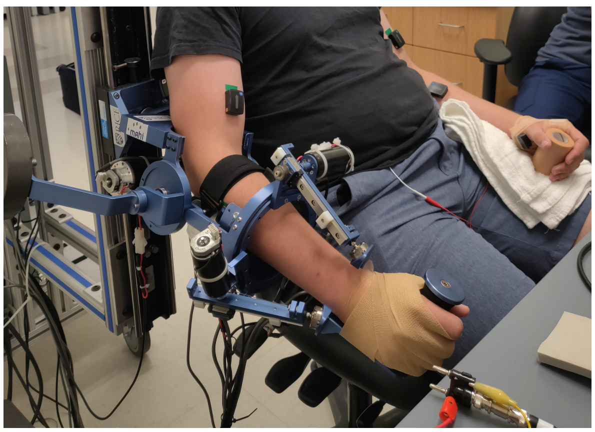

Fig. 2. The subject is seated with their right arm in the MAHI Exo-II, with the forearm and hand secured to the robot with compliant strapping.

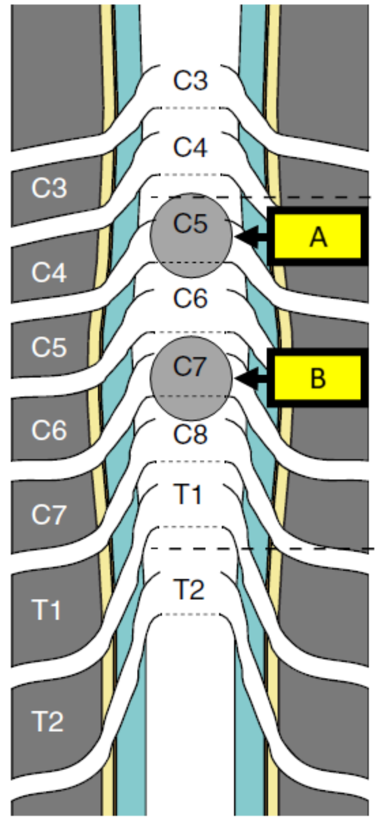

Fig. 3. Two surface electrodes are positioned on the back of the subject's neck, with electrode A located over the C4/C5 vertebrae, and electrode B located over the C6/C7 vertebrae.

torque production. Specifically, we examine the difference in relative torque responses for two different stimulation locations on the spinal cord.

II. METHODS

We used a robotic exoskeleton to measure torque production following stimulation of the cervical spinal cord at two different electrode locations.

A. Participants

Four healthy subjects (3 male, avg age 25) participated in the study, providing informed consent. None of the subjects had any impairments that would have restricted the safe use of TSS during the experiment. The study was approved by the institutional review board(s) of Rice University (IRB-FY2021-326) and Houston Methodist Hospital.

B. Robotic rehabilitation hardware

The MAHI Exo-II, shown in Fig. 1, is an exoskeleton robot with four active degrees of freedom, elbow flexion-extension (F/E), forearm pronation-supination (P/S), wrist F/E, and wrist radial-ulnar (R/U) deviation, designed to provide rehabilitation to the upper limb [4]. Encoders on each of the robot joints provide accurate measurements of robot configuration, and joint torque measurements are based on knowledge of the commanded torque to each joint.

C. Transcutaneous spinal stimulation

Previous pilot studies have determined that locations on the midline of the cervical spine, indicated as points A and B in Fig. 3, are suitable for stimulation of the spinal cord due to their location relative to the dorsal roots, and their connections to the upper limb motor pools [14]. As was shown in our previous work [14] and anatomical maps of the spinal cord, Electrode A (corresponding to C4-C5 vertebra) preferentially activates motor pools projecting to proximal upper limb muscles, whereas Electrode B (corresponding to C6-C7) activates motor pools preferentially projecting to distal muscles.

D. Experimental protocol

Subjects were seated in a chair with the MAHI Exo-II positioned at their right side, as depicted in Fig. 2. Wireless Trigno Avanti EMG electrodes (Delsys Inc., USA) were placed on six muscles on each arm (biceps brachii, triceps brachii, flexor carpi radialis, extensor carpi radialis, first dorsal interosseous, and abductor pollicis brevis). For this experiment, EMG data were not quantified but data were collected for later analysis and comparison. The subject's arm was then inserted into the MAHI Exo-II robot, and their forearm and hand were strapped to the robot handle to ensure that the limb joints were properly aligned with the joints of the robot, and to limit compensatory motions. A test stimulation at 500 microseconds was sent at 10 mA to ensure the electrodes were properly configured in the stimulation setup. The recording of onset of stimulation was captured by the MAHI Exo-II by connecting an analog output from the TSS stimulator to an analog input of the robot's data acquisition device. When the stimulator was commanded to send a pulse, a 10 V analog signal was sent for a period of 10 ms, and the value of this signal was recorded along with other relevant data for post-processing.

For each electrode that was tested, the robot was moved to a neutral configuration and the subject was asked to remain relaxed. Stimulation was first provided starting at 30 mA, a low amplitude that did not induce any movement of the limb. Stimulation was then increased at 10 mA increments. Three repetitions of stimulation were provided at each amplitude at an interval of 5 seconds apart. Throughout this process, the robot was commanded to hold the limb in the neutral configuration using a PD controller acting on each joint of the robot, and the torque required to hold that configuration was recorded as an indirect measure of the resultant torque induced by stimulation. The stimulation was increased until further stimulation would have caused discomfort for the subject. To determine this limit, after each stimulation intensity, subjects were instructed to verbally indicate when they had reached their maximum tolerable intensity. The minimum stimulation current used in the experiment was 30 mA, and the maximum ranged from 90 to 120 mA, depending on the electrode location and the subject's level of comfort during the experiment.

E. Data analysis

Signals representing joint-specific position, velocity, and torque required by the robot to hold the subject in a static neutral configuration were continuously sampled at a rate of 2000 Hz. Data were parsed to isolate each stimulation event and analyzed individually, with buffers before and after stimulation to account for the time course of movement to occur. Peak to peak torque values were collected for each stimulation amplitude by subtracting the minimum torque output from the maximum torque output over each window of data, and these values were averaged for the three stimulation trials at each amplitude level. Between the electrodes, for each subject and for each joint of the robot, the torque values were normalized between 0 and 1 based on the maximum peak to peak torque for that specific joint, to allow for comparison across subjects. The normalized torques for each subject at each joint in response to stimulation at each electrode location were then plotted versus stimulation amplitudes. Due to the low number of subjects, no statistical analysis was carried out.

III. RESULTS

We were able to quantify the required torque output of the robot to hold the limb in a neutral position during stimulation. The averaged torque responses for discrete stimulation amplitudes are shown for two electrode locations in Fig. 4. Results show that the effect of TSS can be observed by measuring the holding torque of the robot. The torque increased as the stimulation level increased once a threshold of stimulation amplitude was overcome. The threshold amplitude varied depending on the joint of interest.

We observed a differential response in torque production based on the location-specific stimulation. Results show that most subjects responded close to their maximum normalized torque for elbow F/E when stimulated by electrode A, with three subjects presenting between 75-100% of the maximum torque (see Table I). In contrast, the average value of subject response to their maximum stimulation from electrode B for elbow F/E was below 30% of their maximum normalized torque. The forearm P/S maximum torques for both electrodes are fairly similar to each other. Stimulation of electrode A resulted in higher average maximum torque responses in wrist F/E compared to electrode B. The trends for the wrist R/U torque responses were fairly similar between the two electrodes, albeit the average maximum torque responses were slightly lower for electrode B.

IV. DISCUSSION

The primary goal of this study was to determine if we can quantitatively and objectively assess the effects of TSS of the cervical spinal cord on upper limb movements. To achieve this, we used an upper limb robotic exoskeleton to measure the torque produced in muscles as a result of stimulation. We showed that TSS induced muscle activation, which was observed by recording the torque required by the robot to hold the limb in the neutral position (see Fig. 4). Increasing the amplitude of stimulation resulted in increased holding torques. The minimum stimulation amplitude required to elicit holding torques varied across the degrees of freedom of the upper limb.

We also explored if there were any differences in joint-level torque outputs based on the locations of the two stimulated electrodes. Stimulation of Electrode A, located higher in the spinal cord than Electrode B (see Fig. 3), resulted in measurable holding torques for all joints at lower levels of stimulation than Electrode B. This is expected, since the location of Electrode A would, from anatomic descriptions of the spinal cord, be expected to generate responses of more motor pools. Stimulation of Electrode B resulted in generally lower maximum holding torques at each joint. The main difference between the two electrode locations lies with the proximal muscles stimulated, with prior literature suggesting that Electrode A is activating more proximal motor pools compared to Electrode B [14]. Therefore, the greater average maximum torque for elbow F/E in the case of stimulation of Electrode A indicates that we were able to use the robot to identify how the TSS electrode placement corresponds to the specificity of the motor pools being activated.

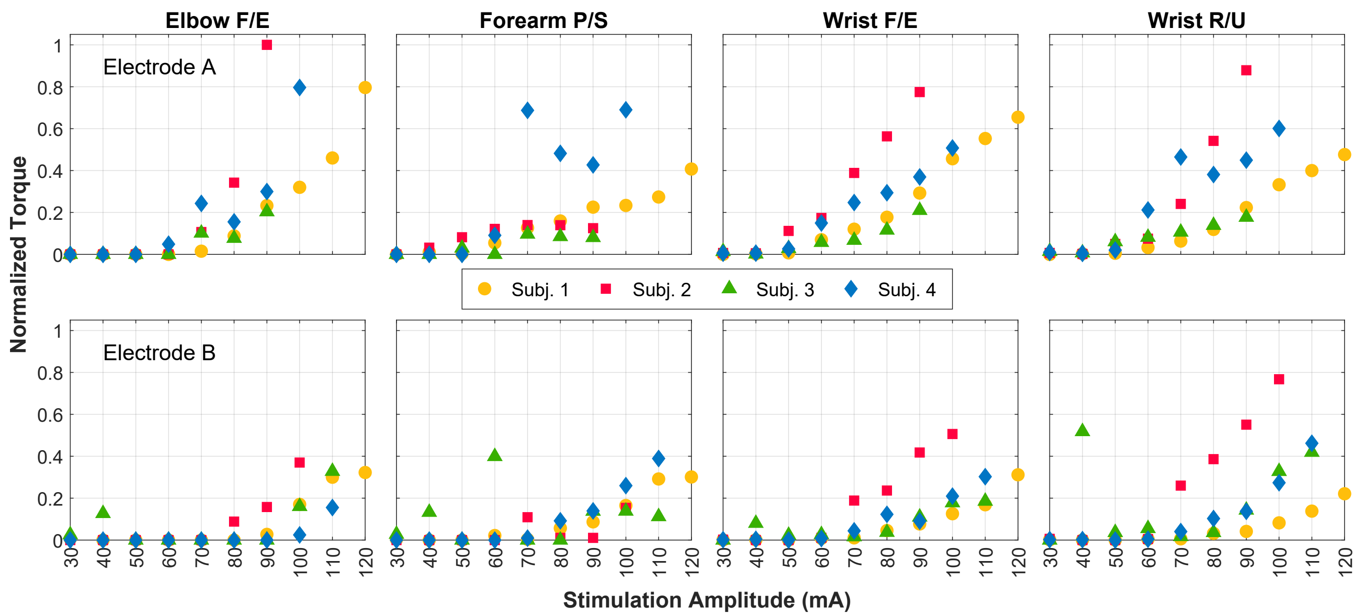

Fig. 4. Results represent normalized torque versus stimulation amplitude for each degree of freedom of robot motion. The top row represents the maximum peak to peak torque for each stimulation amplitude of Electrode A, while the bottom row represents Electrode B. Results for four subjects are shown.

TABLE I
MAXIMUM NORMALIZED TORQUE VALUES REALIZED AT EACH ROBOT JOINT

	Electrode A Elbow F/E	**Electrode B Elbow F/E**	**Electrode A Forearm P/S**	**Electrode B Forearm P/S**	**Electrode A Wrist F/E**	**Electrode B Wrist F/E**	**Electrode A Wrist R/U**	**Electrode B Wrist R/U**
Subject 1	0.796	0.323	0.407	0.301	0.656	0.312	0.476	0.221
Subject 2	1.000	0.370	0.140	0.154	0.775	0.506	0.879	0.767
Subject 3	0.203	0.328	0.097	0.138	0.210	0.186	0.177	0.419
Subject 4	0.796	0.155	0.690	0.389	0.508	0.303	0.601	0.462
Subject Avg.	0.699	0.294	0.334	0.246	0.537	0.327	0.533	0.467

We observed some variability in response to TSS across our small number of subjects. This variability could be attributed to subject tolerance of the cervical stimulation itself. It could also be due to limitations in our robot-based measurements, since in order to generate movement, the robot must overcome static friction. Other variability in participant responses could be attributed to the nature of the electrodes that we used, since TSS, which uses surface electrodes, is less precise in stimulation location compared to epidural electrical stimulation.

Our results show that upper limb robotic exoskeletons can be used as a data collection tool to quantify the outcomes of cervical TSS. Measurement of torque can complement existing methods that rely on measurement of muscle activation via EMG, which is more typically used in TSS. This is because the robotic measurement quantifies the relative resultant torque magnitude and direction at the joint-level resulting from the aggregate activation of several muscle groups. EMG measures the individual muscle response to neuromodulation, which provides insightful information about the combination of muscles involved in movement or torque output. Future approaches can use torque measurements in conjunction with EMG recordings to build a more complete model of the effects of TSS.

Our results show promise for further study on the use of upper limb robotic exoskeletons in combination with TSS. Future directions for our research include testing in various electrode locations and with patterned or sequential stimulation. Such efforts will allow us to more fully characterize the potential for TSS to generate movements across the full upper limb workspace, and enable us to quantify the degree of controllability and repeatability of cervical TSS as a therapeutic intervention for upper limb rehabilitation following SCI.

V. CONCLUSIONS

The cervical spine is impacted in a majority of SCI cases and the resultant upper limb paralysis greatly restricts patient ability to conduct activities of daily living. Both Transcutaneous Spinal Stimulation (TSS) at the cervical level and robotic rehabilitation using exoskeletons have been shown to be viable therapeutic interventions to restore upper limb function. The combination of these two techniques has the potential to reach a broader subject population. To use these devices in concert, it is necessary to be able to quantify the resultant action of TSS delivered to different locations of the cervical spine. An upper limb robotic exoskeleton was used to measure the response from cervical TSS. Peak to peak torque required to hold the four joints of the robot (elbow flexion/extension, forearm pronation/supination, wrist flexion/extension, and wrist radial/ulnar deviation) in a neutral position was compared for stimulations applied at two different electrode locations. Results showed that the robotic exoskeleton can indeed serve as a tool for objective and quantitative assessment of the effects of cervical TSS. We observed a proportional relationship between stimulation amplitude and holding torque. Further, we could identify differences in responses based on the location at which stimulation was applied. This initial validation of torque as a metric for evaluating TSS provides support for combining movement assistance from both TSS and a robotic exoskeleton into a single protocol for a theraputic intervention for individuals with SCI.

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