An EMG-Driven Assistive Hand Exoskeleton for Spinal Cord Injury Patients: Maestro

Youngmok Yun, Sarah Dancausse, Paria Esmatloo, Alfredo Serrato, Curtis A. Merring and Ashish D. Deshpande

***Abstract*— In this paper, we present an electromyography (EMG)-driven assistive hand exoskeleton for spinal-cord-injury (SCI) patients. We developed an active assistive orthosis, called Maestro, which is light, comfortable, compliant, and capable of providing various hand poses. The EMG signal is obtained from a subject's forearm, post-processed, and classified for operating Maestro. The performance of Maestro is evaluated by a standardized hand function test, called the Sollerman hand function test. The experimental results show that Maestro improved the hand function of SCI patients.**

I. Introduction

The number of spinal-cord-injury (SCI) patients is estimated to be 282,000 in the United States in 2016 [1]. Approximately 45% of SCI patients have residual function in their arms and shoulders, but have difficulty performing activities of daily living (ADL) due to insufficient hand function. The goal of our research is to improve their hand function in ADL with an active assistive orthosis.

Most current commercial assistive orthoses are passive devices that either help with passive extension/flexion or locate the fingers/thumb in a predetermined position [2]. Although these orthoses are economical and easy to use, they have several limitations. The passive stiffness or elasticity hinders hand movement when it is not needed. Moreover, they assume the subjects are able to apply enough force in at least one direction. In order to address these limitations, active orthoses have been recently developed. These devices recognize the intention of the subjects and assist them in achieving a task by adding extra strength. Since the active orthosis recognizes the intention, the assistive force is added only when a subject needs the force. In addition, because active orthoses add force, even a subject with weak muscles is able to perform tasks.

There are two major challenges in developing an active assistive orthosis for hand function. First, the design of the device is challenging. The orthosis needs to be light and comfortable to allow subjects to perform tasks while wearing it for a considerable amount of time. The actuation of orthosis needs to be compliant. If the orthosis controls finger positions regardless of interaction force, it may harm the subject's hand when interacting with a rigid object. The orthosis needs to provide various hand poses which are essential to perform various tasks in ADL. Benjuya and Kenney [3] pioneered the research of active hand orthosis. However, the geared-motor system on forearm resulted in a heavy system and non-compliant interaction. The orthosis introduced by DiCicco et al. [4] provided compliant interaction resulting from a pneumatic actuator, but it generated only pinching motion. The tendon-driven glove introduced by In et al. [5] is light and comfortable, but only capable of providing a wrap grasp. Recently developed exoskeletons [6], [7], whose primary purpose is rehabilitation, provide various hand poses, but most of these devices are not portable.

The second major challenge is to recognize the intention of the subject. If an active orthosis fails to reliably identify the intention, it would actively hinder movements of subjects. One promising method is to use EMG signals for intention recognition. Since the EMG signals are obtained from task-relevant muscle groups, operation of the assistive orthosis is intuitive. Several researchers have developed active hand assistive orthoses driven by EMG signals for SCI subjects [3], [8]. However, the operations have been performed only for 1-DoF actuation and mainly with a binary threshold. Recently, Liu et al. [9] showed the potential of EMG signals of SCI subjects to predict their intended hand pose. They attached an EMG sensor array on the forearm of SCI subjects and built a map classifying the EMG signals into various essential hand poses of ADL. However, they have not implemented the classification algorithm for operation of any active assistive orthoses.

In this paper, we present the novel design of an active assistive hand exoskeleton, called Maestro. Maestro is light, comfortable, compliant, and capable of providing various hand poses essential in ADL. Then, we present a reliable user-intention recognition method using EMG signals of SCI subjects. The method classifies EMG signals of hand muscles into intended hand motions, and sends a command to the controller of Maestro, leading to the desired hand pose of the SCI subject. Finally, the improvement of hand function in ADL is evaluated for two SCI subjects by a standardized hand function test, called Sollerman hand function test (SHFT) [10].

This paper presents a system level research including

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the ergonomics and anatomy of the hand, the design of an active assistive hand exoskeleton, the characteristics of musculoskeletal systems of SCI patients, the classification of EMG signals and the control of hand exoskeleton based on EMG signals. Throughout this paper, readers will see system-level problems when integrating these elements, and our approaches to resolve these issues. We also report promising results showing improvement of hand function of SCI patients in ADL. Maestro is the first active assistive hand orthosis that has been tested by a standardized hand function test that is not limited to a specific grasp mode, and the illustrate the potential for improving performance during ADL.

II. Design of Maestro

In this section, we will present novel design features of Maestro. We have designed Maestro to meet the requirements of an active assistive hand orthosis including light weight, comfort in wearing, compliance in actuation, and capability of generating essential hand poses.

The first decision in the development of Maestro was to determine the complexity of device. If an orthosis contains high complexity including high DoF, the device may provide a large number of hand poses but simultaneously also increase weight, size, and cost. To find an optimal answer, we reviewed the literature on ergonomics and anatomy of hand. According to hand ergonomics studies [10], [11], significant portions of tasks in ADL are performed by the thumb, index, and middle fingers. For example, a house maid and a machinist were able to perform about 80% and 70% of grasping tasks with these three digits. Next, according to hand anatomy studies [12], [13], tendons for abduction/adduction of fingers are not critical for grasping, and the distal interphalangeal (DIP) joint motion of each finger is coupled with metacarpophalangeal (MCP) joint and proximal interphalangeal (PIP) joint motions. In contrast to fingers, all joints of the thumb move independently, and the abduction/adduction of the thumb is critical for grasping [11]. Based on these studies, we decided to actuate four-DoF of the thumb (carpometacarpal (CMC) abduction/adduction and CMC, MCP, and IP flexion/extension) and four-DoF of the index and middle fingers in total (MCP and PIP flexion/extension).

We introduced four-bar mechanisms and a glove to ensure comfort in wearing (Fig. 1). Joint misalignment between hand joints and device joints is a common problem in wearable robotics and may cause pain on the joints [14]. Since four-bar mechanisms in the exoskeleton use the hand as part of the mechanism, the joint misalignment problem is fundamentally resolved [14]. In Maestro, flexion/extention of first digit joints (MCP for fingers and CMC for thumb) are carried out by inverted-slider-crank mechanisms (shown in red solid lines in Fig. 1). The flexion of second joints (PIP) of the fingers and the second and third joints (MCP and IP) of the thumb are carried out by basic four-bar mechanisms (shown in green dash and blue dotted lines). All four-bar mechanisms rotate along with the abduction/adduction

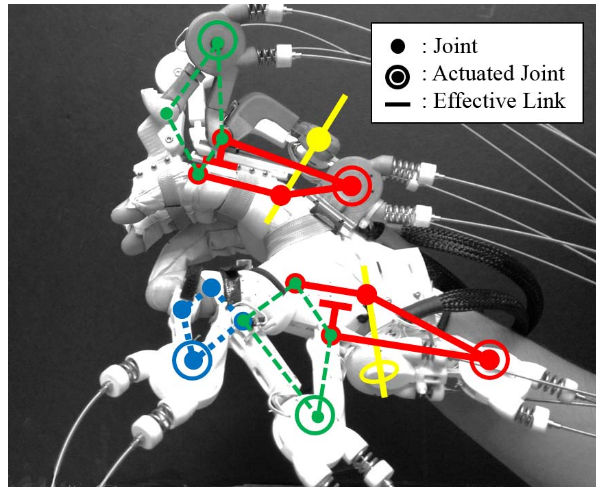


Fig. 1. (Best viewed in color) Maestro includes multiple four-bar mechanisms to avoid a joint misalignment problem. The rigid link mechanism interfaces a hand with a leather glove for comfort.

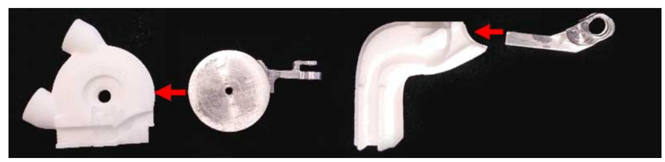


Fig. 2. Most of parts in Maestro were fabricated with Nylon-12 by a SLS machine. To enhance mechanical strength, load-bearing structures were made of aluminum.

motions of the fingers and thumb. The exoskeleton abduction/adduction joints are directly matched with the finger MCP and thumb CMC (shown in yellow line). In kinematics theory, this direct matching may cause a joint misalignment problem. However, because hand anatomy allows significant abduction/adduction motion of the fingers and thumb only at a certain flexion angle, for which the initial alignment is set, all hand joints move comfortably. These rigid link mechanisms interface the hand with a leather glove. We sewed the rigid interface on to the glove to prevent undesired tilting motion of the rigid structure. Leather also avoids direct contact of rigid structure with skin, preventing irritation. After wearing the glove, tightening velcro straps minimizes the play between the exoskeleton mechanism and the hand. The fingertip parts of the glove were cut to preserve sensation. Our studies on the mechanisms with early prototypes of finger module and thumb module have been presented respectively in [15], [16].

We took advantage of additive manufacturing technologies to minimize the weight. Most of the parts in Maestro were fabricated with Nylon-12, the density of which is about three times lighter than Aluminum, by a selective-laser-sintering (SLS) machine. Also, since it is possible to manufacture a complex part without assembly by SLS, the volume and number of parts were decreased. One disadvantage of Nylon-12 is that its mechanical strength is weaker than metals. To overcome this disadvantage, we introduced an aluminum structure for load bearing components (Fig. 2). This hybrid structure resulted in a more compact design than the Nylon-only design. The final weight of one finger module is 57g and thumb module is 91g. The detailed manufacturing process has been presented in [17].

The rigid mechanism is remotely actuated with Bowden cable transmission to reduce the weight, and elastic elements are connected in series with the Bowden cable to make the actuation compliant. We located electric motors remotely, and a pulley on the motor shaft is connected with the actuated exoskeleton joint with a pull-pull mechanism through Bowden cables [18], [15]. It is similar to a timing pulley transmission with Bowden cables. Since the motors are located in a remote place, the weight of orthosis is significantly reduced while maintaining enough power capacity for task performing. However, a substantial amount of friction in Bowden cable transmission and the gear reduction of electric motors make the actuation non-compliant and non-backdrivable. Hence, we introduced series-elastic-components, or compression springs, at the exoskeleton joints (Fig. 1). As a result, the actuation of Maestro to the hand is compliant while the remote electric motors are position-controlled. We selected an optimal stiffness of compression springs that provides comfort while interacting with objects. Due to the compliant actuation, a subject is able to interact with various objects even if the target hand pose of Maestro is somewhat different than the required hand pose for a task. The detailed actuator information has been presented in [18], [19].

III. Control of Maestro with EMG

In this section, we present how the desired hand poses of Maestro are controlled by EMG signals of SCI subjects. The overview of the signal flow from the muscles to the target pose of Maestro is shown in Fig. 3. The goal is to generate commands for Maestro, that are the target hand poses, to perform various tasks in ADL reliably with the EMG signal of SCI subjects.

We first determined a set of target hand poses which is the outputs of the Maestro controller. This decision was made based on hand function studies, EMG patterns for hand poses, and the compliant characteristics of Maestro actuators. According to the previous hand function studies [10], [11], the most frequent hand grips are categorized into 8 poses as

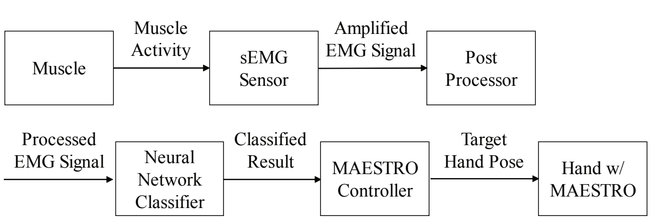


Fig. 3. Signal flow of the muscle activities to the target hand poses of Maestro. The EMG of muscles are measured and amplified by surface EMG sensors, the amplified signal is post-processed with several filters and classified into a target hand pose of Maestro with an Artificial neural network classifier.

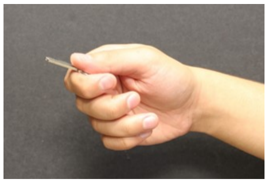
shown in Fig. 4. However, it is not desired to use all of these 8 hand grips as a set of commands for Maestro. Previous research [9] shows that some hand poses are reliably classified, while others might be confused with each other. This wrong classification is especially undesired when controlling an active device because it results in oscillation between the misclassified hand poses. The main reason for this problem is that several hand grips share similar muscle activity patterns, and surface EMG sensors cannot pick up individual muscle signals. For example, the transverse volar grip and spherical volar grip share similar muscle activity patterns; the lateral pinch and diagonal volar grip share similar muscle patterns; and the extension grip, tripod pinch, five finger pinch, and pulp pinch share similar muscle activity patterns. Also, the hand poses are determined not only by kinematics control of hands, but also by the shape of objects in tasks and the stiffness of joints [20]. In this regard, we selected the three most distinctive hand poses that cover the three major muscle patterns stated above: transverse volar grip, lateral pinch, and extension grip, respectively. Then, we created a set of target hand poses which are more flexed than their expected hand poses because the compliance of actuators can accommodate different shapes of objects with required strength.

Next, we determined the locations of surface EMG sensors for the target hand poses. The decision was made based on the anatomy of muscles for hand functions and discussion with an occupational therapist whose specialty is SCI. The criteria for the decision include first that the EMG sensor must be able to measure the muscle activity of a muscle group that generates the target hand poses, second that the EMG sensors must measure non-redundant EMG signals compared to other signals measured by other EMG sensors, and lastly that EMG signals must be available for SCI subjects. We selected the location of the first EMG sensor to target Flexor digitorum superficialis (FDS). For the location of sensors, see Fig. 5. Because FDS is located close to the anterior surface of the forearm, as opposed to the other deeper ones, the flexion of fingers is clearly detected. The second EMG sensor targets a muscle in the posterior forearm called Extensor digitorum (ED), which detects the extension of fingers. Finally, for the thumb abduction and flexion, the third EMG sensor is attached on the palm of hand which detects thumb abduction and flexion by targeting Flexor pollicis brevis (FPB) and Abductor pollicis brevis (APB) together (FPB and APB locate closely). Generally, severer level SCI patients have less finger flexion/extension, but still have some activity in wrist flexor and wrist extensor muscles. Therefore, depending on the level of injury, the locations of EMG sensors are adjusted to measure the EMG of wrist extensors and flexors. The detailed study on EMG signals of SCI subjects is part of our ongoing work.

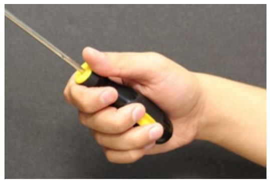
From the selected muscles, the EMG signals are measured and post-processed. First, the offset of signal is removed. Next, the signal is rectified to obtain the magnitude values. Then, the third order Butterworth low-pass filter (cutoff frequency at 4 Hz) is performed to produce a linear envelope representation of the signal. Lastly, the signal is normalized

(a) Transverse volar grip

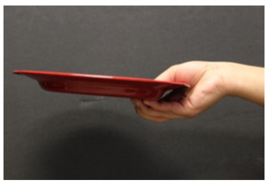
(b) Spherical volar grip



(c) Lateral pinch

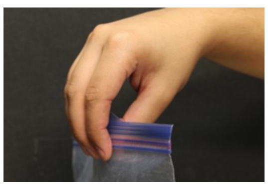


(d) Diagonal volar grip

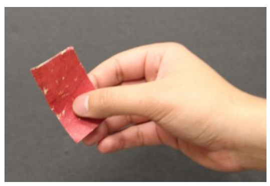


(e) Extension grip

(f) Tripod grip



(g) Five finger pinch



(h) Pulp pinch

Fig. 4. The eight hand grips are the most common in ADL [10]. We categorized the eight hand poses into three groups which share similar EMG patterns. The first group includes Transverse volar grip and Spherical volar grip. The second includes Lateral pinch and Diagonal volar grip. The third group includes Extension grip, Tripod grip, Five finger pinch, and Pulp pinch.

with the maximum voluntary isometric contraction (MVIC) of the muscle.

The post-processed EMG signals are classified into five classes by an artificial neural network (ANN) algorithm. We selected a two-layer feed-forward network with sigmoid hidden and softmax output neurons [21]. The network is trained with a scaled conjugate gradient back-propagation. The five classes consist of the three grip poses stated above, extension, and relaxation. The relaxation class plays a significant role for stable operation of Maestro. The relaxation class is selected when a subject relaxes all target muscles. Compared to other classes, the relaxation class is classified without confusion because the muscle activations are all low so that the EMG pattern is clearly distinguishable from other EMG patterns. We use this distinguishing property of relaxation class to maintain the selected hand pose consistently. That is, if the classification result of ANN is the relaxation class, Maestro does not change the target hand pose and maintains the current pose. Since the subject does not need to keep generating the EMG signal for the specific pose, subjects

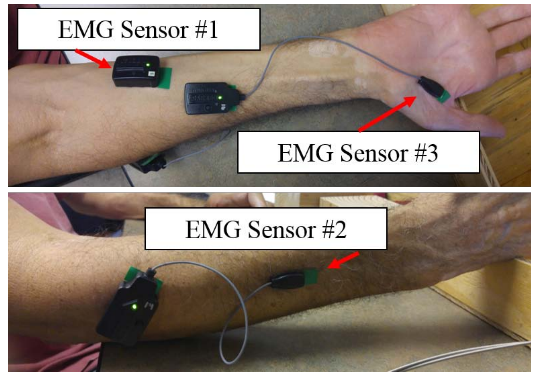


Fig. 5. Three wireless EMG sensors are used to identify the intention of SCI subjects. The first sensor detects the flexion of fingers, the second detects the extension of fingers, and the third sensor detects the thumb flexion and abduction.

can comfortably maintain the desired hand pose with low-rate classification failure.

Lastly, we introduced a probabilistic approach for stable operation of Maestro. Although we reduced the number of target hand poses and introduced the relaxation mode, the noise in EMG signals and the movement of arms and wrist caused problems in the classification and lead to frequent fluctuation between hand poses of Maestro. For the operation of an active device in contrast to gesture recognition, we needed a higher success rate of EMG classification. To enhance the success ratio, the Maestro controller adopted a probabilistic approach. The Maestro controller records the classification results for a certain time duration. Then, classification results are counted for the time window. Lastly, only when the count of a classification result exceeds a certain threshold, the Maestro controller changes the target hand pose. This probabilistic approach filters out wrong classification results occurred by EMG noise or transition of muscle states. One scenario of operation is shown in Fig. 6 to help understanding of readers.

IV. Experiment and Results

In this section, we validate the effectiveness of Maestro for the improvement of hand function of SCI patients. The hand performance of two SCI subjects with and without Maestro was evaluated by a standardized hand function test, called Sollerman Hand Function Test (SHFT) [10]. SHFT evaluates hand function of subjects based on 20 tasks inspired by ADL. Each subtest is scored on a scale of 0 to 4 based on scoring criteria including time to complete the task, successful completion of task, use of the normal hand grip and number of drops. The maximum score of SHFT is 80. Tasks to be performed include closing and opening zippers, picking up coins, using a screw driver, writing with a pen, pouring water from a jug, lifting an iron, etc. The brief description of tasks is listed in Table II. For detailed task descriptions, refer to [10]. All experiments were conducted with an approval of the institutional internal review board (IRB).

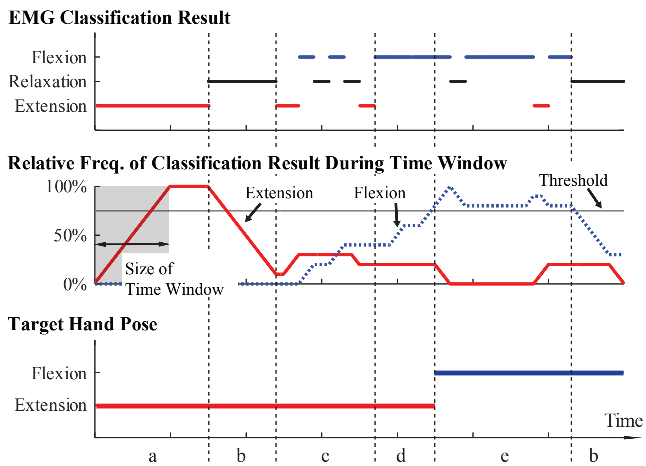


Fig. 6. Control mode change of Maestro with EMG classification results. A virtual classification result, flexion, is introduced instead of transverse volar grip, lateral pinch, and extension grip to effectively illustrate the algorithm. The basic principle for full classification results is the same without loss of generality. We created a virtual scenario to show how a subject changes the target hand pose from extension to flexion. The top plot shows the EMG classification results obtained by ANN. The middle plot shows the relative frequency of classification results. The frequency is counted during a pre-determined time window. The bottom plot shows the target hand poses of Maestro controller. The change of target hand pose is made when the relative frequency of a classification result exceeds a threshold. (a) the frequency of extension crosses the threshold but the target hand pose does not change because it is already extension. (b) the subject relaxes the muscles but Maestro maintains the current target hand pose. (c) the subject changes the muscle activities. During the transition, the classification results are noisy, but the target hand pose is not changed. (d) The classification results are consistent, but the target hand pose is not changed yet due to the delay of a time-window approach. (e) The frequency of the flexion crosses the threshold, and the target hand pose is changed to flexion. Due to the probabilistic approach, the decision is robust to occasional fault of classification.

We recruited two SCI subjects to evaluate the assistance performance of Maestro. Subject 1 has a C5/C7 incomplete SCI and Subject 2 has an incomplete C6 SCI. Both are chronic SCI subjects and have sufficient arm function for reaching objects located on a table in front of them. Subject 1 is a 63 year old male and has been injured 6 years prior to the experiments. He is able to perform extension but has difficulty in finger and thumb flexion, and thumb abduction/adduction. He has limited or no sensory feedback on his fingertips. He reports that muscle stiffness has no adverse effect on his hand function in ADL. Subject 2 is a 34 year old male and has been injured for 5 years. He has relatively strong flexion but weak active finger extension. Both subjects have been right-handed before and after injury. So, the two subjects have opposite challenges, i.e, limited flexion and extension, respectively.

Before the SHFT, the EMG system was set up and data were collected to train the ANN program. First, we attached EMG sensors on the forearm and palm of each subject. Three Delsys Trigno™ Wireless EMG sensors were used for recording EMG signals. Muscle locations were identified by palpating the subject's right forearm and palm. Second, the subject's hand was placed and secured in a hand splint to measure MVIC of each muscle. Subjects were asked to perform maximum finger flexion, finger extension and thumb flexion respectively, while the muscle activity was being displayed to the subject on a computer screen. The MVICs measured in this part were used to normalize EMG data during the experiments. Third, in order to train the ANN, subjects were asked to perform 3 trials including 5 different tasks interacting with real objects while the muscle activities were being recorded. The tasks included holding a jar (transverse volar grip), holding a key (lateral pinch), holding a plate (extension grip) (Fig. 4), relaxing the hand, and extending the fingers. If a subject was not able to complete a task due to his SCI, he was asked to perform the task as best as he can. Each trial comprised of 4 grasp sets each lasting for 10 seconds with 10 seconds of relaxed pose between each grasp. In order to preserve the accuracy of recorded EMG data and eliminate the effects of transitioning between different grasp modes on EMG data, the 2 seconds in the beginning and at the end of each grasp were disregarded and only the midmost 6 seconds were used to train the ANN program.

Next, subjects wore Maestro and we allowed them to get familiar with the system. We helped subjects wear Maestro and adjusted the link lengths of the exoskeleton to fit the subject's hand size and ensure comfort. In addition, we customized the target hand poses of the Maestro controller, including transverse volar grip, lateral pinch, extension grip, and extension. Subjects were able to perform various hand poses, required to perform SHFT, with the four target hand poses as shown in Fig. 7. After the customization of Maestro, the EMG-driven controller was turned on, and the subjects had 20 minutes to practice controlling Maestro with their muscle activities and interacting with objects.

After the practice, subjects performed SHFT with Maestro. A researcher introduced the SHFT and its scoring criteria (Table I) to subjects. They sat at a table whose height had been adjusted for their wheelchair and the SHFT kit was placed on the table. A researcher performed and demonstrated each task of the SHFT using the normal grasp mode and asked the subject to try to do the same task. An occupational therapist observed and timed each task and scored the task on a scale of 0-4 based on the scoring guide provided by SHFT (Table. I).

After the SHFT with Maestro, we removed Maestro and the EMG sensors and had a break for 10 minutes. Then, subjects performed SHFT with their bare hands. Before every task, a researcher again performed and demonstrated each one using the normal grasp mode and asked the subject to try to do the same.

The scores of the SHFT show an increase when wearing Maestro for both subjects (Table II). The overall SHFT score of subject 1 went from 41 to 47 by wearing the exoskeleton, and for Subject 2 went from 45 to 49 by wearing the exoskeleton. Subject 1 had difficulty with active flexion of the fingers and abduction/adduction of the thumb. Therefore, Maestro helped him achieve a higher score by allowing him to successfully complete the tasks with the correct hand grip and provide enough strength in tasks that use these degrees

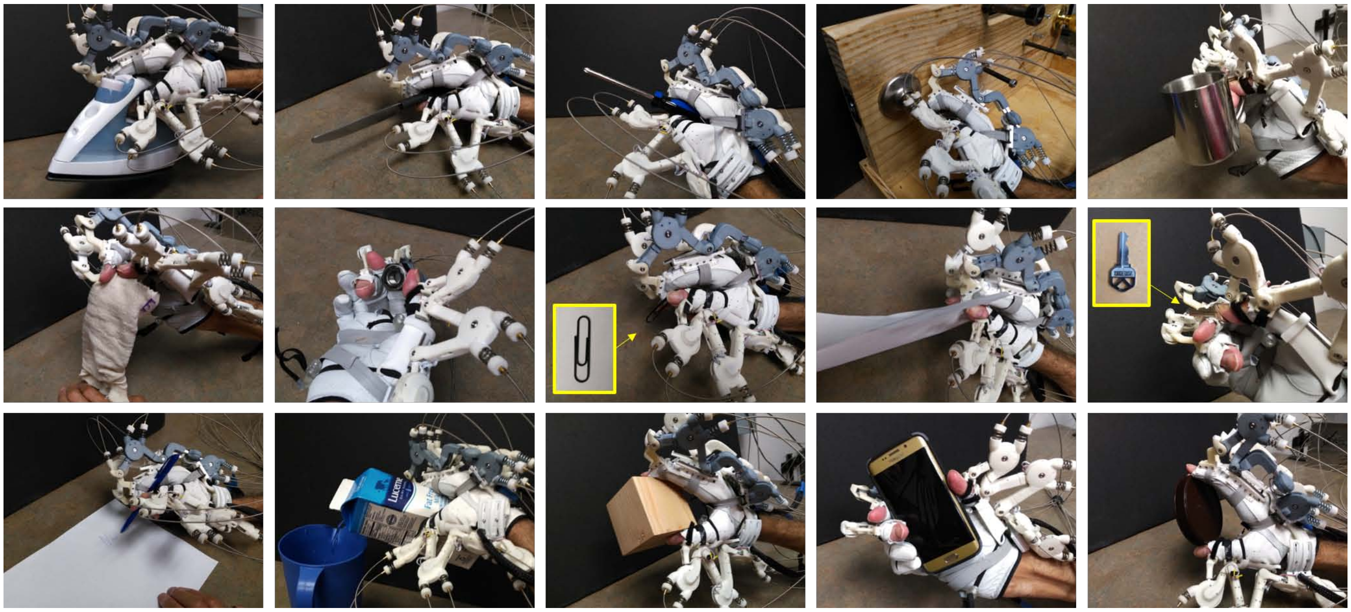


Fig. 7. After wearing Maestro, we adjusted the target hand poses (Transverse volar grip, lateral pinch, extension grip, and extension) of Maestro to perform various tasks described in the Sollerman hand function test. These pictures were taken with Subject 1, having SCI C5/6 incomplete SCI. Due to the compliance of actuators, the subject was able to grasp all objects with the four target hand poses, and the Subject 1 used desired hand grips for the task.

TABLE I
SHFT SCORING GUIDE [10]

Criteria	Score
The task is completed without any difficulty within 20 seconds and with the prescribed hand-grip of normal quality	4
The task is completed, but with slight difficulty, or the task is not completed within 20 seconds, but within 40 seconds, or the task is completed with the prescribed hand-grip with slight divergence from normal	3
The task is completed, but with great difficulty, or the task is not completed within 40 seconds, but within 60 seconds, or the task is not performed with the prescribed hand-grip	2
The task is only partially performed within 60 seconds.	1
The task cannot be performed at all.	0

of freedom. For instance, his scores were improved in lifting the iron, pouring water from a pure-pak, and writing with a pen. Subject 1 had limited sensory feedback on his fingertips, which made it difficult to perform delicate tasks, especially without visual feedback, including picking up coins from a purse mounted on a wall and picking up nuts and putting them on bolts. Subject 2 had stiff flexed fingers and difficulty in finger extension. He usually wrapped around an object by pushing his fingers, and opened his hand by using the other hand or by contacting with an object. When he used Maestro, he could extend his fingers more easily and got a higher score in lifting the iron and pouring water from a jug, cup, and pure-pak. On the other hand, he got lower scores in tasks that included pinching of small objects, such as unlocking a Yale-lock with a key and writing with a pen. Maestro also enabled the subjects to perform tasks using the correct hand poses. Without hand exoskeleton, although subjects were able to accomplish many tasks, they used various compensating motions and help from other hand and body parts. The time to achieve tasks was overall longer with exoskeleton than without exoskeleton. This is due to the delay of the system and implementation of probabilistic approach introduced in Section III that ensures stable operation of Maestro. The average time to complete the tasks for Subject 1 with and without Maestro were 33.5 sec and 26.4 sec respectively, and for Subject 2 were 38.1 sec and 25.2 sec respectively (For the case of incomplete task, we regarded the time as 60 sec).

After the two SHFTs, subjects were asked about the comfort and difficulty of the session and tasks, and the effectiveness of Maestro in accomplishing ADL. Some questions were answered on a scale of 0-10 and others required short answers. According to the feedback form completed by the subjects, both believed Maestro is comfortable to wear and reasonably weighed (Table. III). Subject 1 thinks direct skin contact is better to grasp objects, whereas Subject 2 confirms that the glove interface helps significantly in grasps. They both believe the tasks performed in the session are representative of ADL. The easiest task chosen by both subjects was turning the door handle and the hardest tasks were turning the screw with a screw driver and doing up buttons, for subjects 1 and 2 respectively. Subject 2 believed Maestro brought enough strength for grasps. Both subjects prefer the exoskeleton to be smaller and to have bigger workspace.

V. DISCUSSION

We have presented the design and control of Maestro and the experimental results with two SCI subjects. Maestro is designed to be light, comfortable, compliant, and capable of

TABLE II
SOLLERMAN HAND FUNCTION TEST SCORES

Task Description	Subject 1 w/ Exo	Subject 1 w/o Exo	Subject 2 w/ Exo	Subject 2 w/o Exo
Pick up key, put into Yale-lock and turn 90 deg.	1	1	2	3
Pick up the coins from flat surface, put into purses mounted on the wall.	2	2	3	2
Close and open zips.	1	2	2	2
Pick up coins from purses.	0	1	1	2
Pick up wooden blocks, lift over edge.	2	3	3	2
Lift iron over edge.	4	2	4	2
Turn screw with screwdriver.	2	2	3	3
Pick up nuts and put on bolts.	1	1	1	2
Unscrew lid of jars.	3	2	2	2
Do up buttons.	1	2	1	1
Cut Play-Doh (plasticine).	2	2	2	2
Put elasticated tubular bandage on the other hand.	3	2	1	2
Writing the word "name" on paper	4	2	3	4
Fold paper, put into envelope.	1	2	1	2
Put paper-clip on envelope.	3	2	3	2
Pick up telephone-receiver and put it to the ear.	3	3	3	3
Turn door-handle 30 deg.	3	4	3	3
Pour water from one litre paper milk or juice package (pure-pak).	4	2	3	2
Pour water from jug.	3	2	4	2
Pour water from cup.	4	2	4	2
Total Score	**47**	**41**	**49**	**45**

TABLE III
FEEDBACK FROM SCI SUBJECTS

Question	Subject 1	Subject 2
Is the hand exoskeleton comfortable to wear?	(7/10)	(7/10)
Is the weight of the exoskeleton reasonable?	(10/10)	(9/10)
Is the glove comfortable?	(9/10)	(8/10)
Does the glove help to grasp objects?	(5/10)	(9/10)
Are the tasks representative of daily activities?	(8/10)	(10/10)
Were the tasks difficult to achieve without the exoskeleton?	(6/10)	(3/10)
Were the tasks difficult to achieve with the exoskeleton?	(6/10)	(3/10)

providing various hand poses. Maestro is reliably controlled with EMG signals of SCI subjects. The improvement of hand function of SCI subjects in ADL is evaluated with SHFT. Results show that the hand function is improved with Maestro.

This research reports the potential of an active assistive orthosis to improve the quality of hand function of SCI patients in ADL. Before the current version of Maestro, we conducted SHFTs with early versions of prototypes and other control strategies. While conducting these preliminary experiments with SCI subjects, we found that the improvement of hand function with an active assistive orthosis is very challenging. The ADL need various hand functions, such as picking up objects, holding objects, and moving objects. If an assistive orthosis supports only a part of the hand functions, the unsupported hand functions become worse than that of a bare hand. For example, our prototype with a thumb support fixing the thumb in an abducted position caused negative effects on hand functions which needed thumb adduction. Previous works have shown pinching or wrapping abilities of active assistive orthoses, but have not shown the improvement of comprehensive hand functions required in ADL.

Still, there is room for improvement of Maestro. Since we focused on a system level research, we have selected the most stable methods or base-line technologies for individual components of the system. For example, we have implemented the compliance of actuators with passive stiffness of springs rather than an active impedance control of joints. Another example is the EMG classification algorithm. The hand pose estimation with EMG classification is one of the most actively researched areas in Human computer interaction (HCI). By adopting advanced methods for individual components, the performance of Maestro would be improved.

Our future work includes performing experiments with more subjects and verifying our methodologies with a significant amount of data. One challenge of this research was that most of the hypotheses and methods had to be verified with SCI subjects. However, the recruitment of SCI subjects is difficult and we could not conduct a considerable amount of experiments with individual subjects. Through the research presented in this paper, we were able to determine a direction of future research, and we will perform experiments with more SCI subjects to validate the effectiveness of Maestro and sub-hypotheses.

To bring Maestro to the daily lives of SCI patients, several issues need to be resolved: the size of Maestro needs to be optimized, the orthosis needs be fully portable, the don-and-doff of Maestro needs to be performed by SCI patients independently, and the system calibration needs to be automated.

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