Comparison of Control Strategies for an EMG Controlled Orthotic Exoskeleton for the Hand

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***Abstract*— To restore dexterity to paralyzed hands, we have designed and constructed a lightweight, low-profile orthotic exoskeleton controlled by the user's residual electromyography (EMG) signals. In this paper, we compared several simple strategies to control the orthotic device for a quadriplegic (C5/C6) subject. When contralateral arm control was employed, we found that a simple on/off strategy allowed for faster interaction with objects, while variable control provided more controlled interactions, especially with deformable objects. Furthermore, we designed a control strategy that allowed for a natural reaching and pinching sequence without the use of the contralateral arm. We validated that the EMG signal from the ipsilateral biceps could be used to develop an extremely reliable natural reaching and pinching algorithm. This evaluation showed that different control strategies may be appropriate for different situations, and further investigation on the natural algorithm is crucial.**

Keywords-Hand, Exoskeleton, Orthotics, Electromyography, Spinal Cord Injury

I. Introduction

Over 250,000 people have been diagnosed with spinal cord injuries in the United States with 11,000 new cases being diagnosed every year [1]. Nearly half of these cases result in some loss of sensation or motion to the arms and hands. One realistic solution to this problem is the use of an FES (Functional Electrical Stimulation) system to stimulate muscles that are no longer receiving signals from the central nervous system. While this solution shows promise, it still has significant technical barriers to overcome (such as preventing immediate muscle fatigue, etc). In addition, even when it becomes available, it is not applicable to those subjects who have inflicted local trauma to the muscles. To remedy this problem, a low-profile hand orthotic exoskeleton could provide assistive forces to the user's fingers.

There have been several orthotic exoskeleton constructed [2, 3, 4]. These devices generally consist of rigid molded plastic as a basic support and hard metal hinges as the manipulation method. EMG sensors, when employed, are mounted directly in the housing of the device in proper positions to read muscle signals from the forearm. Grasping motions are achieved by mechanical actuation of the main hinge through gear or ratchet systems so that the device remains rigid when the actuator is not active.

Most exoskeletons have used either voice or electromyography (EMG) signals as the inputs to the controllers [2, 3]. The voice activation system uses verbal commands such as "grasp" or "grip" to trigger the opening/closing of an actuated clasping mechanism in which the user's hand sits. This system allows for good control of objects during steady state operation, however, the typical problems of voice recognition systems still persist, such as background noise or false signals. Furthermore, the voice activation system is limited to providing discrete actions (e.g. open slightly, close half-way, etc) and does not allow fast feedback or error correction (e.g. open, undo).

On the other hand, the control strategies that employ EMG signals could provide continuously variable or fast feedback commands. For example, the magnitude of the muscle activation could be mapped directly to the finger pinching force, and when the user wants to reduce the force by a small increment, he/she can simply reduces the muscle activation level. EMG signals have been used extensively for control of mechanical hardware [8, 9, 10] as well as in simulations [11]. Most of the current work in this area has used binary methods (open or close) to actuate the gripper. For example, Benjuya and Kenny [2] use the EMG signals from one muscle, in their case the wrist extensors of the forearm, to close the pinch when the EMG level reaches a threshold level, and use the natural antagonist group, when available, to open the pinch at a threshold activation level.

In this paper, we report our investigation on three different control strategies for an EMG controlled orthotic exoskeleton for the hand. We designed a binary algorithm (similar to the ones employed by others [2]) a variably control algorithm, and a natural reaching algorithm. We focused our attention on a basic pinching motion between the index finger and the thumb. Pinching motion provides the ability to perform a wide range of daily tasks such as pinching small objects, turning knobs, flipping switches, and opening bottles; while it is a simple enough motion to be supported by a light-weight exoskeleton device. We tested the binary and variable algorithms with a quadriplegic subject who has C5/C6 injuries

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and tested the natural reaching algorithm with able-bodied subjects.

II. Design Goals and Requirements

We set our goals and requirements for designing the orthotic exoskeleton as follows:

- To provide the pinching motion, we focused on articulating the index finger to the thumb. Our design fixed the thumb in a position that intersected the index finger movement.
- To ensure a normal interaction with real world objects we targeted to minimize the exoskeleton material on the palmer side of the hand. This would allow the user to pinch objects with their skin and would ensure that our mechanism would not interfere with interaction between the object and fingers.
- The weight of the device had to be minimized to less than one pound to prevent fatigue of the user.
- Seven pounds of contact force at the fingertip was deemed sufficient to hold onto various common objects. We targeted this force to be the baseline force level for our orthotic exoskeleton.
- To preserve the minimum appearance, we required a small profile.
- The comfort of the user had to be preserved to prevent any discomfort or injuries.
- The device had to be easy to apply and remove such that the user may do this without assistance.

III. Mechanical Design

The human index finger has three joints and four degrees of freedom. From the distal end, the joints are: the DIP (distal interphalangeal), PIP (proximal interphalangeal), and MCP (metacarpophalangeal). The DIP and PIP joints have flexion/extension degree of freedom, while the MCP joint has both flexion/extension and abduction/adduction degrees of freedom. To enable a steady pinching motion to the fixed thumb, flexion and extension of all three joints are required. The flexion/extension of the DIP and PIP joints are coupled, but the DIP/PIP and MCP flexion/extension are independent. Active abduction/adduction movements are not used to allow the tip of the index finger to meet the thumb, but passive abduction/adduction movement is allowed so as to aid the finger in conforming to its target object.

To support such movements, we needed to provide (1) a coupled active degree of freedom for the DIP and PIP flexion/extension, (2) an active degree of freedom for the MCP flexion/extension, and (3) a passive degree of freedom for the MCP abduction/adduction. For both active degrees of freedom, we used pneumatic pistons (models 007 and 007-R from Bimba Manufacturing Company, Monee, IL) activating a cabling system. These pistons were connected to variable pressure pneumatic valves (model 4088x from Herion USA, Inc.). Our analysis showed that these movements could be accomplished by a linear actuation of 1 to 1.5 inches, depending on the hand size of the user, and the required 7 lbs of contact force could be accomplished by 10 lbs of linear force. We did not use artificial muscle actuators such as McKibben pneumatic muscles and shaped memory alloys, used in similar devices [4, 5, 6, 7], to keep the small profile outlined in our design criteria.

Figure 1 shows our orthotic exoskeleton system. The mechanical framework of the exoskeleton consisted of an aluminum anchoring plate mounted to the back of the hand and three aluminum bands, one for each of the finger bones. The aluminum bands were designed to be adjustable for different finger sizes. The flexion of the PIP and DIP joints was produced by steel cable running along the front of each finger band and through to the backside of the hand. These cables were pulled by a pneumatic cylinder acting in compression. The MCP flexion, on the other hand, was achieved by a linkage mechanism: a floating link was mounted between the finger band closest to the base plate and a second pneumatic actuator, acting in extension (labeled as linkage mechanism in Fig.1). When the extension pneumatic piston pushed this link mechanism forward (distal), the MCP joint resulted in flexion. To achieve smooth repeatable motion and the passive abduction/adduction motion, we added a flexible coupling between the base-plate and first finger band made from a canvas-like cloth material. The cloth was rigid in tension but was easily deformable along its length, which allowed for the device to maintain a set distance between the base plate and first finger band while not inhibiting flexion. Small springs were used at all three joints to extend them passively. When the finger was at rest, the springs kept the finger at full extension, and the pistons worked against the spring forces during flexion.

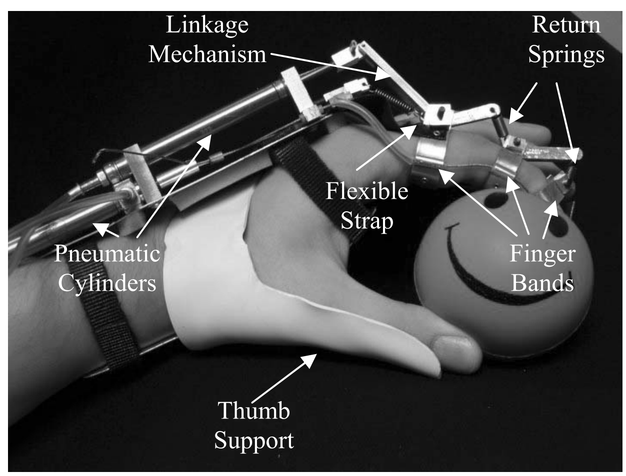

Figure 1: Our orthotic exoskeleton system.

IV. CONTROLLER DESIGN

A. EMG Signal Processing

Our exoskeleton is targeted for those with some residual biceps EMG signals, even if it is not strong enough to move the joints. Quadriplegics with C5 and/or C6 injuries typically have good control of their biceps even though they are mostly unable to control their hands. Biceps muscles are easily accessible from the skin surface, and it is intuitive to control the signals by moving the elbow. For the first two control algorithms, we chose to use the contralateral biceps (the biceps of the opposite arm from the one with the exoskeleton) to isolate the control movement from the actual pinching task. Ideally, the control signal would be a part of the natural reach and pinch movement rather than using the contralateral arm. Therefore, for the third control algorithm, we used the ipsilateral biceps (the arm with the exoskeleton) and used the signals that were part of a natural reach and pinch movements. There was no detectable level of EMG activities for the finger flexors.

The biceps EMG signal was recorded using a Delsys Bagnoli-8 system. The signal was amplified and digitized at 500 Hz. The digitized EMG data was then rectified and smoothed using a Butterworth low-pass filter. This data was normalized using the maximum voluntary contraction (MVC) level of the user. This processed EMG signal was then used to control the pressure level in the pneumatic valves.

Our system schematic is shown in Figure 2. The figure illustrates the possible location of all system components, including all of the electronics and pneumatics which would be located in the user's wheelchair or in an appropriate carrying case. The mechanical and electrical components of our system did not contain any sensors to establish the closed-loop system. Instead, the user judged the output and controlled their muscle contraction in a closed-loop format.

B. Binary Control Algorithm

As one of the three control algorithms for the exoskeleton, we designed a binary control algorithm similar to the ones employed by [2]. This algorithm is called a binary controller because its output to the pneumatic valves was either off (0 volts) or on (10 volts). The output binary value was determined by the EMG signal: when it was above a specified EMG threshold value, the output was "on", and when it was below, the output was "off". We implemented a hysteresis in the valve triggering system to prevent the output oscillation. The mean threshold value was originally set to be at 55% MVC to turn on, and 45% MVC to turn off, but we adjusted it to the subject's comfortable setting before each experiment.

The surface electrode was placed on the contralateral biceps. When the bicep was contracted above the threshold value, both pneumatic pistons produced 120 psi at the same time. This resulted in the compression piston to flex the PIP and DIP joints and the extension piston to flex the MCP joint together in approximately 0.5 seconds. Once the full flexion was established, the exoskeleton maintained the same posture. When the EMG signal dropped below the threshold value, both valves turned off completely and the springs in each joint pulled the finger to full extension. Using this control algorithm, there was no way to flex the finger half way or to produce less force during flexion.

C. Variable Control Algorithm

The second controller scheme was designed to explore the benefit of continuous variable control of the pneumatic pressure. To accomplish this controller, a simple proportional controller was employed using the filtered EMG signal. We set the minimum pressure level (20 psi) to be at 15% of the maximum muscle contraction level to avoid the twitching of the pneumatic system. Also, we set the maximum pressure level (120 psi) to be at 70% of the maximum muscle contraction level. As in the previous control algorithm, we adjusted these values to the subject's comfortable setting before each experiment.

D. Natural Reach and Pinch Algorithm

Ideally, the control signal would be a part of the natural reach and pinch movement rather than using the contralateral arm to control the pinching motion. If we could tap into the residual EMG signal of a muscle that used to control the index finger flexion and amplify it, it would make the most natural controller. However, most patients (including our subject) do not have detectable or usable amount of EMG signal on those muscles. The muscle that is most reliably available for the target population is the biceps muscle. Therefore, for the third control algorithm, we used the ipsilateral biceps (the arm with the exoskeleton) and used the signals that were part of the natural reach and pinch movements.

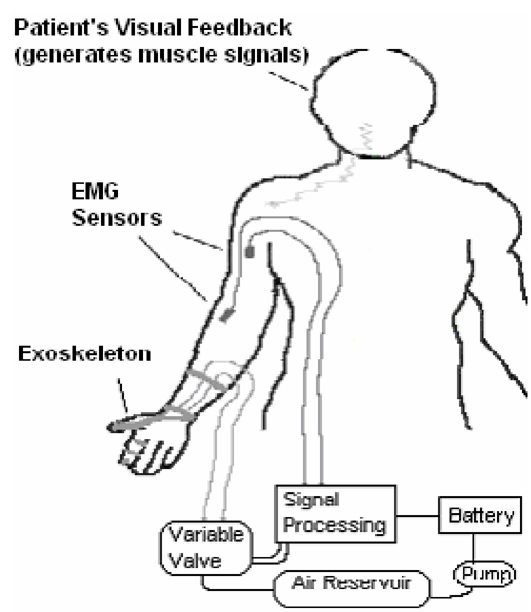

Figure 2: System Schematic

To understand the relationship between the biceps EMG signal and the timing of the grasp, we collected data from two able-bodied subjects while they reached and pinched a cylinder. The EMG signal was collected and filtered the same way as for the other algorithms. The cylinder was instrumented with a touch sensor to detect the exact contact timing. Subjects were asked to repeat this movement 60 times, and their typical movements are shown in Figure 3.

Using these 60 movements, a clear trend between the pinching and the slope of the EMG signal was determined. As shown in Fig.3, the pinch occurred after the first peak and where a negative slope was observed for a few hundred milliseconds. The slope, *S*, at time sample *T* of the smoothed EMG function was calculated by

$$S(T) = \frac{\sum_{n=0}^{50} EMG(T+n)}{50} - \frac{\sum_{n=1}^{50} EMG(T-n)}{50} \qquad (1)$$

where each data point of smoothed EMG at time *T* is *EMG(T)*.

To use the data from the future EMG data, the slope calculation was delayed by 50 sample points (100msec). Because there was additional delay from EMG smoothing itself, we designed the algorithm to pinch when the mean slope of the previous 50 sample points (100 msec) were negative. For subject 2, we added additional 80msec before executing the pinch. Once one pinch was detected, the algorithm terminated. For this experiment, we did not train for release timing, and performance was based on correlation between EMG data and the actual pinch/release recorded by the touch sensor.

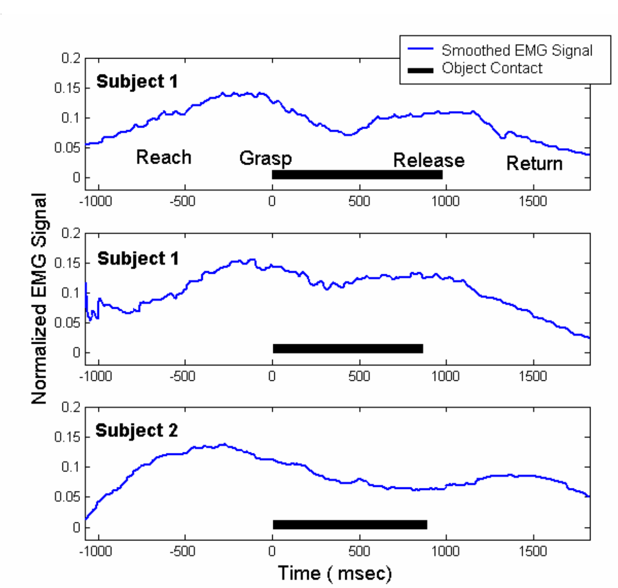

Figure 3: EMG signals recorded during pinching motion on 2 subjects. The thick line below represents the time that the hand was in contact with the object.

Figure 4: User with exoskeleton holding roll of tape and Twinkie

V. Validation

A. Contralateral Arm Controllers

We tested the efficiency, usability, and comfort of our orthotic exoskeleton system using the binary and variable control algorithms on an individual with an upper spinal cord injury. The individual was 19 years old, 6 years post-injury, with diffused C4/C5/C6 injury. He is able to move both shoulders and the right elbow, had some control over his right wrist and the left elbow, and no control on his left wrist and both of his hands. We used his right biceps muscle to control the orthotic exoskeleton on his left hand as shown in Figure 4.

After placing the surface electrode on the subject's right biceps and putting the exoskeleton on his left hand, we collected his EMG signals at complete rest when the arm rested on a table and at MVC for 5 seconds. The mean of the filtered signals were used as 0 and 100% contraction levels. The on/off threshold was set to 50% of his contraction level at first (which corresponded to an amplifier gain of 500) and we allowed the subject to adjust this level until he was comfortable with the threshold level. His final gain selection was at 200 (which corresponded to approximately 28% on and 18% off). We also calibrated the proportional controller's range to be comfortable for the subject, and it was set to have the minimum pressure level at 15% of MVC and maximum pressure level at 50% of MVC.

We compared these two controllers by having the subject attempt a pinch grasp of four different objects spanning a wide range of size, weight, and compliance: a 1 inch diameter rubber ball, a 3 inch diameter (1 inch thick) plastic hockey puck, a 3.5 inch diameter (3/4 inch thick) roll of masking tape, and a 1 inch thick Twinkie. For all of these objects, we asked the subject to reach, pinch, lift, place it on the table, and release as fast as he could without failing the task. He repeated the pinch/lift/place/release for 5 trials per object per control strategy. He was also instructed to not break the Twinkie in multiple pieces, requiring him to control his force level and pinch it delicately.

Figure 5 shows typical EMG signals recorded during pinch/release for both control strategies. We measured the total time it took for the subject from the initial go signal till the object was fully grasped for all four objects and it is plotted in Figure 6. We also conducted the same experiment on an able-bodied subject, and the total time it took to execute the task is shown in Figure 6 along with the result from the disabled

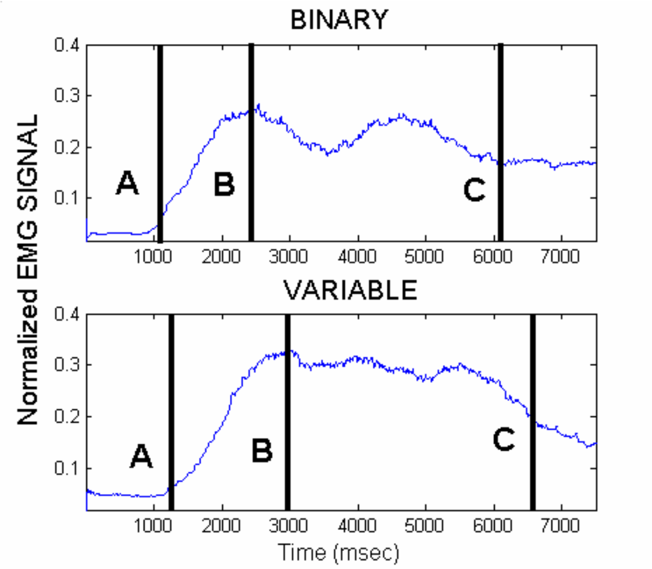

Figure 5: Typical EMG signals recorded during reach/pinch/life/place/release for binary and variable strategies. Line A indicates initial contact, B indicates full closure, and C indicates final release.

subject. The success rate (i.e. whether the object was successfully lifted off the table) for each object is shown in Table 1.

These results indicate that the exoskeleton was extremely effective in pinching a variety of objects. The disabled subject executed the task slightly slower (on average by 0.44 seconds) but comparable to the able-bodied subject. While there was a trend that the task was executed faster with the binary control strategy, it was not statistically different with the exception of the hockey puck. There was a high correlation with the amount of time it took to pinch the object and the object weight (correlation coefficient: .89) while there was no significant correlation between the size of the object and the execution time (correlation coefficient: .57).

An electric toothbrush and a packaged deck of cards were never successfully pinched after multiple tries. The electric toothbrush may have been heavier than other objects, but the major cause of failure was the slippery surface of the object. The deck of cards also had slippery cover.

The Twinkie pinching experiment proved to be useful in our functional analysis of the exoskeleton. To pick up the Twinkie without breaking it into many pieces required a well-calibrated light pinching force. To provide this light and controllable pinching force, the variable control algorithm proved to be more successful than the binary control. In a few trials on the variable control, the subject was able to bring the Twinkie to his mouth, release it into his mouth and eat it.

The use of our device marked the subject's first active control of the limb to lift a heavy object since his injury, an experience that he found to be exhilarating. While the binary control offered slightly faster task completion time, the user expressed his content with the range of manipulation offered by the variable control algorithm. Another beneficial feature of the variable control algorithm was the controlled release of an

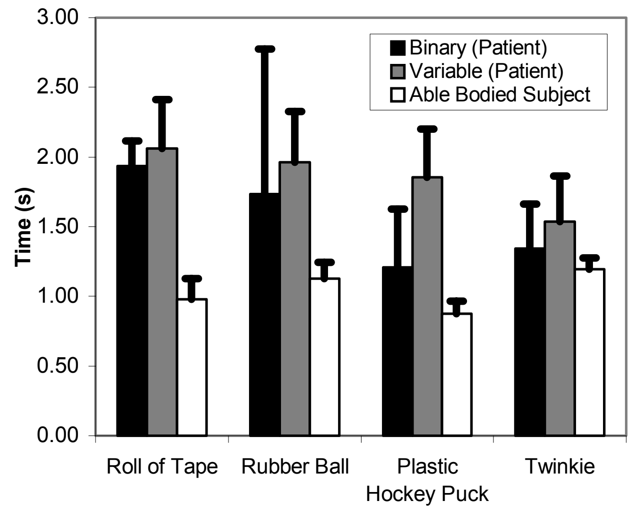

Figure 6: Total time from go signal to final release plotted for various objects. Bars indicate Binary control, variable control and able bodied patient, respectively.

object over the sudden release in the binary control algorithm. On a few occasions, the object dropped out of the exoskeleton grip in the binary control strategy when his biceps lapsed, an effect that is not so sudden in the variable control mode. We counted these sudden drops as successes in our tallies because he successfully grasped the object, but faults in EMG signal processing caused the exoskeleton to retract.

B. Natural reach and pinch controller

For the natural reach and pinch algorithm, we used the trials recorded from our able-bodied subjects to evaluate how closely the pinching timing could be predicted with our algorithm. Out of the 120 trials used (from both subjects), there were three trials where the algorithm did not detect any pinch. For the rest of the trials, the average absolute error between the predicted and real pinching timing was 0.31 seconds (SD = 0.32) for the first subject, and 0.28 seconds (SD = 0.30) for the second subject. Majority of the errors (67%) showed that the predicted pinch occurred after the time that the real pinch occurred.

These three failure trials mostly occurred early in the experiment (3^{rd}, 7^{th}, and 14^{th} trials). Even though some of the predicted pinches happened very close to the time that the subjects desired to pinch, if the pinch occurred before they were properly positioned by the object it could not be considered as a successful trial. In this algorithm, it is better to be too slow than to be too early. If we added an additional 200msec delay before the pinch, all but three predicted pinch would have occurred after the desired pinch.

The advantage of having a natural pinching motion with an EMG signal from the ipsilateral biceps is that the user does not have to concentrate on straining their contralateral arm to maintain the desired stage of the pinch. This algorithm is suitable for those subjects who are paralyzed completely on

Trial Object	Pinching Thickness (inches)	Weight (lbs)	Frequency of Grasping Success (minimum 5 trials)	
			Binary	Variable
Roll of Tape	3/4	0.33	100%	100%
Rubber Ball	1	0.23	100%	100%
Plastic Hockey Puck	1	0.13	100%	100%
Twinkie	1	0.09	50%	60%
Toothbrush	1 3/16	0.71	0%	0%
Deck of Cards	1/2	0.31	0%	0%

Table 1: The list of objects used in our reaching/pinching/lifting/placing/releasing experiment and their success rates for the quadriplegic subject. The rate was determined based on minimum of 5 trials.

one of the arms or when bimanual tasks are required. After development of the release algorithm, the entire system will tested with the disabled subjects.

VI. Conclusions

Our exoskeleton system has shown to be effective in enabling pinching movements to those who lack hand mobility regardless of the control algorithms used. We met many of the mechanical design criteria that we specified. First, the device was constructed to be comfortable. The user showed no signs of having to adjust the exoskeleton to perform any of the desired motions. Second, our design kept minimal materials on the palmer side of the hand. The exoskeleton never interfered with the manipulated objects. In addition, the exoskeleton only weighed 6.67 oz. and kept a low profile on the hand.

We tested binary, variable, and natural control algorithms. We found that binary control algorithm allowed for faster interaction with objects, while variable control provided more controlled interactions, especially with deformable objects. Furthermore, we validated that the EMG signal from the ipsilateral biceps could be used to develop extremely reliable natural reaching and pinching algorithm. This evaluation showed that different control strategies may be appropriate for different users and situations, and further investigation on the natural reaching and pinching algorithm is needed.

Some major functional problems with the system seem to be entirely related to friction between the exoskeleton and the target object or improper alignment between the actuated finger and the braced thumb. The exoskeleton fails in its requirement to ensure normal interaction. We are confident that redesigning the thumb brace and adding supplemental friction pads can fix both of these problems.

The assembly of the exoskeleton onto the user's hand is critical to the function of the exoskeleton. For every user, there is a right way to attach the exoskeleton to the wrist guard that guarantees a natural straight pinching motion. If the exoskeleton is rotated radially on the hand, the finger will misalign during the pinch. The unit can also be displaced axially on the hand, forcing the finger too far in the bands, or not pulling the finger far enough through. The thumb guard needs to be redesigned to fit comfortably under the wrist guard, which currently makes it difficult to put the thumb guard on after the wrist guard is placed. As one of our next steps, we plan to make the device so that it can be worn easily without worrying about its orientation on the hand.

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