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Evaluation of volitional control of hand with vertical force assist device for high tetraplegia

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Abstract— **Individuals with high tetraplegia have lost motor and sensory function below the neck. This population is highly disabled and requires some method of assistance to accomplish activities of daily living. To date, rehabilitative interventions available in the clinic are limited and have not been designed to exploit residual volitional control. The goal of this study was to validate the presence of volitional control at the hand in individuals with high tetraplegia when the arm is supported against gravity with a vertical assist device. Any volitional control is pertinent to the development of rehabilitative interventions for high tetraplegia because it can be utilized to improve the overall performance and user acceptance of the device. The results from this study provide evidence toward the possibility of an individual with high tetraplegia being able to position their hand and generate forces volitionally in a functional workspace if the weight of their arm is supported by a vertical assist device.**

I. Introduction

Spinal cord injury causes paralysis and sensory loss below the level of injury. Individuals with high tetraplegia due to a high level cervical spinal cord injury have lost function below the head and neck. Fig. 1 provides an illustration of the extent of paralysis and denervation for individuals with this type of injury. The figure shows extensive paralysis of arm muscles for both C3 and C4 and denervation of key shoulder and elbow muscles at the C4 level.

Generally, individuals with high tetraplegia are young with a nearly normal life expectancy and no cognitive burden [1,2]. However, the inability to voluntarily control movement below the neck results in these individuals requiring some form of assistance in performing activities of daily living such as eating, personal hygiene, etc. Traditionally, this has been addressed with outside assistance from a professional throughout the day to accomplish activities of daily living [2].

Means of improving independence by restoring the individual's ability to accomplish functional tasks have been researched and developed, i.e. robotic assistive devices or functional electrical stimulation systems. Robotic assistive devices that have been developed include exoskeletons which guide the individual's limbs or as a "third limb" that manipulates the environment [3]. Functional electrical stimulation (FES) provides a means of controlling an individual's own anatomy that has been paralyzed. This technology is based on the electrical stimulation of the peripheral nerves innervating paralyzed muscles to elicit muscle contractions. The forces generated from the muscle contractions of paralyzed muscles in combination with any muscles still under volitional control can be coordinated to restore functional activity [4]. For those with high tetraplegia after a C1-C4 spinal cord injury, the entire upper extremity including the shoulder and elbow need to be controlled and stabilized in order to restore functional movement. For a high level cervical injury, denervation and atrophy of key shoulder and elbow muscles makes it very difficult to generate enough force to flex/abduct the shoulder thereby elevating the arm against gravitational forces. Moreover, performing a functional task could require the arm to remain elevated for an extended period of time, making FES alone an impractical solution due to muscle fatigue. Therefore, some type of external vertical assist device will be a very important factor in the implementation of an FES system to provide restoration of functional motion in high tetraplegia [5,6]. Thus, for the practical implementation of either a robotic exoskeleton or an implanted FES system, some mechanism will be employed that provides vertical assistance to alleviate the burden of gravitational force. Not only is a vertical assist device necessary, but preliminary data has shown it can actually enhance the action of muscles still under voluntary control.

The goal of this study was to validate the presence of volitional motion and force generation at the hand in individuals with high tetraplegia when the arm is supported

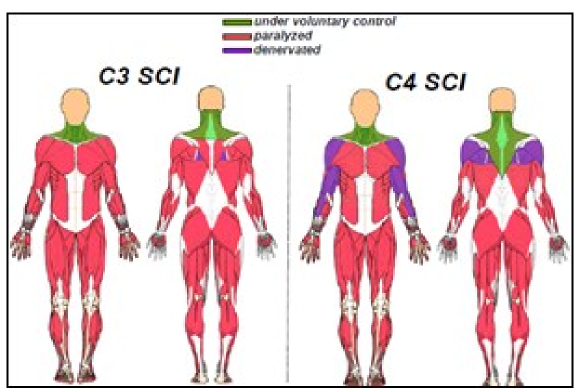

Figure 1. Typical representation of muscles that are under voluntary control (green), paralyzed (red), and denervated (purple) post high cervical spinal cord injuries.

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against gravity with a vertical assist device. Any volitional control is pertinent to the development of rehabilitative interventions for high tetraplegia because it can be utilized to improve the overall performance of the device, whether it is a robotic exoskeleton or FES system.

II. Methods

The MetroHealth Medical Center Institutional Review Board approved the experimental procedures and the subjects provided informed consent prior to participating in the study.

To date, two subjects with high level spinal cord injury have participated in this study. Both subjects were asked to reach as far as they can in a series of directions with vertical force assistance. In one subject, we also measured the maximum isometric endpoint forces at the wrist. The first subject (Subject 1) is a 55-year-old female with a C1-C2 level spinal cord injury. Currently, she is 18 years post injury. As a result of the injury, her right upper extremity is completely paralyzed and functional movement in her left upper extremity is greatly limited. The second subject (Subject 2) is a 32-year-old male with a C3 level spinal cord injury. Currently, he is 5 years post injury. Both his right and left upper extremity are completely paralyzed. For this study, all measurements were taken using the right arm of each subject. A programmable robotic arm (MOOG FCS HapticMaster) was used to provide vertical assistance and record position and force measurements. Fig 2. provides an illustration of the experimental setup.

A. Range of motion at the hand

High level cervical spinal cord injury results in a loss of motor control below the head and neck. Every spinal cord injury is unique, but generally, it has been seen that when individuals with this type of injury try to move their arm there will be no visible motion without some rehabilitative intervention. However, once the arm of an individual with high tetraplegia is elevated in front of the body with constant vertical force ("anti-gravity" force), it is possible for the individual to produce motion at the hand using muscles that are above the level of injury.

Two subjects with high level spinal cord injury were asked to move as much as possible up-down, left-right, and in-out (forward-backward) with the weight of their right arm supported and no assistance from electrical stimulation. This support against gravity was provided by a robotic arm (MOOG FCS HapticMaster) attached at the forearm and programmed to produce a constant upward force. The constant force value was set by increasing the value until the subject's arm was at equilibrium parallel to the ground in front of the body.

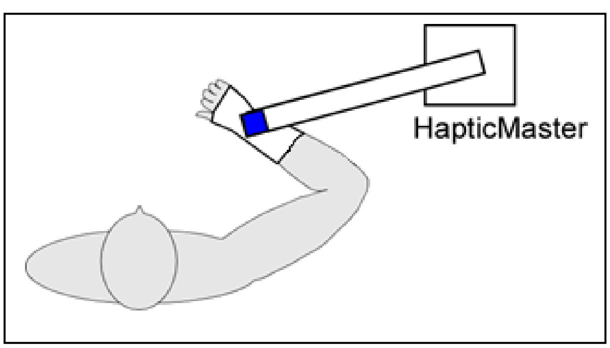

Figure 2. Illustration of methods used to collect volitional positioning and force generation at the right hand using the HapticMaster.

B. Force generation at the hand

Force generation at the hand is important for successfully accomplishing many activities of daily living (e.g. using a fork, pressing elevator buttons). Volitionally generated maximum forces at the right hand were evaluated in the positive and negative directions of all 6 standard coordinate directions (up, down, in, out, left, and right). The hand was set at a static position in front of the subject, which could be representative of completing tasks on a lap table. Force measurements were collected over time using the robotic arm (MOOG FCS HapticMaster). The robotic arm was programmed to maintain a static position and measure forces applied at the end effector, which was rigidly connected to the subject's hand. The average maximum force in each direction over 0.5 seconds from 3 trials was calculated and normalized to the passive force measured at rest at the beginning of each trial.

III. Results

A. Range of motion at the hand

The maximum distance reached was recorded along all standard axes. Both subjects reached at least a 10 cm range all 3 directions (Fig. 3). Subject 2, was able to reach at least 30 cm in every direction. It should be noted that the results in Fig. 3 are representative of a single trial for each subject.

B. Force generation at the hand

Maximum isometric endpoint forces were measured in each direction of the coordinate axis and averaged across 3 trials. The average maximum force generated over 0.5 seconds in each direction is shown in Fig. 4. It appears that for each axis, the subject is capable of generating more force in one direction than the other. Using only the muscles above the level of injury, the subject was able to generate

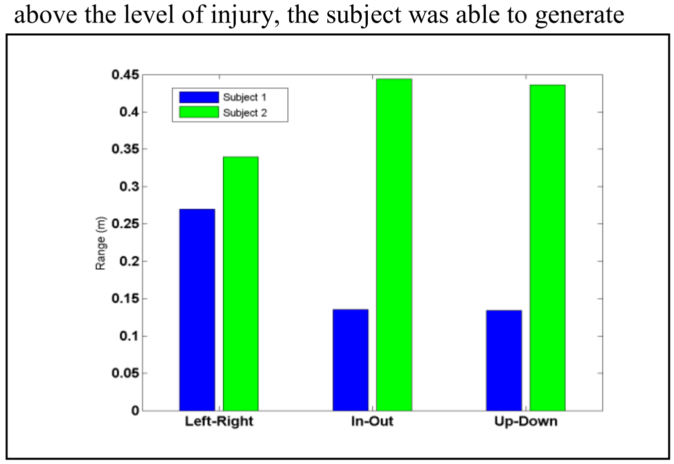

Figure 3. Range of motion at hand along 3 standard axes for Subject 1 and Subject 2.

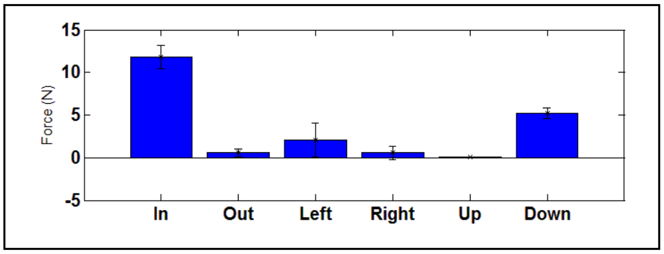

Figure 4. Average force generated in 6 standard directions for Subject 1.

the most force in towards their body. The force generated downward was also generally higher than the forces generated in the remaining directions.

IV. Discussion

The results from this study provide evidence toward the possibility of an individual with high tetraplegia being able to position their hand and generate forces volitionally in a functional workspace if the weight of their arm is supported by a vertical assist device.

A limitation of the study in quantifying the range of motion at the hand was that the data was recorded as a single trial over an extended period of time as the subject was asked to move as much as possible in each direction. This allowed the subject to build up momentum and use it to their advantage in generating a larger range of motion. The data quantifies positions in space that the hand was capable of passing (reachable space), but this does not necessarily indicate that the hand can maintain a position or generate substantial forces in that position (controllable space) [6]. Evaluation of the maximum isometric endpoint forces within a functional workspace showed that the volitional forces capable of being generated were dependent on the desired direction of the force. At this level of injury, it is likely that the muscles generating force are the trapezius and levator scapulae [7]. These muscles are capable of mobilizing the shoulder girdle, which translates into motion at the hand by way of the elbow and wrist joint. The directional dependence of volitional force generation is a result of the limited directional action of the muscles in the neck that are still under voluntary control after high level cervical spinal cord injury. The isometric endpoint force generated at the hand is an indicator of the controllable space. The controllable space may exhibit a less impressive range than the reachable space exhibited in the range of motion study, but it is more relevant for completing a functional task.

The results from these studies were expected to vary between subjects due to varying muscle strength, joint stiffness, and residual volitional control after spinal cord injury. However, despite paralysis of almost all muscles controlling the shoulder and elbow, both individuals with high tetraplegia still had considerable volitional movement control of the hand in a functional workspace once the weight of the arm is alleviated.

V. Conclusion

Volitional control of the hand has the potential to be very useful in the practical implementation of any rehabilitative device attempting to restore functional movements of the upper extremity for individuals in the high tetraplegia population. Taking advantage of the volitional control of the hand provides a means to make corrections to any errors in forces generated or movements driven by an artificial device. Allowing volitional adjustments has not been previously exploited and there is potential to improve the overall ability of reliably completing functional tasks using either a robotic exoskeleton or an FES system.

We have designed further studies to characterize the fine control of movement and force generation that is available after high level cervical spinal cord injury in the context of restoring arm function. Data will be collected with more high-tetraplegia subjects using both (right and left) limbs. Given an understanding of the volitional control that is available for this population, cooperative control will be developed between the rehabilitative device and the volitional control of the user. FES systems have several benefits for rehabilitation. FES systems utilize the user's muscles as the actuator of motion which promotes tissue health, muscle strength, and metabolic processes, in addition to the increased user satisfaction associated with controlling their own anatomy [9]. A rehabilitation system that combines electrical stimulation for restoring functional movement and the user's volitional control provides a solution that could greatly increase the quality of life for individuals with high tetraplegia with improved performance and user acceptance when compared to what is currently available.

Acknowledgment

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