The Design and Development of a Wrist-Hand Orthosis

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The Design and Development of a Wrist-Hand Orthosis

by

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering
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Dedication

For mom and dad
Acknowledgments

I would like to extend my gratitude and appreciation to many people who helped me get to where I am today.

To my mom and dad, whose love and support fueled me to strive for greatness.

To Cindy, Shanna, Andrea, Sharon, and Rutecleia, who became my “work moms” and constantly supported me during my studies.

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Abstract

Individuals with an incomplete C5-C7 spinal cord injury (SCI) lose grasping abilities but wrist function is almost universally retained. Most rehabilitation techniques apply the tenodesis effect, however, current tenodesis wrist-hand orthoses (WHOs) engage only the thumb and index finger, meaning that only 20% of activities of daily living (ADLs) can be completed.

This study tested the feasibility of a student-designed powered WHO by testing the device on healthy subjects to see if they could complete a variety of ADLs. A simulation software was then used to analyze wrist, thumb, and index finger joint angles. Additionally, an Assistive Technology Survey was distributed to members of the SCI population to gather information on whether there is a need for this assistive device, the population that could benefit from using this orthosis, and current level of difficulty and methods used when grasping everyday objects. The successes and failures of the orthosis testing, along with responses from the survey provided valuable information for future orthosis iterations that will be tested on the SCI population.

Moving forward, the orthosis should be constructed with (1) a stronger motor and (2) rubber grips on the inside of the hand. Both enhancements will facilitate more secure grasping for testing the WHO on the target population. A future version of this WHO would be as a rehabilitation device so that it could be utilized to help a wider range of individuals (e.g. individuals who have suffered a stroke).
Chapter 1: Introduction

1.1 Purpose

According to recent data available through 2016, the United States has approximately 282,000 persons living with a spinal cord injury (SCI), and that number is estimated to increase by nearly 17,000 new cases each year [1]. About 45% of reported SCI cases are classified as incomplete quadriplegia, ranking it the most common classification of SCI and approximately 13% of SCI cases are complete quadriplegia [1, 2]. The majority of cervical spinal cord injuries occur in the C5-C7 segments, which cause patients to lose upper and lower limb functionality [3]. Among quadriplegic SCI patients, studies have shown that restoring arm and hand function is their highest priority. Therefore, providing them the ability to grasp objects will allow for independent completion of activities of daily living (ADLs) that would otherwise require assistance [3-6]. Patients with an incomplete C5-C7 SCI, lose prehension abilities, but wrist function is almost universally retained [3, 7-10], thus most prehension rehabilitation techniques apply the tenodesis grasp and release effect. This orthopedic phenomenon takes advantage of retained wrist function and is achieved through wrist extension for grasping and wrist flexion for releasing [7, 8, 11]. However, these motions are exactly opposite to the way able-bodied individuals grasp and release objects. Given that approximately 90% of all SCI cases are non-congenital, the target population was able-bodied prior to their injury, therefore, if grasping could be achieved through more intuitive motions, rehabilitation could be easier for patients [1, 2]. Current wrist-hand orthoses (WHO)s may help with ADL completion, provide some degree of independence, but they cannot be donned/doffed independently [12], meaning, complete independence is never achieved.
1.2 Specific Aims

This technology is a powered wrist-hand orthosis (WHO) designed to help individuals with a C6-C7 SCI independently complete activities of daily living (ADL). The purpose of this study is to test the WHO on healthy subjects to assess its feasibility in assisting individuals with an incomplete cervical spinal cord injury (SCI). The specific aims for this project are described below.

The first aim is to design a wrist-hand orthosis that will help individuals with an incomplete C6-C7 SCI re-gain grasping capabilities and complete multiple ADLs.

The second aim is to have healthy subjects use the orthosis to demonstrate its feasibility and effectiveness, providing the basis for simulation software inputs.

The third aim is to use a simulation software to illustrate how the orthosis interacts with a human upper limb, and further, how this orthosis and upper limb combination would act as a singular system. Use simulation software to test the operational effectiveness of the orthosis-upper limb system within limited wrist motion boundaries (from Assistive Technology Survey).

The fourth aim is to create a survey to distribute to members of the SCI population to determine: (1) the size of the sub-population that could benefit from this WHO, (2) whether there is a need for a WHO to assist with independent completion of ADLs, and (3) the preferable means of grasping.

1.3 Current Wrist Hand Orthoses

1.3.1 Broadened Horizons PowerGrip Assisted Grasp Orthosis

The Broadened Horizons PowerGrip Assisted Grasp Orthosis, pictured in Figure 1, is a powered prehension orthosis designed to help individuals with neurological or upper extremity limitations that negatively affect their grasping abilities. This powered WHO keeps the thumb in a static position, and upon hitting a button, the index and middle fingers either move towards or
away from the thumb. The Broadened Horizons orthosis provides the user with limited wrist extension, which gives the user the ability to grasp, pick up, hold, and manipulate objects so they can eat, shave, brush teeth, comb hair, open a door, and other ADLs [13].

One major drawback to this orthosis is it cannot be donned/doffed independently. Additionally, although there have not been publications centered around the PowerGrip Orthosis, a member of a SCI forum stated that he has been using this orthosis for about a year and still struggles reach an acceptable comfort level. He does mention that it is designed for all day use, which is not his preference, and although the user did not state this, if he was able to remove the orthosis independently he may be consider the orthosis to be more comfortable [14]. Further, as stated earlier, the Broadened Horizons Orthosis only engages the user’s index and middle fingers during grasping/releasing motions, resulting in a lack of whole-handed grasping. This leaves the user limited to grasping objects that are thin/narrow enough to fit between the thumb and index finger, while considering that the ring and pinky fingers could obstruct a secure grasp.

1.3.2 Exo-Glove Poly

Seoul National University’s robotics department created The Exo-Glove Poly to help bridge the gap between disabled individuals and their independence. The Exo-Glove Poly is described as a “soft, wearable robot for the hand” because it fits the hand and has the flexibility similar to that of a regular glove. This orthosis is aimed at restoring hand and digital function to a person that has suffered a spinal injury, stroke, or other neural issues [15].
The Exo-Glove Poly uses the thumb, index, and middle fingers with wires attaching to the glove’s finger covers and to a small motor. The motor is activated by neural impulses; brain signals are detected by the device’s wiring, which will activate the motor and perform the motion the brain intended. The Exo-Glove Poly was designed to allow users to independently complete ADLs, however, this design will never allow the user to be completely independent. As seen in [15], a second individual is assisting in putting the device on, meaning the user is unable to independently don/doff the orthosis and without the aid of another person, the device cannot be used.

1.3.3 SCRIPT Passive Wrist Hand Orthosis

The SCRIPT Passive Orthosis (SPO) is a wrist, hand, finger orthosis (Figure 2) will help patients after a stroke. The current version cannot actively generate or control movements, therefore, would not be a viable option for individuals with a C6-C7 SCI [12]. Although the SPO can become powered, user critiques point out undesirable characteristics. Two main complaints were: 1) the device felt heavy after using it for long periods of time and 2) the device was difficult to don/doff. Users found it most difficult to fasten Velcro straps, especially ones designed to secure the finger caps [12]. The donning/doffing complaint came from healthy subjects or patients that have some finger function, therefore, if this becomes a powered orthosis, patients with a C6-C7 SCI, who do not have finger function, would not be able to don/doff the orthosis independently.

Figure 2 The SCRIPT passive orthosis [12]
1.3.4 Lateral Key Grip Orthosis

The lateral key grip orthosis (LKGO), Figure 3, employs wrist extension to operate on the basis of the traditional tenodesis grasp, which is achieved through contact between the thumb and index finger. This orthosis was designed to allow specifically for lateral key grip, which is only used in approximately 20% of all ADLs [17]. The lateral key grip is used to grip objects that fit between the thumb and index finger, limiting the functionality of the LKGO to grasping small objects. The LKGO does not allow for whole-hand grip, nor does any literature explain how it allows for a controlled release (releasing and placing down without actually dropping the object). Although literature on the LKGO states that the orthosis can be donned/doffed independently, it still has a drawback in not being powered [17]. This orthosis relies completely upon user input (i.e. strength and physical coordination), meaning that individuals who may not have the ability to fully extend their wrist would receive no help from this orthosis, and would likely not have the ability to perform and complete many desired tasks.

Figure 3 Lateral key grip orthosis [17]
Chapter 2: Background

2.1 Spinal Cord Injury

2.1.1 Quadriplegia

According to data available through 2016, The United States has approximately 282,000 persons living with a SCI, and that number is estimated to increase by nearly 17,000 new cases each year [1]. Recent statistics have shown that between 45%-60% of all reported SCI cases are classified as incomplete quadriplegia, ranking it the most common category of SCI [1, 2]. Quadriplegia is the result of a spinal cord injury in the cervical region of the spine. The majority of cervical spinal cord injuries occur in the C5-C7 segments, which cause patients to lose upper and lower limb functionality, along with loss of the ability to control certain bodily functions [3].

2.1.2 Main Causes

Approximately 90% of SCI causes are non-congenital or non-surgical cases, (vehicle crashes-38%, falls-30.5%, acts of violence-primarily gunshot wounds-13.5%, sports/recreation activities-9%, medical/surgical/other-9%) [1].

2.1.3 Symptoms

Current literature specifically states that individuals with a complete C5-C7 spinal cord injury typically lose finger and wrist function, causing a severe impairment in prehension (grasping capabilities). However, literature also states that for individuals with an incomplete spinal cord injury, wrist function is almost universally retained [3, 7-10].
2.1.4 Possible Treatments

2.1.4.1 Tenodesis Grasp in Occupational Therapy

Most prehension rehabilitation techniques apply the tenodesis grasp and release effect, which can be attributed to two distinct phenomena: wrist extension and wrist flexion. With a relaxed hand, palm side down, wrist extension causes the thumb to meet the index finger and fingers to meet the palm resulting in a curling (closing) motion. Alternatively, wrist flexion forces all fingers outward resulting in an uncurling (opening) motion [7, 8, 11]. A pictorial demonstration of these motions can be seen in Figure 4. Although the tenodesis grasp is implemented in occupational therapy, it does have two major drawbacks. First, given that the majority of patients with a SCI were able-bodied prior to their spinal injury, the tenodesis grasp motions are counter-intuitive to the way they grasped items as an able-bodied individual [1]. That is, grasping is accomplished with wrist flexion and releasing with wrist extension. Second, the tenodesis grasp uses only the index finger and thumb in such a way that it limits the items an individual can pick up to those that are light and small/thin/flat enough to fit between the two fingers. The tenodesis grasp does not allow for whole-hand grasping, meaning larger items such as, a bottle, cup, or mug cannot be grasped, ultimately limiting independence.

![Figure 4 Tenodesis effect. Left: wrist flexion leading to digital uncurling motion. Right: wrist extension leading to digital curling motion [7]](image-url)
2.1.4.2 Functional Electrical Stimulation (FES) and Tendon Transfer Surgery

Current approaches to rehabilitate hand prehension rely on either tendon transfer surgery and subsequent occupational therapy, or functional electrical stimulation (FES) [3]. Tendon transfer surgery is when the tendon of a working muscle is repositioned to take over the functions of a paralyzed muscle, enabling the working muscle to do what the paralyzed muscle can no longer do. Tendon transfer surgery helps restore critical capabilities of the upper extremity that are necessary for increased independence: (1) ability to extend/flex the elbow, (2) ability to extend/flex the wrist, and (3) ability to grip with the fingers and hand [18].

FES delivers a shock to the paralyzed muscle, which activates the nerves and makes the muscle move. It is theorized that the brain may be able to relearn these movements without the stimulation. In the case of wrist flexion/extension, electrodes would be placed on the wrist extensor muscles of the forearm. The patient begins with a relaxed hand, and then contracts the wrist extensor muscle to cause movement. This movement triggers an electric shock to the muscle, which causes greater movement of the hand [19].

A recent clinical study shows that 60% of the quadriplegic population would benefit from tendon transfer surgery, and only 7% would be candidates for FES. Since patients typically refrain from surgical options and FES would not be feasible, the proposed powered orthosis [the subject of this thesis] would provide a viable alternative solution to surgery and FES [3].

2.1.4.3 Wrist Hand Orthoses

As stated in section 1.3 current orthoses include those that are powered and those that are dynamic (allows for movement but does not generate movement). The Broadened Horizons PowerGrip Assisted Grasp Orthosis and the Exo-Glove Poly are powered, whereas the Script Passive Orthosis and the Lateral Key Grip Orthosis are dynamic. Two common drawbacks
associated with these orthoses include are: (1) not having the ability to complete a whole-handed grasp (Lateral Key Grip Orthosis), limiting the objects that can be securely grasped and (2) the inability to don/doff the orthosis independently (all orthoses listed). The Broadened Horizons orthosis, the Exo-Glove Poly, and the SCRIPT orthosis are all cumbersome, costly, and complex. While the LKGO is not, all four are limited in their effectiveness.

2.2 Independence

Among quadriplegic SCI patients, studies have shown that restoring arm and hand function is their highest priority. These patients often experience diminished independence when they lose the ability to use their arms and hands. Therefore, restoring function to hands and providing the ability to grasp objects will allow for independent completion of ADLs that would otherwise need assistance to complete [3-6]. Restoring hand prehension and gripping ability through the application of the tenodesis effect allows patients to independently complete more activities of daily living, such as feeding, grooming, and oral/personal hygiene [8, 11]

2.3 Hand Function Tests

The most common rehabilitation measure tests that specifically assess unilateral hand performance of individuals with a SCI are the Jebsen Hand Function Test, the Action Research Arm Test (ARAT), and Graded and Redefined Assessment of Strength, Sensibility and Prehension (GRASSP) [2, 3, 20, 21].


Chapter 3: Design Methodology

3.1 First Orthosis Iteration

This technology is a powered wrist-hand orthosis (WHO) designed to help individuals with a C6-C7 SCI independently complete activities of daily living (ADL). This WHO utilizes a modified tenodesis grasp to operate in a more intuitive manner, allowing for whole-hand gripping and completion of more ADLs. There are only two mechanical linkages (Figure 5): a thumb and index finger linkage, each configured with a slight angle to mimic the natural bend in fingers during grasping/releasing motions. The first iteration of the prototype requires securing linkages to respective fingers creating a pincer-like design; index, middle, ring and little fingers are bound as one side and the thumb acts as the other side (Figure 6). This orthosis operates via wrist motion input that is detected by a flex sensor on either the dorsal or ventral side of the wrist. Wrist flexion sends a signal to the motor, driving the linkages (and by extension the fingers) into a grasping motion. Conversely, wrist extension creates a releasing motion. This orthosis design is customizable, lighter, and easier to use than currently available WHOs [22].

![Figure 5 Thumb and index finger linkage system](image-url)
3.1.1 Orthosis Control Algorithm

Figure 7 shows the orthosis operational diagram.

![Orthosis operation diagram](image)

The entire orthosis operational code is found in *Appendix C*. The line of code below executes the approximate one-one relationship for wrist motion input and finger motion output. In order to create dis-proportionate output to enable orthosis use for restricted wrist range of motion input, these values (350/880/0/180) would be determined and customized to the individual user during actual orthosis fitting.

\[
\text{val} = \text{map}(	ext{sensorValue}, 350, 880, 0, 180)
\]

To edit the operational code, the current orthosis design requires the microcontroller to be plugged into a computer, however, a future design modification would be to have a graphical user interface on the orthosis. This would allow users to quickly and easily modify their wrist motion.
input and finger motion output. Additionally, if the orthosis is modified to be a rehabilitative device (section 10.5 Contribution to the Field) this would allow users to modify the amount of assistance the device provides.

### 3.2 Second Orthosis Iteration

Based on user feedback, the first iteration of the orthosis had to be modified. The compression glove that was originally used does not allow an individual with a SCI to insert their hand into the glove independently, therefore, a stiffer, more stable device had to be designed. Since current wrist-hand orthoses do not account for independent don/doff [12], this orthosis was modified so, when coupled with its stand, users can independently don/doff the orthotic device.

Figure 8 illustrates the replacement splint (versus the compression glove) and Figures 8 and 9 show the complete orthosis and don/doff system, which allows the individual to insert or remove his/her hand from above the stand. Three rings were added to the existing orthosis: the first on the left side of the thumb, the second on the left side of the wrist, and the third on the right side of the wrist finger (Figure 8). These rings are intended to slip on to three conical pegs (Figures 8 and 9) of the stand to ensure the orthosis stays in a steady and stable position while the user fastens/unfastens Velcro straps with their other hand. Our target population does not have motion in their fingers, but they can make use of their other hand to “hook” their thumbs into rings to fasten/unfasten Velcro. Therefore, if rings are added to the end of the Velcro straps, the modified orthosis design and the new stand design will be a success in independent donning/doffing. This second prototype, in conjunction with the don/doff system, provided enough stability that it could be donned/doffed independently, however it no longer allowed for unencumbered wrist movement, meaning the motor could not be activated and ADLs could not be completed. For this reason, participants in the study used a version of the first prototype to complete the ADL testing.
3.3 Orthosis Used During Testing

The WHO used during testing was similar to the first iteration (Figures 5 and 6). That is, the WHO was constructed with a compression glove, 3-D printed linkages, a flex sensor and a servo motor. A compression glove was chosen since it creates a tight fit that holds the flex sensor flush to the wrist and prevents it from bending in the wrong direction. A piece of fabric was sewn inside the glove to create a compartment which housed the flex sensor during testing (Figure 10).
The WHO has only two 3-D printed linkages, an index finger and a thumb linkage. Each were designed with a slight bend to mimic fingers during a grasping motion. The two linkages are joined by a servo motor. The motor has a maximum torque of 3.06lbs-in, weighs 0.05lbs, and has 180 degrees of allowable rotation. Additionally, a button (shown in Figure 11) was installed which allows the motor to be switched from an active state to a non-active state. This was an extremely important design aspect, because after an object is grasped or grasped and picked up, the user can push the button to deactivate the motor so he/she can freely move his/her wrist and use the object without risk of an accidental release [22].

![Figure 11 Close-up of button that activates and deactivates motor](image)

### 3.4 Don/Doff Stand

The stand was designed small enough to be portable, but wide enough such that the user’s hand will fit comfortably. The stand is comprised of a base plate, three posts, three conical pegs, and an armrest (seen in Figure 12). Most individuals with a SCI do not have substantial arm muscle, so the armrest is intended to bolster the forearm so users do not become weak in trying to hold-up their arm on their own. The three posts vary in height, with the forward most post being the shortest; this puts the orthosis in a downward orientation, making it easier for the orthosis to
be donned and doffed. The armrest was originally designed to be slightly taller than each of three posts, however after donning and doffing the orthosis with the aid of the stand, the armrest was much more useful when it was approximately the same height as the back two posts.

![Figure 12 Orthosis stand](image)
Chapter 4: Testing Methodology

4.1 Inclusion/Exclusion Criteria

All participants were required to be between the ages of eighteen and seventy, be able to understand the informed consent form, and be able to follow directions. These participants had to be right-handed dominant and could not have any injury or pain affecting their hands.

4.2 General Information Survey

Each participant completed a general information survey in which information such as gender, age, height, and weight were collected. Other anatomical measurements such as upper arm length, forearm length, hand width, and finger length were taken and recorded.

4.3 Activities of Daily Living

The most common rehabilitation progress measurement tests that specifically assess unilateral hand performance of individuals with a SCI are the Jebsen Hand Function Test, the Action Research Arm Test (ARAT), and the Graded and Redefined Assessment of Strength, Sensibility and Prehension (GRASSP) [2, 3, 20, 21]. Participants used the WHO to complete certain activities of daily living (ADLs) involving feeding, grooming, and donning/doffing the orthosis. The activities, listed below in Table 1, are a compilation of activities from the above-mentioned tests and were chosen because they have the greatest likelihood of being completed with this orthosis. Excluded activities, such as acute digital manipulation, are not in the design scope of this orthosis.
### Table 1 Activities of daily living

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Feeding</strong></td>
<td></td>
</tr>
<tr>
<td>Grasp and pick up</td>
<td>Grasp and pick up empty water bottle (16.9 fl oz, 2.25” diameter).</td>
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<tr>
<td>empty water bottle</td>
<td></td>
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<tr>
<td>(16.9 fl oz, 2.25”</td>
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<tr>
<td>diameter)</td>
<td></td>
</tr>
<tr>
<td>Grasp and pick up</td>
<td>Grasp and pick up empty Verve (8.3 fl oz, 2” diameter) can.</td>
</tr>
<tr>
<td>empty Verve can (8.3</td>
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<td>fl oz, 2” diameter)</td>
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<tr>
<td>Try to drink and</td>
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<tr>
<td>pour.</td>
<td></td>
</tr>
<tr>
<td>Grasp and pick up</td>
<td>Grasp and pick up full water bottle (16.9 fl oz, 2.25” diameter). Try to</td>
</tr>
<tr>
<td>full water bottle</td>
<td>drink and pour.</td>
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<td>(16.9 fl oz, 2.25”</td>
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<td>diameter)</td>
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<tr>
<td>Grasp (horizontal</td>
<td>Grasp (horizontal orientation), pick up Verve can (8.3 fl oz, 2” diameter).</td>
</tr>
<tr>
<td>orientation), pick</td>
<td>Try to drink and pour.</td>
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<tr>
<td>up fork.</td>
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<tr>
<td>Try to use.</td>
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<tr>
<td>Grasp (vertical</td>
<td>Grasp (vertical orientation), pick up fork. Try to use.</td>
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<tr>
<td>orientation), pick</td>
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<tr>
<td>up fork.</td>
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<td>Try to use.</td>
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<tr>
<td><strong>Grooming</strong></td>
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<tr>
<td>Grasp (horizontal</td>
<td>Grasp (horizontal orientation), pick up toothbrush. Try to use.</td>
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<tr>
<td>orientation), pick</td>
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<tr>
<td>up toothbrush.</td>
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<td>Try to use.</td>
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<td>Grasp (vertical</td>
<td>Grasp (vertical orientation), pick up toothbrush. Try to use.</td>
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<td>up toothbrush.</td>
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<td>Try to use.</td>
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<td>Grasp (horizontal</td>
<td>Grasp (horizontal orientation), pick up hairbrush. Try to use.</td>
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<td>orientation), pick</td>
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<td>up hairbrush.</td>
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<td>Try to use.</td>
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<tr>
<td>Grasp (vertical</td>
<td>Grasp (vertical orientation), pick up hairbrush. Try to use.</td>
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<td>orientation), pick</td>
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<td>up hairbrush.</td>
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<tr>
<td>Try to use.</td>
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<tr>
<td>Grasp (horizontal</td>
<td>Grasp (horizontal orientation), pick up razor. Try to use.</td>
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<tr>
<td>orientation), pick</td>
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<td>up razor.</td>
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<td>Try to use.</td>
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<td>Grasp (vertical</td>
<td>Grasp (vertical orientation), pick up razor. Try to use.</td>
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<td>orientation), pick</td>
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<td>up razor.</td>
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<tr>
<td>Try to use.</td>
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<tr>
<td><strong>Other</strong></td>
<td></td>
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<tr>
<td>Don/Doff orthosis</td>
<td>Don/Doff orthosis independently</td>
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<tr>
<td>independently</td>
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#### 4.4 Vicon Motion Capture System

**4.4.1 Description of Vicon**

The Vicon (Vicon, Englewood, CO) Motion Capture system utilizes an 8-camera 3D set-up, which allows for a 3-dimensional global coordinate system to be estimated from multiple 2-dimensional views. Eight of these cameras are infrared and two are video cameras. Figure 13 below shows the motion capture set-up.
4.4.2 Advantages and Disadvantages of Vicon

A benefit of using the Vicon motion capture system is that if markers cannot be seen in a frame, if a frame is particularly noisy, or if there are false markers, the segment and model can still be observable. Conversely, a disadvantage of this system is the potentially sizeable amount of extrapolation required to replace a missing point in numerous consecutive frames. A large amount of extrapolation would then add to the general error of each trial.

4.5 Procedure

To begin, each subject agreed to participate and signed the necessary consent form. Additionally, a short survey provided gender, age, weight, and height. Subjects also had certain physical attributes measured including: upper arm length, forearm length, hand width, and finger length. Once the informed consent and photo release forms were signed and the general information survey completed, a member of the study team put the orthosis on the individual. Using adhesive stickers, a set of fourteen spherical reflective markers were placed on each participant at specific anatomical landmarks to track their motion using the Vicon motion capture system (see Figures 14 and 15 below).
A member of the study team then reviewed details of how the device works, making sure each participant knew that he/she would have to completely relax their hand in order to allow the motor to do all the work. The subjects were also shown the on/off button and how it could be utilized during the trials. (Moving the button to “off” locks the orthosis position to assist with maintaining a desired grasp).

Participants were then led to the testing area which consisted of a straight-back chair and small table at the center of the motion capture system (see Figure 13). Participants used the WHO
to complete ADLs involving feeding, grooming, and donning/doffing the orthosis (list can be found above in Table 1). Before beginning each new task, a member of the study team explained exactly what the participant would be attempting and gave the participant time to practice. After the practice period, with the motion capture system running, each subject attempted to complete the task. There were 3-4 outcomes observed: successful grasp, successful pick up while maintaining grasp, successful use of the object, and in the cases of the full water bottle and full soda can, successful pouring of liquid. For the task of donning/doffing, success was based on whether the subject could independently don/doff the device. Each task was performed three times in full view of the motion capture system. Orthosis design modifications will focus on improving device capability to successfully accomplish activities that were not originally completed.

Motion capture data were then visualized in OpenSim to illustrate how the orthosis interacts with a human upper limb, and further, how this orthosis and upper limb combination would act as a singular system. Additionally, limited wrist ranges of motion (from responses Assistive Technology Survey responses), will be programmed into the OpenSim model to test the operational effectiveness of the orthosis-upper limb system within these limited wrist motion boundaries.
Chapter 5: Assistive Technology Survey

5.1 Survey Purpose

This study was a feasibility study in which the device was not tested on individuals with a spinal cord injury, however, there was still a need to gather information on whether the target population (SCI) would benefit from an assistive device to help with grasping motions. A survey was created in Survey Monkey and distributed (via an emailed link) to individuals with a spinal cord injury. Information gathered through this survey included [23]:

- Difficulties (if any) when grasping objects.
- Activities of Daily Living (ADLs) that can and cannot be completed independently.
- Whether any upper limb orthoses had been tried in the past.

5.2 Survey Questions

The survey included questions related to [23]:

- Level of spinal cord injury
- The amount (degrees) of wrist motion (flexion and extension)
- Ability and/or inability to grasp objects
- Abilities and/or inabilities to independently complete activities of daily living (brushing teeth, eating, drinking, etc.)

A full copy of the survey questions can be found in the Appendix A.
Chapter 6: Data Analysis: OpenSim

OpenSim is an open-source simulation software application originally developed at Stanford University that allows users to develop, edit, and merge existing musculoskeletal models to create dynamic movement simulations. These models are useful in understanding aspects of biomechanics and motor control, including ranges of motion and muscle load during motor tasks.

This project used an existing model, 2nd_Hand_Model, which consists of a healthy human torso, upper arm, forearm, and hand, as well as all the muscles in that single arm (see Figure 16 below).

![OpenSim 2nd_Hand_Model with marker set](image)

This particular model depicts motion of all joints: shoulder, elbow, wrist, and all five fingers. This was of utmost importance because all tasks completed during this study required the use of all of these joints (excepting the middle, ring and little finger joints- those three fingers move together as one with the index finger during testing). Other models considered were: (1) WristModel, which
included only the wrist joint with two moving fingers- index finger and thumb, [an excellent model of the orthosis motion], (2) \textit{MoBL-ARMS Dynamic Upper Limb}, which was similar to the \textit{2nd Hand Model}, except all five fingers were in a curled position, and none were able to move [not an acceptable model for this orthosis], and (3) a combined model of (1) and (2). This third model did not simulate motion correctly (in the motion file), most likely due to misalignment of the local coordinate axes of both models. All three models are shown in Figure 17.

![Figure 17](image)

Figure 17 Left to right: (1) \textit{WristModel}: only wrist joint, index finger and thumb motion, (2) \textit{MoBL-ARMS Dynamic Upper Limb}: all fingers in a permanently curled position (do not move), (3) combined model of (1) and (2): simulated motion was not accurate

Both the \textit{WristModel} and the \textit{MoBL-ARMS Dynamic Upper Limb} model were existing models available for anyone to download. The combined model was created by modifying and merging each of these specifically for this project. The \textit{2nd Hand Model} was chosen, since it was openly available for download, had no issue with axes alignment, and was a combination of the first two models (with added middle, ring, and little finger motion capability not used).

Initially, there were two main issues with the \textit{2nd Hand Model}. The first issue was that the model did not include code for marker names or marker placement. This meant when a motion file, which includes marker names and trajectories, was uploaded, the trajectories did not have anything to “attach” to (i.e. motion file marker inputs were not recognized), resulting in non-execution of that simulation. Once the marker names and placement were properly coded into the
model, motion trajectories could “attach” to each marker and the simulation was then successfully executed. The second model issue was the torso being fixed to the ground position, not allowing it to move, and causing a problem for arm motion. Take the *Empty Water Bottle* motion file for example; a healthy subject was seated, reached out (extended) their right arm, grasped the empty water bottle, lifted it to their mouth, set it back down, and then released the bottle. When this motion was loaded into the fixed-torso *2nd_Hand_Model*, the OpenSim output motion merely moved the arm up and down, not in the manner expected as described above. This inaccurate output was due to the simulation model torso being fixed and therefore could not replicate motion toward the target object. In other words, OpenSim adjusted input motion data to calculate a solution within its capabilities resulting in output motion that does not accurately duplicate reality. This is a limitation of OpenSim that will be discussed further in section 9.2: *OpenSim Limitations*. As soon as code was added to the torso allowing it free translational and rotational movement, the simulated output motion was accurate.

With an accurately working model, the next step was to alter the healthy upper limb model to simulate a person with a SCI. The orthosis linkage computer aided design (CAD) files were then uploaded into the model to help visualize and simulate how the device would help a person with a SCI (Figure 18)

![Figure 18 Orthosis linkage CAD files loaded into OpenSim model](image)
However, due to OpenSim limitations, this was not possible; a person with a SCI could not be simulated and the added CAD models did not interact with the model, they ended up being strictly for visual purposes. It was also planned to utilize OpenSim to help determine optimal orthosis design configuration(s) by testing various designs of orthosis parts (linkage bend angle, motor torque, and placement of the flex sensor, but again, OpenSim unfortunately does not allow for this type of experimentation. Other OpenSim limitations will be discussed in section 9.2: OpenSim Limitations.

Although there were many limitations with using OpenSim, it did allow the input data to be analyzed to output wrist, thumb, and index finger joint angle graphs. Analyzing the wrist joint angle graphs led to conclusions about the required wrist flexion/extension for successful completion of ADLs. These joint angle graphs are discussed in the next chapter, Results, section 7.3: OpenSim Analysis and Results.
Chapter 7: Results

7.1 Population

A total of ten individuals participated in the study, six of whom were male and four female. These subjects varied in age, whether they had prior knowledge of how the device worked, and whether they had an engineering background. This study enrolled four individuals in their twenties, two individuals in their fifties, and four individuals in their sixties. Forty percent (40%) of the subjects had prior knowledge of how the device operated and forty percent (40%) had an engineering background. Thirty percent (30%) of the subjects had both prior knowledge of how the device operates and an engineering background; one subject had prior knowledge, but not an engineering background and another subject had no prior knowledge, but did have an engineering background. It was hypothesized that the individuals who had prior knowledge and/or an engineering background would be able to learn the device operation much more quickly and achieve a higher level of success compared to those who were seeing the device for the first time and had no engineering background. However, study participants' performance and success rate was not aligned with this hypothesis. Individuals who did have prior knowledge and/or an engineering background did not exhibit any greater degree of aptitude or success in completing the assigned ADLs. All study participants initially experienced difficulty using the device (it got much easier for all subjects as testing proceeded) and were equally successful or unsuccessful in completion of ADLs. This is important because it means individuals with a SCI, who will have no prior knowledge of the device, will have a good chance at using it successfully.
7.2 Completion of Activities of Daily Living

7.2.1 Feeding

All ten subjects used the orthosis to attempt to complete six feeding ADL tasks; those results are summarized in Figure 19 below.

![Figure 19](image)

Figure 19 Summary: number of individuals who were successful and unsuccessful in completing feeding ADL tasks

The first task required subjects to grasp, pick up, and bring an empty water bottle (16.7 fl oz) to their mouth. Eighty percent (80%) of the subjects could grasp, pick up and bring it to their mouth. Twenty percent (20%) of the subjects could not grasp, therefore could not pick up and bring to mouth. This was most likely due to a combination of two circumstances: (1) the empty water bottle was the first task and subjects were still getting used to the device, and (2) the subjects’ difficulty with initially understanding how the device works, in particular, preventing themselves from using their own grasping ability. It is worth noting that one subject who could not complete the first task was able to complete the second and further tasks. This is most likely due to increased familiarity and aptitude as the trials continued.
The second task required subjects to grasp, pick up, and bring an empty soda can (8 fl oz) to their mouths. Ninety percent (90%) of the subjects were successful in grasping, picking up and bringing the empty soda can to their mouths. The one subject that was unsuccessful admitted to not being at all comfortable using the device rather than their own grip strength. Every subject commented that this object was easier to grasp, compared to the water bottle, because it was smaller in diameter.

The third task tested whether subjects could grasp, pick up, drink, and pour from a full water bottle (16.7 fl oz). All subjects (100%) were able to grasp the full water bottle, but none (0%) were able to pick it up, and therefore could not drink or pour from it. The full water bottle was too heavy for the orthosis motor to maintain a secure grasp. Many subjects commented that if the motor was stronger, they could have achieved and maintained a tighter grasp and would have had a better chance of picking up and pouring from the full water bottle. Additionally, subjects also noted that rubber grips on the inside of the orthosis and fingers would help with maintaining a grasp.

The fourth task tested a full soda can (8 fl oz). Similar to the full water bottle, all subjects (100%) were able to grasp the full soda can, but none (0%) were able to pick it up, and therefore could not drink or pour from it. Again, the full soda can was too heavy for the strength of the orthosis motor. Many subjects had the same comments in regards to the motor strength and rubber grips. One subject even commented that having a removable “ledge” after the little (pinky) finger that extended medially could slide under the bottom of the bottle/can, and would add extra stability when picking up and using upright cylindrical objects.

The fifth and sixth tasks tested whether subjects could grasp, pick up, and use a common utensil. The utensil was first placed in a horizontal orientation (Figure 20 and third set of pictures
in Figure 41), then in a vertical orientation. It was hypothesized that subjects would be more successful when the utensil was in a fully vertical orientation, but the subjects had more success when the utensil was placed in a slightly raised orientation, specifically when it was placed diagonally at a height of 49mm (Figure 20). This particular positioning allowed enough space under the utensil stem for the subjects’ fingers so he/she could achieve a grasp, as well as, putting the utensil in a usable orientation.

![Figure 20 Utensil resting diagonally at a 49mm height. This positioning put space under the stem which allowed users to slip their finger(s) under the stem to get a good grasp](image)

When the utensil was in a vertical orientation, ninety percent (90%) could grasp it, seventy percent (70%) could pick it up, but only ten percent (10%) said they could use the utensil. For the more successful, horizontal positioning all subjects (100%) were able to grasp the utensil, eighty percent (80%) could pick it up, and thirty percent (30%) said they could use the utensil. Although many subjects commented that their grip was not tight enough to be able to use the utensil, a stronger motor combined with a horizontal orientation would allow the utensil to be used.

7.2.2 Grooming

The next set of ADL tasks addressed those that involve grooming; a summary of these results is graphed in Figure 21 below. Attempting to grasp, pick up, and use the toothbrush were the seventh (horizontal orientation) and eighth (vertical orientation) tasks.
As hypothesized, subjects had greater success at grasping, picking up, and using the toothbrush in a vertical orientation. In fact, for one subject, when the toothbrush was initially placed in a horizontal orientation, she grasped it and re-oriented her hand it was in a vertical orientation, slightly released until it landed on the table, and then re-grasped it from that vertical position. This subject noted that she did not have a secure grasp when the toothbrush was in the horizontal orientation. For both orientations, all subjects (100%) were able to grasp the toothbrush. For the horizontal orientation, sixty percent (60%) could pick up the toothbrush, but only twenty percent (20%) said they would be able to brush their teeth. The vertical orientation allowed seventy percent (70%) of the subjects to pick up the toothbrush, but most commented that their grip was not strong enough to use the toothbrush; thirty percent (30%) did believe they had a strong enough grasp to use the toothbrush. The thirty percent (30%) who thought they could brush their teeth noted that since toothbrush was electric, the user would not have to do much work. Subjects who thought they could not brush their teeth thought their grip was not strong enough to overcome the slipping caused by vibration. These issues could be addressed/solved with a stronger motor.
The ninth and tenth tasks involved a hairbrush in both horizontal and vertical orientations. Again, it was hypothesized that when the hairbrush was in a vertical orientation, users would be more successful in grasping, picking up, and using the object. All subjects (100%) were successful in grasping the hairbrush in a horizontal orientation, eighty percent (80%) were successful in picking up and seventy percent (70%) said they would be successful using the hairbrush. However, when the hairbrush originated in a vertical position, subjects were much more successful; all subjects (100%) were able to grasp, pick up, and use the hairbrush.

The eleventh and twelfth tasks tested whether a razor could be grasped, picked up and used when it was in a horizontal orientation and then a vertical orientation. As with other objects, it was hypothesized that users would be more successful when the razor was placed in a vertical orientation, however, subjects were equally successful in grasping the razor regardless of orientation. In both instances, all subjects (100%) were able to grasp the razor, ninety percent (90%) were able pick up the razor and fifty percent (50%) thought they would be able to shave.

Testing only looked at shaving the face (for men), as shaving legs or other area (for women) would usually require the individual to be in the shower, but orthosis is not designed to go in water. Just like with all the other objects, the ability to use is subjective, and relies on whether the subjects think they can use the razor. Those that thought they could not use the razor did not have an actual grasp on the handle, but had the razor head “caught” in the hand opening created by the orthosis linkages. This led the subjects to believe they could not achieve the force needed to stabilize the razor and shave. Figure 22 shows the difference in the razor in an actual grasp between the thumb and index finger and the razor “caught” in a hand opening, balancing on the linkages.
7.2.3 Other

The final task asked subjects to independently don/doff (put on/take off) the orthosis. The result from this test is pictured below in Figure 23. Given that this device is ultimately meant to help individuals who do not have full use of either hand, subjects were told they could move their wrist, but not their left hand or fingers. All subjects (100%) declined to try to independently put the device on or take it off; this result was exactly in line with the hypothesis. As stated earlier in section 3.2: Second Orthosis Iteration, the second iteration of the orthosis could be independently donned/doffed, with the use of the don/doff stand, however, that orthosis design used a wrist splint which restricted wrist motion and would not allow the user to complete any ADLs. Therefore, a version similar to the first iteration was used for testing, one that allowed for wrist motion and completion of ADLs but could effectively prohibited independent don/doff.

Figure 23 Summary: all subjects were unsuccessful with independent don/doff
7.3 OpenSim Analysis and Results

The motion capture data was loaded into the OpenSim model to create simulated motion for the twelve ADL trials. The OpenSim simulated motion data was analyzed to obtain wrist and finger joint angles. For the motion capture stage, healthy Individuals were instructed to attempt to mimic individuals with a SCI: there was no restriction on wrist motion, but each was informed to override their natural tendency to use their fingers; the motor should be driving all finger movements. The wrist joint angle graphs show wrist angles from user input (no restriction on wrist motion), but the resulting finger joint angle graphs show angles produced from the motor output for each trial.

7.3.1 Wrist Joint Angle Graphs

Graphical data review shows that a greater degree of wrist extension was used versus wrist flexion in the majority of tasks. In all twelve task trials, wrist extension was consistently close to the maximum reading (-70 degrees); actual graphical readings were between -50 and -60 degrees. The lone exception is the Full Water Bottle, which can be considered an outlier due to the difficulty in picking up the full bottle. The beginning wrist extension for the Full Water Bottle should match within ±5 degrees to that of the Empty Water Bottle. Actual results are -54 degrees for the empty water bottle and -39 degrees for the full water bottle. These results should have mirrored those of the two soda can trials. Although there was also some difficulty in picking up the full soda can, the beginning wrist extension data for full (-45 degrees) and empty (-46 degrees) soda can are well within expected limits. This can be seen when examining the four graphs: Empty Water Bottle, Full Water Bottle, Empty Soda Can, and Full Soda Can graphs, in Figures 24 and 25.
Figure 24 Wrist joint angle graphs for the empty water bottle, empty soda can, full water bottle
A greater degree of wrist flexion was required when grasping thinner, smaller diameter objects (less than 0.5 inches in diameter). Healthy individuals tend to utilize a “pinch” grasp, only using the thumb and index finger, on these smaller diameter objects versus whole-hand grasping. However, the orthosis was not intended to emulate digital dexterity, so greater wrist flexion is required to complete these ADL tasks. An exception to this finding is in the case of the full water bottle and full soda can, there was greater wrist flexion than when each object was empty. This is most likely due to the fact that the motor was not strong enough to create and maintain a secure grasp, so subjects over compensated by increasing wrist flexion in their attempts to pick up the full, heavier, objects. This increased wrist flexion can be seen by looking at the Full Water Bottle and Full Soda Can graphs in Figures 24 and 25 and comparing it to the degree of wrist flexion seen in the Empty Water Bottle and Empty Soda Can graphs in the same figure.

For the smaller diameter objects (utensil, brush, toothbrush, razor) the horizontal orientation required more wrist flexion than the vertical orientation. Wrist flexion for horizontal orientation is between +30 degrees and +40 degrees, with the exception of the utensil, which requires full wrist flexion (approx. +70 degrees). This is due to the fact that the utensil is the
thinnest object. Wrist flexion for vertically orientated objects ranged from +5 degrees to +30 degrees. All of this information can be seen in the eight graphs below in Figures 26, 27, and 28.

Figure 26 Wrist joint angle graphs for utensil (horizontal and vertical) and brush (horizontal)
Figure 27 Wrist joint angle graphs for brush (vertical) and razor (horizontal and vertical)
7.3.2 Finger Joint Angle Graphs

As stated earlier, OpenSim was used to analyze the motion capture data to get joint angle graphs for the index finger and thumb. Specifically, index finger flexion/extension for the metacarpophalangeal (MCP2) joint and thumb flexion/extension and abduction/adduction for the carpometacarpal (CMC) joint. Index finger flexion/extension and thumb flexion/extension and abduction/adduction are demonstrated in Figure 29. The MCP2 and CMC joints are pointed out in Figure 30.

Figure 28 Wrist joint angle graphs: toothbrush (horizontal orientation and vertical)
Figure 29 Index finger (left) and thumb (right) motions [24, 25]

Figure 30 Metacarpophalangeal (MCP2) and carpometacarpal (CMC) joints

Below in Figures 31-42 are 36 graphs that show joint angles for the index finger and thumb. For all tasks, thumb flexion/extension remains relatively constant throughout the trial, which is accurate for the motions associated with all tasks. In all cases, subjects’ thumbs were in a slight extension. The variation of thumb flexion/extension is most likely due to the fact the subjects were healthy and had motion in their fingers, so some inadvertent motion would have shown up on the graphs. Again, for all tasks, the graphs show there is thumb abduction/adduction present, however, knowing the motions associated with each task, this is not accurate. The thumb linkage does not actually move, the index finger linkage pivots to move toward or way from the thumb linkage. OpenSim did not recognize that the thumb should remain relatively stationary and most likely misinterpreted wrist flexion/extension in combination with index finger flexion/extension as thumb abduction/adduction. For example, when the wrist would flex, the index finger also would flex, moving the index finger closer to the thumb. Since the two fingers became closer, OpenSim most likely modeled this action to include some thumb adduction. Conversely, when the wrist
would extend moving the index finger away from the thumb, OpenSim misconstrued this to be some thumb abduction [essentially “undoing” or reversing the modeled action above].

Figure 31 Index finger flexion/extension for empty and full water bottle and empty soda can
Figure 32 Index finger flexion/extension for full soda can and utensil (horizontal and vertical)
Figure 33 Index finger flexion/extension for brush (horizontal and vertical) and razor (horizontal)
Figure 34 Index finger flexion/extension: razor (vertical) and toothbrush (horizontal and vertical)
Figure 35 Thumb flexion/extension: empty and full water bottle and empty soda can
Figure 36 Thumb flexion/extension: full soda can and utensil (horizontal and vertical)
Figure 37 Thumb flexion/extension: brush (horizontal and vertical) and razor (horizontal)
Figure 38 Thumb flexion/extension: razor (vertical) and toothbrush (horizontal and vertical)
Figure 39 Thumb abduction/adduction: full and empty water bottle and empty soda can
Figure 40 Thumb abduction/adduction: full soda can and utensil (horizontal and vertical)
Figure 41  Thumb abduction/adduction: brush (horizontal and vertical) and razor (horizontal)
Figure 42 Thumb abduction/adduction: razor (vertical) and toothbrush (horizontal and vertical)
7.4 Survey

7.4.1 Level and Type of Spinal Cord Injury

Since this study was a feasibility study, and testing the device on individuals with a SCI was not an option, an Assistive Technologies survey was distributed to a small sampling of the SCI population to gain insight into whether or not an assistive device would benefit members of the target population. Thirty-five individuals responded to the survey; thirty-three identified as having some classification of a SCI, one was a clinician, and one had cerebral palsy (CP). Approximately 33% of these responders (11/33 responses) have a C6-C7 SCI with at least 6% (2/33 responses), or at most 12% (4/33 responses) falling into the original target population- individuals who have an incomplete C6-C7 SCI (see Figure 43). Two responding individuals did not answer whether their spinal cord injury was a complete or incomplete injury, hence the 6% minimum / 12% maximum levels cited previously. It was originally hypothesized that only individuals with an incomplete C6-C7 SCI would have retained wrist motion and would benefit from this device but based on survey responses, individuals with both an incomplete and a complete C6-C7 SCI retain some wrist motion and would be able to use this orthosis. If the two responses that were left blank are complete SCIs then based on the original hypothesis this orthosis would have only helped only 6% of the population, however, this device can actually benefit 33% of the SCI population, roughly 6 times the original supposition. If, on the other hand, the two undeclared responses are actually incomplete SCIs then this orthosis would have gone from helping 12% of the population to 33% of the population, almost 3 times as many individuals. Regardless of the actual classification of the two undeclared respondents, the key takeaway is that the target population has drastically increased to greater than 30% of the SCI population, several orders of magnitude greater than originally hypothesized [23].
7.4.2 Wrist Flexion/Extension Limitations

As stated earlier, the original hypothesis was that this device could help only those individuals who have an incomplete C6-C7 SCI, as they would have retained wrist motion, which is the basic requirement for the device’s operation. However, self-reported survey results clearly indicate that individuals who have a complete C6-C7 SCI still retain some wrist motion. Specifically, all seven individuals who responded as having a complete SCI also responded that they retained wrist motion (Table 2). Since the survey relies on self-reported, non-verified information, some additional work needs to be done to validate the survey results.

Table 2 Respondents with a complete or incomplete SCI retain wrist motion

<table>
<thead>
<tr>
<th>Level of Injury</th>
<th>Incomplete or Complete</th>
<th>Wrist Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>C5/C6</td>
<td>Complete</td>
<td>Yes</td>
</tr>
<tr>
<td>C6</td>
<td>Complete</td>
<td>Yes</td>
</tr>
<tr>
<td>C6</td>
<td>Complete</td>
<td>Yes</td>
</tr>
<tr>
<td>C6</td>
<td>Complete</td>
<td>Yes</td>
</tr>
<tr>
<td>C7</td>
<td>Complete</td>
<td>Yes</td>
</tr>
<tr>
<td>C7</td>
<td>Complete</td>
<td>Yes</td>
</tr>
<tr>
<td>C7</td>
<td>Complete</td>
<td>Yes</td>
</tr>
<tr>
<td>C6/C7</td>
<td>Incomplete</td>
<td>Yes</td>
</tr>
<tr>
<td>C7</td>
<td>Incomplete</td>
<td>Yes</td>
</tr>
<tr>
<td>C5/C6</td>
<td>Unspecified</td>
<td>Yes</td>
</tr>
<tr>
<td>C6</td>
<td>Unspecified</td>
<td>Yes</td>
</tr>
</tbody>
</table>
It is worth noting that 1 individual who responded as having a complete C6 SCI did comment that he/she had a tendon transfer surgery which increased his/her tenodesis grasp (wrist extension) capability. This particular response clearly indicated that this individual had some wrist flexion/extension prior to the tendon transfer surgery, however, wrist extension was increased afterwards. To reiterate the main point, 100% of respondents that self-identify as having C6-C7 SCI retained some wrist motion and are candidates for using the orthosis to independently complete ADLs. The breakdown of the wrist flexion/extension ranges for responders are shown below in Figure 44.

![Figure 44 Percentages of wrist flexion and extension ranges for individuals who have a complete or incomplete C6-C7 SCI and for those that did not specify](image)

For individuals with a complete C6-C7 SCI there was 1 response for each wrist flexion range 11°-20°, 31°-40°, 41°-50°, 51°-60° and 3 responses for the wrist flexion range 61°-70°. Similarly, there was 1 response for each wrist extension range 21°-30°, 31°-40°, 41°-50°, 51°-60°
and 3 responses for wrist extension range 61°-70°. For individuals with an incomplete C6-C7 SCI, responses for wrist flexion and extension ranges were the same: 11°-20° and 41°-50°, with each range receiving 1 response. As mentioned earlier, there were two individuals who did not specify whether they had an incomplete or a complete SCI, however, they did respond positively regarding retained wrist motion. One individual had 41°-50° of both wrist extension and wrist flexion, while the other individual had 0°-10° of wrist flexion and 61°-70° of wrist extension. The above wrist flexion/extension information is shown in Table 3 and Appendix B pareto charts (Figures 66 and 67). Important note: all self-reported information needs to be independently verified.

Table 3 Survey results: respondents self-reported limited wrist flexion and extension ranges

<table>
<thead>
<tr>
<th>Level of Injury</th>
<th>Incomplete or Complete</th>
<th>Wrist Motion</th>
<th>Wrist Flexion Ranges</th>
<th>Wrist Extension Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>C5/C6</td>
<td>Unspecified</td>
<td>Yes</td>
<td>0°-10°</td>
<td>61°-70°</td>
</tr>
<tr>
<td>C6/C7</td>
<td>Incomplete</td>
<td>Yes</td>
<td>11°-20°</td>
<td>11°-20°</td>
</tr>
<tr>
<td>C5/C6</td>
<td>Complete</td>
<td>Yes</td>
<td>11°-20°</td>
<td>21°-30°</td>
</tr>
<tr>
<td>C6</td>
<td>Complete</td>
<td>Yes</td>
<td>31°-40°</td>
<td>31°-40°</td>
</tr>
<tr>
<td>C7</td>
<td>Complete</td>
<td>Yes</td>
<td>41°-50°</td>
<td>41°-50°</td>
</tr>
<tr>
<td>C7</td>
<td>Incomplete</td>
<td>Yes</td>
<td>41°-50°</td>
<td>41°-50°</td>
</tr>
<tr>
<td>C6</td>
<td>Unspecified</td>
<td>Yes</td>
<td>41°-50°</td>
<td>41°-50°</td>
</tr>
<tr>
<td>C7</td>
<td>Complete</td>
<td>Yes</td>
<td>51°-60°</td>
<td>51°-60°</td>
</tr>
<tr>
<td>C6</td>
<td>Complete</td>
<td>Yes</td>
<td>61°-70°</td>
<td>61°-70°</td>
</tr>
<tr>
<td>C6</td>
<td>Complete</td>
<td>Yes</td>
<td>61°-70°</td>
<td>61°-70°</td>
</tr>
<tr>
<td>C7</td>
<td>Complete</td>
<td>Yes</td>
<td>61°-70°</td>
<td>61°-70°</td>
</tr>
</tbody>
</table>

Individuals who have asymmetric flexion/extension ranges would be candidates for special programming of the orthosis control system (wrist motion input is dis-proportionate to the finger motion output) [23]. For example, the orthosis can be programed to output 4° of finger motion for every 1° of wrist motion input. If a user is limited to 10° of wrist extension input, the device can be programmed to output 40° of finger motion.
7.4.3 Level of Difficulty and Method of Grasping Objects

Figure 45 Survey responses indicating the difficulty in grasping everyday objects

Among the target population (11 individuals), the most common response, with 50%, was “some difficulty”. Objects in a vertical orientation are the easiest for responders to grasp; 46% have no difficulty grasping a toothbrush in a vertical orientation, 36% have no difficulty grasping a utensil and hairbrush in a vertical orientation, and 27% have no difficulty grasping a razor in a vertical orientation. Survey responses indicated the full ceramic mug is the most difficult to grasp; 45% of the target population responded that they “cannot grasp” a full ceramic mug.

Figure 46 shows the method the target population survey responders use to grasp everyday objects. For all twelve objects, one handed grasping is the most common method, with it being used 61% of the time. The full ceramic mug, full plastic bottle, and empty ceramic mug were objects that required most respondents to use both hands to grasp; 82% required both hands to grasp the full ceramic mug and full plastic bottle, and 55% required both hands to grasp the full plastic bottle [23].
7.4.4 Previous Orthosis Use and Likes and Dislikes

Table 4 below shows that about 27% (3 individuals) of responders, within the target population, have used an orthosis. Although the actual types of orthoses were not always given, each person liked that their device allowed them either to independently complete ADLs or that the device could be independently donned/doffed, or both. Reasons for these individuals to dislike their orthosis included it not being customizable, it was not aesthetically pleasing, and/or it was too larger (bulky) and heavy. [23]

Table 4 Survey responses indicating prior orthosis use and the likes and dislikes

<table>
<thead>
<tr>
<th>Level of Injury</th>
<th>Incomplete or Complete Injury</th>
<th>Have you used an Orthosis?</th>
<th>Orthosis Likes</th>
<th>Orthosis Dislikes</th>
</tr>
</thead>
<tbody>
<tr>
<td>C6</td>
<td>Complete</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C6</td>
<td>Complete</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C6/C7</td>
<td>Incomplete</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C7</td>
<td>Complete</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C7</td>
<td>Complete</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C7</td>
<td>Incomplete</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C6</td>
<td>Unspecified</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C5/C6</td>
<td>Unspecified</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C5/C6</td>
<td>Complete</td>
<td>Yes</td>
<td>Ability to don/doff</td>
<td>Not Customizable</td>
</tr>
</tbody>
</table>
7.4.5 ADL Ranking

Below is Figure 47, which shows how survey respondents rank the importance of independently completing five everyday activities: drinking, eating, brushing teeth, brushing hair, and shaving. Independently drinking and eating were the highest priorities among the target population. Approximately 55% of the target population respondents ranked independently eating as their highest priority, and about 36% rank independently drinking as their highest priority. Similarly, 55% responded with independently drinking as the second most important ADL and about 45% believe independently eating the second most important ADL. Most responses, 64%, rank “shaving” as the least important ADL to complete independently; 18% ranked “brushing hair” as their least important priority [23].

![Figure 47: Assistive Technology Survey responses: ADL importance ranking](image_url)
Chapter 8: Observations/Comments

8.1 Orthosis Testing

During testing, there were many common comments regarding improvements on orthosis design and observations on grasping techniques.

8.1.1 Orthosis Design

All ten subjects had two comments that dealt with modifying the orthosis: (1) adding rubber grips to the inside of the Velcro strips would help the user maintain their grasp while picking up, holding and using the object, and (2) a stronger motor is needed maintain an adequately strong grip in order to pick up heavier objects. One subject suggested that adding a “shelf” located below the little (pinky) finger that extends medially would help stabilize objects when they are picked up. If this piece were added, it would most likely interfere with grasping and picking up other objects, so a possible solution would be to have this piece easily attachable/detachable or automatically retractable.

The linkages need to be customized to each individual user’s hand/fingers. In one particular instance a subject was fitted with the Medium sized linkages (based on finger length) but, by chance, that particular set malfunctioned about half way through testing, so the Medium linkage set was switched out for the Large linkage set. The subject commented that the Large linkage set fit much better. The index linkage of the Medium protruded off the index finger and would actually push objects out of grasp. When testing resumed with the Large set, it was observed the index linkage no longer protruded off the index finger, but fit perfectly in line with the finger. The subject felt that a correctly sized linkage set made such a difference with the second half of the tasks that
he asked to repeat the tasks he had completed while wearing the Medium sized set. This better fit allowed the subject to be more successful in grasping objects and maintaining that grasp while using these objects. This emphasizes the point that linkage customization is crucial for the WHO to be successful, especially when dealing with the target population whose hands/fingers may not be shaped like those of the healthy subjects in this study. Fortunately, the low cost of 3D printing means that individual customization can be readily achieved, and easily iterated for optimization after individual hand measurements are obtained.

For two subjects, the X-Large glove was a little too small for their hands, so it ballooned on the lower palm, upper wrist area, causing the flex sensor to not sit flush against the wrist. With the sensor not flush against the wrist, it does not adequately detect wrist motions causing the linkages to not open and close enough to complete tasks. Since there was not a larger glove, these two users had to hold the sensor against their wrist in order for the linkages to operate properly and complete the tasks. Figure 48 shows a user pushing the flex sensor against their wrist to complete the hairbrush task, and Figure 49 a second user doing the same to complete a water bottle task.

Figure 48 X-Large glove that was too small for user’s hand caused a balloon effect on the lower palm, upper wrist area. Subject had to push flex sensor flush against wrist so linkages could open/close enough to complete hairbrush task
8.1.2 Water Bottle and Soda Can Tasks

Nine out ten subjects were able to successfully grasp, pick up, and use the empty water bottle and empty soda can. All nine subjects commented that the empty soda can was much easier to grasp because the diameter was smaller, and body was thinner (2” diameter) than those of the water bottle (2.25” diameter). Figure 50 shows the body shape of the soda can and water bottles exactly as they were utilized in the testing of all subjects.
For the water the bottles and soda cans, one subject grasped and then “paddled” the object towards the edge of table instead of lifting straight up. This subject found by doing this movement, the object moved further into the back of the palm creating a more secure grasp before picking up the object. Figure 51, below shows four stages, from the bottle in the initial grasp, the bottle being “paddled” closer to the table edge, and the subject successfully picking up the bottle.

![Figure 51](image)

Figure 51 Subject "paddled" the bottle towards the edge of table before picking it up. Top Left: bottle initially in grasp, Top Right: second position, closer to edge, Bottom Left: bottle at edge, Bottom Right: Subject successfully picks up the empty bottle

8.1.3 Tasks with Objects in a Horizontal Orientation

Objects such as the toothbrush, hairbrush, utensil, and razor were placed in a horizontal orientation, laying down on the table’s flat surface, but no one was successful in grasping any of these objects in this strictly horizontal orientation. Each object was then placed to rest diagonally on a duct tape roll (at two different heights), which created space under the object and made attempts grasp much more successful (Figure 52).
Figure 52 Objects in horizontal orientation, resting diagonally on duct tape roll; left: duct tape is 49mm (~2in) high, right: duct tape is 96mm (~3.8in) high
For the toothbrush and hair brush, the set-up on the right (duct tape at 96mm) worked best for subjects to complete a successful grasp, maintain that grasp and use the object. For the fork and razor, the set-up on the left (duct tape at 49mm) worked best for executing a successful grasp, maintaining that grasp and being able to use the object.

One subject asked for the hairbrush (horizontal orientation) to be placed on its side, handle resting on the duct tape roll (96mm height), bristles pointing away from body (see Figure 53). Also seen in Figure 53 is this particular subject’s starting hand position. This is noteworthy because once the subject grasped the hairbrush it was in a position where it could then be used without further manipulation of the hairbrush orientation. If the subject had used a different starting position, the hairbrush would not be in a usable position.

![Figure 53](image)

Figure 53 Subject asked for the hairbrush to be placed on its side, handle resting on the duct tape roll (96mm height), bristles pointing away from body. Also, the subject’s starting hand position allows the hairbrush to be in a usable position when grasped.

Similarly, this subject asked for the toothbrush (horizontal orientation) to be placed such that the head was on the table, bristles pointing up, and base was resting on the duct tape roll (96mm height). Again, the initial hand positioning allowed the toothbrush to be in a useable position upon grasping. Figure 54 shows the toothbrush starting position, the subject’s initial hand position, and the subject initializing the grasp which will put the toothbrush in a usable position.

![Figure 54](image)
Figure 54 Subject asked for the toothbrush to be placed with the head on the table, bristles pointing up, and base was resting on the duct tape roll (96mm height). The subject’s initial hand position and starting grasp put the toothbrush in a usable position.

8.1.4 Utensil Tasks

The thin stem on the fork caused some subjects to have difficulty when grasping. Figure 55 (left and middle) shows that some users were able to grasp the thin stem between their thumb and index finger. In other instances, the fork was not actually grasped, but balanced on fingers, as seen in Figure 55 (right). An overall comment, even among those that had little difficulty, was that utensils with a fatter stem would make grasping and using easier. Sometimes markers on the orthosis got caught on markers on the object, or on the Velcro strips, which prevented the object from slipping when it otherwise would have slipped out of the subject’s grasp (Figure 56).
8.1.5 Toothbrush Tasks

Many subjects commented that they could grasp, pick up, and bring the toothbrush to their mouths, but definitely would not be able to brush their teeth. Subjects agreed that the force caused from pressing the toothbrush against teeth and the action of brushing would cause the toothbrush to slip out of their grasp. An orthosis with a stronger motor is needed to create a tighter grasp, thereby preventing the toothbrush from slipping during the action of brushing teeth. Similarly, for the razor and utensil, subjects could grasp, pick up, and bring to their faces, but without a stronger motor creating a tighter grasp, the pressure needed to use these objects would cause each to slip out of the orthosis grip.

8.1.6 Hairbrush Tasks

Subjects commented that since the hairbrush handle is made of a gel material, it helped maintain a grasp while picking it up and using the brush (Figure 57). For the specific task of grasping the brush while in a horizontal orientation, one subject asked for it be placed such that the brush head was on the table, bristles up with the handle hanging off the edge of the table, see Figure 58.
Once the handle was grasped and the subject lifted the brush. This specific orientation allowed for the handle to “fall” further toward the orthosis grasp and creating a more secure hold on the handle.

In instances where the hairbrush was successfully grasped, picked up, and brought to the users’ heads, subjects noted that with the current grasping force, the hairbrush could only be used on very short, thin hair (see Figure 59). The force needed to brush long, thick hair would cause the hairbrush to slip out of orthosis grasp.
Figure 59 Subject with short hair- hairbrush would be able to be used on this type of hair

It was also noted by some subjects that the loose grip on the brush would only allow the brush to be used on one side of the head. For example, the subject seen in Figure 60 below, said he would only be able to brush the left side of his head. Once he tried to switch sides, the brush would fall out of his grasp.

Figure 60 Subject noted that he would only be able to use brush on left side of his head; once he switched sides, the brush would fall out of his grasp
8.1.7 Razor Tasks

Given that the razor used in testing was small and thin many subjects had issues keeping it in the orthosis grasp. In some cases, once the razor was grasped, the razor head was larger than the hand opening and would balance on the orthosis linkages or the linkage markers (Figure 61).

Figure 61 Razor not actually in a grasp, the razor head was larger than hand opening, so it balanced on linkages or linkage markers

Figure 62 shows a similar situation which occurred with the hairbrush; the hairbrush head was larger than the orthosis hand opening and would not slip through.

Figure 62 Hairbrush head is larger than hand opening, so it does not slip out of grasp
When the razor was in the diagonal orientation, grasping at the first contour was easier for subjects. When the razor was in a vertical orientation, grasping just below the first contour was easiest (see Figure 63).

Small, thin objects, like the razor were difficult to grasp because the required hand position often put the wrist in flexion, causing the linkages to close position and not allowing the user to execute a successful grasp. Subjects who encountered this issue, chose to use orthosis “locking” the button to help with successful grasping; they would extend their wrist to get a “max open” position, press the button to disengage the motor, position their hand around the object, press the button again to re-engage the motor causing the linkages, and therefore, the fingers, to close around the object and create a successful grasp. Users would then press the button again to disengage the motor, so they could freely move their wrist to use the object and avoid unintentional releasing. When the subject was ready to release the object, he/she would move their hand down towards the table and press the button once again to re-engage the motor, then extend his/her wrist to release the object. Figure 64, below, shows this process.
Figure 64 Subject implementing the button to help with grasping razor and to prevent unintentional releasing. Top Left: subject extended wrist to get a “max open” position and pressed the button to disengage the motor. Top Middle: subject positioned hand around the object, pressed the button to re-engage the motor causing the linkages, and thereby the fingers, to close around the object. Top Right and Bottom Left: subject pressed button again to disengage the motor, so she can freely move her wrist to use the object and avoid unintentional releasing. Bottom Right: to release, subject moved hand down towards the table, pressed the button to re-engage the motor, and extend wrist to release the object.

8.1.8 Other Observations/Comments

There was a common issue of an “uncontrolled release” with the fork, the toothbrush (in a horizontal orientation), and the razor. During release, each of these objects would have just dropped if someone was not there to catch it or hold in place. These common observations offer supporting evidence that a potential additional business opportunity exists: designing and manufacturing specialized stands or bases for these common items. (Further extrapolation of the idea would be to create a WHO-compatible set of utensils and common-use items).
It was observed and frequently commented that the starting orientation of the object is key to usability; if the starting orientation is correct during grasp, objects can easily be used, however, if there is an inadequate initial grasp the object slips out of the orthosis and cannot be used. Section 8.1.3 Tasks with Objects in a Horizontal Orientation and Figures 53 and 54 also explains the importance of an object’s starting orientation.

Similar to an object’s starting orientation, subjects stated that their own body orientation and arm placement also played key roles in achieving successful grasp. Some of these preferences are pictured below in Figure 65 and include: (1) angling their body, (2) standing, and (3) resting the arm in use on the table for added stability. Additionally, the bottom right of Figure 51 shows one subject using her left hand to restrict her right arm from moving. This made it easier for the subject to only use wrist motion to completed the tasks.

![Figure 65 Different body orientations helped subjects to achieve a successful grasp. Left to Right: angled body, standing, and resting arm on table](image)

Further, virtually all subjects felt that the tasks became easier as trials progressed because each subject became more familiar with the orthosis and its basic operation and control. Also, subjects that implemented more natural, quick motions were more successful in completing tasks when compared to individuals who moved more cautiously and slowly.
8.2 Survey Comments

The Assistive Technology survey asked ten questions, each one having a comment section. When asked about grasping difficulty and method of grasping (one hand or both hands), respondents commented that they could grasp everyday objects (plastic bottles, ceramic mugs, utensils, toothbrush, hairbrush, and razor), but they have trouble maintain a grasp due to weight, especially the full water bottle and the empty and full ceramic mug [23]. It was also commented that the ability to grasp cups, bottles, mugs greatly depends on circumference; the larger the circumference, the more difficult it is to grasp. For smaller, thinner items some respondents remarked that they could not grasp them but could “wedge” in their hand or “weave” though their fingers. Respondents try to only use one hand but noted that method of grasping depends on size of object, weight, texture, and location [23]. One individual commented that for horizontally orientated objects (utensil, toothbrush, hairbrush, and razor) he/she will slide them to an edge to grasp with one hand, otherwise he/she will use two hands.

Only three respondents with a C6-C7 SCI previously used an orthosis and only one listed the type of orthosis, a tenodesis splint. Individuals who used an orthosis did not have any comments (outside of the answer to the question- discussed in Results section) on what they liked about their orthosis, but did comment on what they did not like. One individual commented that their orthosis took too long to put on and hurt after a very short period of time, while another commented that the orthosis was large in size to carry on a daily basis. Outside of the C6-C7 SCI respondents, only one individual used an orthosis, a dynamic splint.
Chapter 9: Discussion

9.1 Problems Encountered with Orthosis Design

As stated in Chapter 3: Design Methodology, the first iteration of this orthosis was shown to an individual who has a C6-C7 SCI and he liked the design and basis of operation, but said that he would like to be able to don/doff the device independently, otherwise he would feel completely independent. The second prototype was designed in combination with a don/doff stand that would allow the user to don/doff the orthosis independently. Unfortunately, in order to get the rigidity needed for independent don/doff with the stand, a static splint was used, but that did not allow for unrestricted wrist motion, which is the basis for the orthosis operation. It was concluded that the integral orthosis and splint device would need to be specifically manufactured, not made from existing splints or gloves. Therefore, the first prototype was used for this study with the understanding that independent donning/doffing would not be possible. Future iterations will combine the first iteration’s wrist range of motion with the second iteration’s stability needed for independent donning/doffing from the second iteration.

9.2 OpenSim Limitations

The biggest problems encountered during this study occurred when adapting OpenSim to the requirements of this study ADLs. OpenSim had many limitations that were not known prior to beginning this study; limitations are discussed below. First, this study tested healthy subjects, with the intention that OpenSim could be used to [1] simulate an individual with a cervical SCI and [2] determine whether this orthosis could be successfully employed to complete the ADL tasks. To this end, finger muscles were “paralyzed” by deactivating them in OpenSim, however, since
OpenSim always finds a solution, even after paralyzing finger muscles the ADL task motion was still completed. In the case of this project, OpenSim was unable to demonstrate success/failure of the device with specific muscle paralysis. Additionally, OpenSim did not allow [wrist] muscles to be partially paralyzed, so an individual with an incomplete SCI (original target population) could not be accurately simulated. Since OpenSim did not allow muscle paralysis, it was theorized that changing the model code such that impaired wrist flexion/extension limits could be modeled by limited ROM was a reasonable alternate approach. Graphing the total force on wrist muscles would then provide insight into muscle limitations on someone with a SCI. However, this was not the case; although the wrist limits were changed, the input motion capture data was still from a healthy subject, so the resulting “limited ROM” graph was merely a partial “snapshot” of the “full ROM” graph. This led to the conclusion that, with only motion capture data from healthy subjects, OpenSim could not be used to simulate whether the device would work for a SCI subject.
Chapter 10: Conclusion

10.1 Activities of Daily Living Completion Conclusion

The main take away from testing is that the wrist-hand orthosis is that the device needs a stronger motor in order to maintain a firm, no-slip grip and complete all ADLs. This is especially true since the target SCI population does not have any appreciable finger motion and will need the WHO to create and maintain a strong, tight grasp. The healthy test subjects could not pick up the heavier objects (full water bottle and full soda can), without using their own gripping strength, because the motor did not create a strong enough grasp. Subjects were able to complete the tasks involving the empty water bottle and the empty soda can, but, because of its thinner body, individuals found the soda can to be much easier to grasp.

For all other objects, the utensil, the toothbrush, the hairbrush, and the razor, the hypotheses were the same: these objects would be easier to grasp, pick up, and use if they are in a vertical orientation rather than a horizontal orientation. However, this was only true for the toothbrush and the hairbrush. The utensil was easiest to grasp when it was placed diagonally at a height of 49mm and subjects were equally successful at grasping the razor in a vertical or horizontal orientation. For all of these objects, subjects commented that thicker objects, toothbrush and hairbrush, were easier to grasp and maintain that grasp versus the thinner objects, the utensil and the razor. This conclusion led to a future view of commercializing not just the orthosis, but also an entire product line of WHO compatible products. Everyday objects such as those tested in this study: water bottles, soda can, utensils, toothbrushes, hairbrushes, razors, etc. would be manufactured so their shape, size, and weight would work perfectly with the orthosis.
10.2 OpenSim Conclusion

Unfortunately, OpenSim had limitations that were unknown prior to beginning this study, so it could not be utilized for its originally intended purposes. It was, however, able to give joint angles for wrist flexion/extension, thumb flexion/extension and abduction/adduction, and index finger flexion. Detailed analyses of these plotted movements provided insight into the ranges of motion needed to complete grasp, pick-up and use of everyday objects. OpenSim could be better utilized if the input motion capture data came from individuals with a SCI along with electromyography (EMG) data. (Additionally, if the OpenSim programming could be modified to not always find a solution, the motion capture data could be used to approximate the movements of a people with a SCI.) Motion capture data from an individual with a SCI coupled with EMG readings would provide an accurate impaired OpenSim model along with accurate simulations of those associated limited ranges of motion.

10.3 Assistive Technology Survey Conclusion

The Assistive Technology Survey was distributed to a small SCI population. Responses indicate that this WHO can help a much larger percentage of SCI patients than was originally hypothesized. Approximately 33% of responders identified as having a C6-C7 SCI with at least 6% (or at most 12%) having an incomplete C6-C7 SCI, and at least 21% having a complete C6-C7 SCI. It was originally hypothesized that only individuals with an incomplete C6-C7 SCI would retain wrist motion and benefit from this orthosis due to the WHO reliance on retained wrist motion. But, based on self-reported survey responses, individuals with either an incomplete or a complete C6-C7 SCI actually retain wrist motion and would benefit from use of this orthosis. According to the original hypothesis the orthosis was projected to help between 6% and 12% of the SCI population [incomplete C6-C7 only], but based on actual survey results, it can now
realistically claim to help up to 33% of the population (between three and six times the original estimate). Regardless of the original 6% minimum or 12% maximum [incomplete C6-C7 only], the key takeaway is that the target population has considerably increased to greater than 30% of the SCI population, several orders of magnitude larger than originally hypothesized. Since the survey relies on self-reported, non-verified information, some additional work needs to be done to validate the survey results. The first step is to determine the necessary sample size. To obtain the correct sample size and accurately show if this information is statistically significant, a statistical power analysis should be completed. In one of several attempts to complete a power analysis, an online Sample Size calculator [26] was utilized, but these results did not seem accurate.

Additionally, it can be concluded that individuals with a C6-C7 SCI (complete or incomplete) retain wrist motion, although in many cases it is a limited range of motion. Even though this WHO operates on wrist motion, individuals with limited wrist motion can still use the device because its code can be individually customized such that the wrist motion input is disproportionate to the finger motion output. For example, the orthosis can be programmed to output 4° of finger motion for every 1° of wrist motion input. If a user is limited to 10° of wrist extension input, the device can be programmed to open the finger linkages 40°.

Further, information from the Assistive Technology Survey shows that objects in a vertical orientation are easiest for responders to grasp. This is in-line with the original hypotheses posed prior to ADL testing of the orthosis. The full ceramic mug, full plastic bottle, and empty ceramic mug were the objects that required most respondents to use both hands to grasp. This is most likely due to both the heavy weight of these objects, as well as, to respondents thinking “grasp” meant “grasping and picking up” the object. A similar experience could be seen in ADL testing with the full plastic water bottle and full beverage can; all subjects were able to grasp, but because of the
combination of the heavy object weight and under-powered orthosis motor, none were able to pick up these objects. Although posed hypotheses were not always supported by the ADL testing results, the difference could be attributed to the fact that testing took place among healthy subjects and not individuals with a SCI [23].

To obtain a larger sample size this Assistive Technology survey should continue to be distributed. Questions regarding respondents’ age and time since their injury should also be added.

10.4 Specific Aims

The first aim was to design a wrist-hand orthosis that will help individuals with an incomplete C6-C7 SCI re-gain grasping capabilities and complete multiple ADLs.

Successfully accomplished Aim #1 in several phases. The initial WHO [version 1.0] was comprised of a single set of 3-D printed linkages adapted to a compression glove which ensured the wrist-activated flex sensor remained flush against the user’s wrist. The orthosis operational code can be customized; wrist motion input dis-proportionate to finger motion output. Figure 7 in section 3.1.1 Orthosis Control Algorithm shows the orthosis operational diagram and Appendix C shows the entire orthosis operational code. As stated in section 3.1.1, to edit the operational code, the current orthosis design requires the microcontroller to be plugged into a computer, however, a future design modification would be to have a graphical user interface on the orthosis. This would allow users to quickly and easily modify their wrist motion input and finger motion output. Additionally, if the orthosis is modified to be a rehabilitative device (section 10.5 Contribution to the Field) this would allow users to modify the amount of assistance the device provides.

Although Version 1.0 successfully demonstrated proof-of-concept, it had two limitations: it could not be independently donned/doffed, and it was limited to a smaller hand size. Version 2.0 addressed the don/doff issue by mounting the WHO motor and linkages to a modified off-the-shelf
wrist stabilizing splint. This evolution of the WHO successfully demonstrated independent don/doff feasibility. The main issue with Version 2.0 was the rigidity of the splint caused interference with the flex sensor operation. Version 3.0 addresses the size limitation by adapting three sets of linkages to three sizes of compression gloves. Additionally, the gloves were modified to securely hold the flex sensor in an optimal location for WHO operation.

*The second aim was to have healthy subjects use the orthosis to demonstrate its feasibility and effectiveness, providing the basis for simulation software inputs.*

Ten healthy individuals tested the orthosis and proved its feasibility and the effectiveness of its conceptual design. Wrist flexion/extension is effective in controlling the grasping/releasing motions, and all subjects were able to complete the majority of ADLs. However, all healthy subjects agreed that a stronger motor is needed to provide a tighter grasp on objects in order to prevent them from slipping out of grasp when they are picked up and used.

*The third aim was to use a simulation software to illustrate how the orthosis interacts with a human upper limb, and further, how this orthosis and upper limb combination would act as a singular system. Use simulation software to test the operational effectiveness of the orthosis-upper limb system within limited wrist motion boundaries (from Assistive Technology Survey).*

The motion capture data was loaded into an OpenSim model and the linkage CAD files were added onto the same model. However, due to limitations in OpenSim’s source code, the linkage CAD files did not actually interact with the model, they served only a visualization purpose. OpenSim was also unable to effectively simulate the restricted range of motion reported by survey respondents. However, analysis of the OpenSim “restricted motion” cases led to the understanding that finger and forearm muscle loads and forces are actually irrelevant when the orthosis is used for ADLs. This realization led to the conclusion that ADL completion depends
more on the subject’s muscle strength, not wrist ROM. The WHO will provide the necessary grasping power provided there is wrist motion coupled with customized programming to activate the motorized linkages. Although Aim 2 was not met through this study, it could be achieved in possible ways: the input motion capture data has to be from an impaired individual, or more likely, the source code of OpenSim has to be modified to simulate an impaired individual.

The fourth, and final, aim was to create a survey to distribute to members of the SCI population to determine: (1) the size of the sub-population that could benefit from this WHO, (2) whether there is a need for a WHO to assist with independent completion of ADLs, and (3) the preferable means of grasping.

An Assistive Technology Survey was distributed to a sample population of individuals with a SCI. Contrary to conventional thinking, survey responses showed that both individuals with an incomplete C6-C7 SCI as well as those with a complete C6-C7 SCI retain wrist motion. The significance of this discovery cannot be overemphasized. Both also experience difficulty grasping everyday objects, therefore this larger population would benefit from using the WHO tested in this study. All C6-C7 SCI respondents had some level of difficulty grasping everyday objects, but the majority have never tried an orthosis. Those that had previously attempted to use an orthosis commented that they require one that helps them independently complete ADLs, is lightweight, and is customizable. Additionally, most respondents prefer to use only one hand when grasping and using everyday objects. It is clear from the information provided in the survey results that there is a need for a WHO that engages only one hand, allows the user to independently complete ADLs, is lightweight and is customizable. The three WHO prototypes tested in this study meet 100% of these requirements and have the added attractive feature of being inherently lower cost than existing orthoses.
10.5 Contribution to the Field

Results and information from this study made a significant contribution to the assistive and rehabilitation technology field. Information from the survey reveals that there is a need for a wrist hand orthosis that will help individuals with a SCI regain grasping abilities. The individuals prefer an orthosis that is lightweight, customizable, allows them to independently complete ADLs while preferably using only one hand. The orthosis tested in this study is designed such that all these preferences are met. First, the orthosis is currently made from a lightweight compression glove, 3-D printed linkages, and a servo motor that is approximately 0.05 lbs. A requirement for the future manufactured orthosis is to keep it lightweight. Second, the 3-D printed linkages will be customized to the dimensions of the user’s fingers and the operational device code will be customized for the specific user’s limited wrist motion. Lastly, the orthosis was designed such that it would engage only one hand for independent completion of ADLs. Results from testing the orthosis proved the concept that wrist flexion/extension can be the sole input controlling the orthosis grasping/releasing motions. The most prevalent criticism was the weak motor; in order for the orthosis to be entirely effective in completing ADLs, a stronger motor is needed.

Currently the device is considered an assistive technology device, but if a variable assistance motor is installed, the orthosis can also be used as rehabilitative device, therefore helping a much broader population. For example, individuals who have suffered a stroke will have weakened grip strength, but with rehabilitation, gain that strength back. The variable assistance motor will allow the device to do all of the work at the beginning, and as the patient’s motor skills improve, he/she can do more work and the motor will do less work. Regardless of whether this device is an assistive technology device or a rehabilitative technology device, it has the potential to help a wide range of individuals.
10.6 Future Studies

The first future study should be to test the orthosis on the newly defined, larger target population, individuals with both incomplete and complete C6-C7 SCIs. This study should begin with measuring the subjects’ limited wrist ranges of motion, so, if necessary, the device programming can be modified. As explained earlier, the code can be customized such that input is dis-proportionate to the output. For example, subject only has 10° of wrist extension, the device will open to finger linkages 44°. Additionally, the proportion for opening could be unequal to that of closing. For example, 1° of wrist flexion input could output 5° of linkage closure, but 1° of wrist extension input could output 10° of linkage opening. This type of coding would allow the user to grasp more delicate objects (i.e. paper cups). An even more sophisticated code could be developed, such that, as the limited wrist motion nears its maximum, the orthosis responds in a disproportionate manner. i.e. 5° wrist motion results in 15° orthosis opening/closing, but 11° wrist motion results in 60° orthosis opening/closing. The same disproportionate method could also apply in cases where wrist flexion and extension ranges are drastically different.

A recreation therapist responded to the Assistive Technology Survey and commented that assistive devices should consider the ability to participate in social and recreational activities, as they can be paramount to persons with a SCI returning to participation in their previous leisure activities or to finding new ones. The ability to grasp creates opportunity to fish, kayak, play active sports like tennis or pickle ball, and passive activities such as play cards, chess or dominoes, gardening, etc. Once the device has proven its capabilities in allowing the SCI population to grasp, a future study into recreational activities could further develop the device capabilities.

Lastly, the vision for this orthosis has always been to expand it from an assistive device to a rehabilitation device, thereby expanding the target population. For example, with minor design
modifications, such as a variable assistance motor, the orthosis could be used on individuals who have suffered a stroke to rehabilitate their grip. At the start of rehabilitation, the device can be programmed to do 100% of grasping, but as the patient gains strength (through the use of the device and outside rehabilitation), the device programming can be altered to do less work. For example, the user does 70% of the work and the orthosis does 30%. This can continue until the user no longer needs the orthosis to help in grasping capabilities.
References


Appendix A: Assistive Technology Survey Questions

1. What is your level of injury? Is it a complete or incomplete spinal cord injury?
   - C3
   - C4
   - C5
   - C6
   - C7
   - Complete
   - Incomplete
   - Other (Please Specify)

2. Do you have wrist motion?
   - Yes
   - No

3. If you answered yes to question 2, approximately how much wrist flexion (moving your wrist downward) do you have?
   - 0-10 degrees
4. If you answered yes to question 2, approximately how much wrist extension (moving your wrist upward) do you have?

5. How much difficulty do you have grasping each object?
<table>
<thead>
<tr>
<th></th>
<th>No Difficulty</th>
<th>Some Difficulty</th>
<th>Cannot Grasp</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty Paper Cups</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full Paper Cups</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Empty Plastic Cups</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full Plastic Cups</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Empty Ceramic Mug</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full Ceramic Mug</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Utensils (laying down on a surface)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Utensils (standing up or in a holder)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toothbrush (laying down on a surface)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Toothbrush (standing up or in a toothbrush holder)</td>
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<tr>
<td>Hair brush/ comb (laying down on a surface)</td>
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<tr>
<td>Hair brush/ comb (standing up or in a holder)</td>
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</tr>
<tr>
<td>Razor for shaving (laying down on a surface)</td>
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<td></td>
</tr>
<tr>
<td>Razor for shaving (standing up or in a holder)</td>
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<td></td>
</tr>
</tbody>
</table>

Comments: __________

6. How do you/ would you grasp these everyday objects?

<table>
<thead>
<tr>
<th></th>
<th>Using Both wrists</th>
<th>Using Both Hands</th>
<th>Using Only One Hand</th>
<th>Cannot Grasp Object</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty Paper Cups</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full Paper Cups</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Empty Plastic Cups</td>
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<td></td>
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<tr>
<td>Full Plastic Cups</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Empty Ceramic Mug</td>
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<td></td>
<td></td>
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<tr>
<td>Full Ceramic Mug</td>
<td></td>
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<td></td>
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<tr>
<td>Utensils (laying down on a surface)</td>
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<tr>
<td>Utensils (standing up or in a holder)</td>
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<tr>
<td>Toothbrush (laying down on a surface)</td>
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<tr>
<td>Toothbrush (standing up or in a toothbrush holder)</td>
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<tr>
<td>Hair brush/ comb (laying down on a surface)</td>
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<tr>
<td>Hair brush/ comb (standing up or in a holder)</td>
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<tr>
<td>Razor for shaving (laying down on a surface)</td>
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<td></td>
</tr>
<tr>
<td>Razor for shaving (standing up or in a holder)</td>
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<td></td>
</tr>
</tbody>
</table>

Comments: __________

7. Do you use or have you used an orthosis/brace to help grasp objects?
   - Yes
   - No
   - If yes, which orthosis/brace? _______

8. If you answered yes to question 7, what did you like about the orthosis/brace?
   - Ability to independently complete activities of daily living
   - Weight
   - Aesthetics
   - Customizable
   - Ability to independently put on and take off
• Other (please specify): _________

9. If you answered yes to question 7, what did you NOT like about the orthosis/brace?
   • Ability to independently complete activities of daily living
   • Weight
   • Aesthetics
   • Customizable
   • Ability to independently put on and take off
   • Other (please specify): _________

10. Please rank the importance of independently completing each activity of daily living.

<table>
<thead>
<tr>
<th>Activity</th>
<th>1: Least Important</th>
<th>2</th>
<th>3: Moderately Important</th>
<th>4</th>
<th>5: Most Important</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drinking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eating</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brushing Teeth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brushing/Combing Hair</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Shaving</td>
<td></td>
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</table>

Other (Please Specify): ____________

**Survey Reflections**

- Wrist flexion/extension ranges are self-reported and estimated by the respondent based on personal interpretation of the graphics shown in question 3 and 4. A clinical setting with standardized measurement equipment is needed to verify and validate reported information, including SCI classification, and whether it is an incomplete or a complete C6-C7 injury.
Appendix B: Wrist Flexion/Extension Pareto Charts

Wrist Flexion Ranges

<table>
<thead>
<tr>
<th>Range</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-20</td>
<td>2</td>
</tr>
<tr>
<td>41-50</td>
<td>3</td>
</tr>
<tr>
<td>81-90</td>
<td>2</td>
</tr>
<tr>
<td>0-10</td>
<td>1</td>
</tr>
<tr>
<td>31-40</td>
<td>1</td>
</tr>
<tr>
<td>51-60</td>
<td>1</td>
</tr>
<tr>
<td>61-70</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 66 Wrist flexion ranges ordered from least to most

Wrist Extension Ranges

<table>
<thead>
<tr>
<th>Range</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>61-70</td>
<td>4</td>
</tr>
<tr>
<td>41-50</td>
<td>3</td>
</tr>
<tr>
<td>11-20</td>
<td>1</td>
</tr>
<tr>
<td>21-30</td>
<td>1</td>
</tr>
<tr>
<td>31-40</td>
<td>1</td>
</tr>
<tr>
<td>51-60</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 67 Wrist extension ranges ordered from least to most
Appendix C: Orthosis Operation Code

#include <Servo.h>

Servo myservo; // Create servo object to control a servo

const byte interruptPin = 3;

int sensorPin = A0; // Select the input pin for the potentiometer
int ledPin = 13; // Select the pin for the LED
int sensorValue = 0; // Variable to store the value coming from the sensor
int val; // Variable to read the value from the analog pin

byte state = LOW;

void setup() {
  // put your setup code here, to run once:
  pinMode(ledPin, OUTPUT);
  pinMode(sensorPin, INPUT_PULLUP);
  myservo.attach(9); // attaches the servo on pin 9 to the servo object
  pinMode(interruptPin, INPUT_PULLUP);
  pinMode(4, OUTPUT);
  digitalWrite(4, LOW);
}

void loop() {
  // read the value from the sensor:
  sensorValue = analogRead(sensorPin);

  // Scale it to use it with the servo (value between 0 and 180)
  val = map(sensorValue, 350, 880, 0, 180);
  if((state == LOW)) { // If button is pressed, program proceeds but code does
    myservo.write(val); // Sets the servo position according to the scaled value
    digitalWrite(ledPin, LOW);
  }
  else{
    digitalWrite(ledPin, HIGH);
  }
}
delay(100);
}

if(digitalRead(3) == LOW){
    state = !state;
    delay(100);
}
}
Appendix D: Copyright Permissions

The permission below is for the use of Figure 1.

---

Mark E Felling
Re: Image Copyright Permission
To: Amber Gatto

Amber, yes you have my permission to use any photos of the PowerGrip you can find.

I know we have a number of others that depending on what you're looking for might fit you better also. As well as some great videos on the Broadened Horizons YouTube channel. But I think those are also in the inclusive Technologies retail website listing page. If you can't find them let me know.

I'd be happy to talk to you more about it and some history such as various univeristy studies we've supported and have used the PowerGrip for stroke rehabilitation.

The only thing I ask is that you put "Broadened Horizons' PowerGrip" for credit on the photos or where you reference it in any other description such as "powered wrist hand orthosis" I could tell you about some really messed up things where Medicaid cut the funding from 1980’s prices by another 30% this last year for L-code 3904.

I only ask you to share a copy of your completed work if possible?

Mark Felling
President, Broadened Horizons Inc.
www.Broadened.com
Director, InclusiveAdventures.org 501(c)3 Non-profit
763-742-0612 Mobile
mark@broadenedhorizons.com

---

The permission below is for the use of Figure 2.

---

Hi Dr. Basteris,

My name is Amber Gatto, I am a Masters Mechanical Engineering Student at the University of South Florida in Tampa, FL. I am currently writing my thesis on upper limb orthoses and would like to use a picture of the SCRIPT passive wrist and hand orthosis in my manuscript. My thesis will be made electronically available via USF’s institutional repository. On the first page of the paper “Technical evaluation of and clinical experiences with the SCRIPT passive wrist and hand orthosis” there is a picture in the upper right corner of the device that I would like to use.

Thank you,
Amber

Dear Amber,
thank you!
No reply from him - but as author of the publication you have my permission to go ahead with reusing the picture - with or without blur (since he's not a patient, I would be less concerned about privacy).

Kind regards,
Angelo
The permission below is for the use of Figure 3.

Hi Amber,
Yes that is fine to use that image with acknowledgment. Best of luck with your thesis

Cheers
Marcus

---

On 27/02/2020, at 4:35 AM, Amber Gatto <ambergatto@mail.usf.edu> wrote:

Hello,
My name is Amber Gatto, I am a Masters Mechanical Engineering Student at the University of South Florida in Tampa, FL. I am currently writing my thesis on upper limb orthoses and would like to use a picture of the key grip orthosis in my manuscript. My thesis will be made electronically available via USF’s institutional repository, so I wanted to ask your permission to use the image in Figure 2 of your RESNA paper: An Improved Lateral Key-Pinch Grip Orthosis For Tetraplegics WithWhilst Extension: https://www.resna.org/sites/default/files/legacy-conference/proceedings/2007/PracticeOntherKInfig.html

Thank you,
Amber Gatto
US32650940
ambergatto@mail.usf.edu

---

The permission below is for the use of Figure 4.

Hi Dr. Rode,

My name is Amber Gatto, I am a Masters Mechanical Engineering Student at the University of South Florida in Tampa, FL. I am currently writing my thesis on upper limb orthoses and would like to use a picture of the tenodesis grasp in my manuscript. My thesis will be made electronically available via USF's institutional repository, so I wanted to ask your permission to use the image of tenodesis grasp from the paper "Neuroplasticity of imagined wrist actions after spinal cord injury: a pilot study"

Thank you,
Amber

---

Hi
I agree

Best
G.Rode
The permission below is for the use of the left image in Figure 28.

Hello,

My name is Amber Gatto, I am a Masters Mechanical Engineering Student at the University of South Florida in Tampa, FL. I am currently writing my thesis on upper limb orthoses and would like to use a picture of finger flexion/extension in my manuscript. My thesis will be made electronically available via USF's institutional repository, so I wanted to ask your permission to use the image Figure 2.5: Abduction/adduction (Ab/Ad), flexion/extension (F/E) for one finger from 'Virtual Human Hand: Grasping Strategy and Simulation'.

Thank you,
Amber

Hello Amber,
Yes, you can use the image.
Best regards,
Esteban
About the Author

Amber Gatto is originally from Jupiter, Florida. She graduated with her Bachelors of Science in Mechanical Engineering from USF in December 2015 and will graduate with her Masters of Science in Mechanical Engineering in May 2020. During her time at USF, Amber has worked in Research Management helping with proposal submission, as well as, performing research at the Center for Assistive, Rehabilitation and Robotics Technologies. Ms. Gatto hopes to continue her efforts to improve human life and performance within the assistive and rehabilitative technology industry.