# IMU-Controlled Soft Orthotic for Power Grasping

Drew McPherson, Jason Torres, Anna Wolfe

Augmenting Human Dexterity – Spring 2021
P4: Final Project Report

## Abstract

Individuals suffering from loss of hand strength due to C5-6 spinal cord injury, lose the ability to independently perform many tasks of daily living. An assistive hand device that provides a strong grasp can help regain much of this ability. Inherent in the need are devices that are simple to control, easy to don/doff, and provide variable grasp strength. This paper proposes an assistive grasping orthotic using a pneumatic actuator capable of conforming to many object shapes and a IMU control system. Subsystems are used for proof-of-concept testing to show functionality of sole IMU control, which could be used with existing pneumatic technologies. Preliminary results show IMU control using shoulder shrugs for activation as well as wrist flexion and extension for varying grasp position/strength are achievable. These findings can be the foundation to design a complete pneumatic grasping orthotic that is easy to control and convenient to wear.

## I. INTRODUCTION

According to the national spinal cord injury statistical center, there are approximately 17,900 new spinal cord injuries (SCI) cases in the US each year, of which 67.1% are tetraplegic. An estimated 296,000 persons live with SCI in the US as of 2021 [1]. Individuals with high-level spinal cord injury, or tetraplegia, often have difficulties with grasping and manipulating objects. Amongst this population, of 565 subjects with tetraplegia surveyed, 77% expected an important or very important improvement in quality of life if their hand function improved. This was consistently one of the top 3 concerns this population expressed [2]. Current research seeks to address this need. In fact, between 2006-2016, “over 140 hand exoskeletons [were] developed, 48 of which were intended to assist in daily life” [3] and surely many more since then. However, very few of these devices have made it out of the lab, into the market, and into users’ homes. A major challenge of current devices is to make them light and portable enough to be used in the home while integrating an intuitive user control scheme.

### A. Background

The complexity of SCI and its impact on daily life has prompted the creation of many different types of assistive devices in use today. As one of the top factors affecting a person’s ability to independently perform tasks of daily living (ADLs), hand function and dexterous manipulation remains of particular interest in research today. There are many different types of assistive and rehabilitative hand devices in research which fall into two primary categories, rigid or soft, and can be broken down further by actuation methods. Within the rigid design space, there are several device architectures including matched-axis, remote center of rotation, redundant mechanism (four-bar link mechanisms), and base to distal [4], all of which must be precisely aligned to the center of rotation of the associated joints of the wearer. These are typically direct-drive, using electromechanical motors. Alternatively, soft hand devices consisting of cable/tendon driven [5], or pneumatic jointless structures [6], [7] which depend on the kinematics of the user’s hand and are generally remote-actuated by motor or compressed air/hydraulics, respectively. This means the actuator is located remotely from the hand and possibly mounted on the wheelchair allowing for a lighter weight device. Soft pneumatic actuators on the dorsal side of the hand are the most common joint-less actuator, and have the benefits of being lightweight, strong, and safe as they do not apply potentially dangerous loads on a user’s finger joints.

Though there has been a large body of research exploring the physical implementation of hand actuation and grasping [4], understanding users grasp intention remains a challenging, unsolved research question.

The simplest devices use push buttons to open and close [8], while others use voice control [5], motion as in inertial measurement unit (IMU) [9], or biosensors such as EMG [9] and EEG [6] or a combination of the above. One of the most common combination is an IMU paired with EMG control [9], though EMG is hard to work with given the noise signal and variation due to location, muscle hydration, electrolyte concentration, and many more variables. No published hand assistive device found in literature currently implements only IMU control.

User intention and gesture recognition is a difficult design problem even with the available sensors, which is a potential reason IMU-only control has not typically been incorporated in many designs. An IMU is a sensor used to measure motion with 9-axis IMUs utilizing a 3-axis accelerometer, 3-axis gyroscope, and magnetometer to provide estimates of orientation, velocity, and gravitational forces, respectively. An individual with intact spinal cord function would complete a movement by first having the intention to do so, which then would prompt the motor cortex to send neural signals down the spinal cord and to the muscle to initiate movement. At this point, a task could be executed. The IMU-control, however, relies on the motion of the user prior to reading and sending this information back to the device. This means that the IMU is reading inputs only after a motion has been initiated, which can make it difficult to predict exactly which hand motion is desired. Knowing this, the main challenge is creating a robust control scheme that can accurately recognize the intention of the user in order to control the device with little delay.

While the process for predicting desired hand movement may be a difficult task, using an IMU has distinct advantages over push buttons and biosensors. Looking for subtle changes in arm movement would provide the opportunity to have precise and variable control of a hand assistive device. Using an IMU alone as opposed to an IMU-EMG sensor combination is also advantageous because of the process for donning a device. An EMG-incorporated device would require the user to place the device precisely over the specific muscle of interest and make good skin contact to function, whereas an IMU alone could be donned much easier since the location is not required to be as precise, nor must it make skin contact. Moreover, the signals from EMG are much harder to decode into useful features, so using acceleration and angular information from an IMU would be more repeatable. Thus, designing a purely IMU-controlled assistive hand device may allow for easy donning and doffing as well as for intuitive control when combined with a soft pneumatic orthotic glove.

### *B. Overview*

From a prior art review, we observed that despite the vast number of research devices that have been developed, hand assistance for tetraplegics remains a significant unmet need, with few researchers exploring how to recognize the user's intention and integrating this into the control of the device. For this reason, our work focuses on a control scheme and test bed with the hypothesis that IMUs can be used to provide variable and intuitive control of an assistive grasping hand device for use by individuals with tetraplegia. An initial interview with a potential user with C5-6 complete SCI is discussed in section II, illustrating the need for intuitive control. Section III describes the proposed design of a soft actuated, hand assistive device, the IMU control scheme, and study methods to test this hypothesis. If our hypothesis proves valid, this IMU control scheme could be implemented in research and ADL devices around the world as described in section IV. Finally, section V presents how these findings, when implemented, can have a profound impact on the quality of life and independence for individuals suffering from paralysis worldwide.

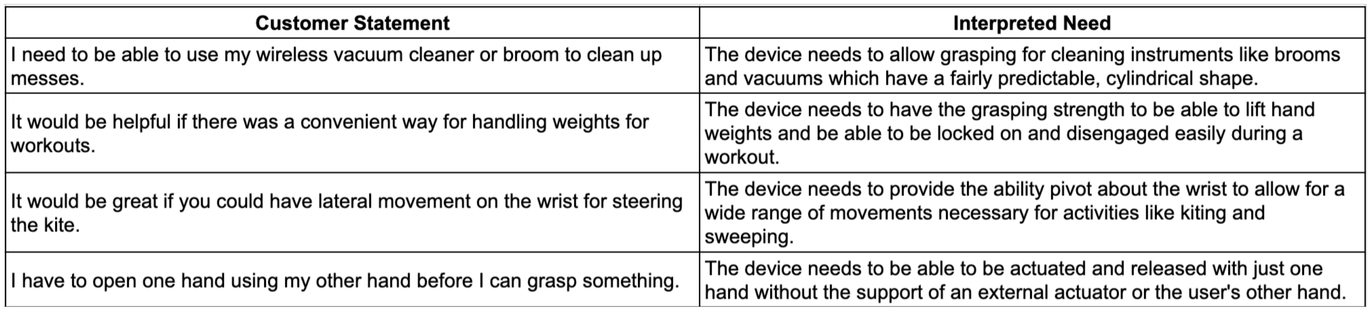
## II. Preliminary Results

To motivate our work, our team performed a preliminary interview, seeking to learn as much as possible about the daily life, and barriers faced by those experiencing loss of hand function. Our interview participant was an adult with C5-6 SCI resulting in tetraplegia, whose daily impairment is significantly unaddressed by current therapies and technologies. They currently use a manual wheelchair to get around despite not having muscle control of their fingers, and thus lack the ability to grip objects within their hands. Much of their professional work is computer-based, using voice dictation to type and two trackball mice to navigate. When not working, they enjoy spending a lot of time doing physical activities, such as wheelchair rugby, wheelchair kiting, camping, and errands around town. Thus, they have learned adaptations and compensatory strategies such as tenodesis for gripping objects during said activities.

The interview was structured by first asking the subject to walk us through their typical day, having them highlight the biggest pain points in daily activities. They were then asked to describe their top hobbies in terms of time spent, and the pain points experienced in these prominent hobbies. This structure was found to be very helpful in gaining insight into their life and needs and collecting as much usable and actionable information as possible.

After the interview, we discussed the insights collected, and wrote down the specific statements the interviewee said associated with potential hand grip needs. We discussed how one could design assistive devices to be as impactful as possible for the subject and for individuals who have similar hand function impairment. The biggest through line we found was that grasping of basic object shapes was hindered by C5-6 SCI hand impairment, due to the inability to open and close the fingers. We chose to focus on assisting power grasping of cylindrical objects since we found this would cover most of the activities that our subject mentioned as grasping difficulties. Examples of cylindrical shaped objects our subject specifically highlighted were: handles of cleaning tools such as brooms, vacuum cleaners, and mops; gripping hand weights; structural handlebars for kiting; and gripping surfaces for vessels like pill and beverage bottles.

Even though cylindrical-shaped objects seem fairly simple and predictable, the size and surface contours of the items mentioned varied enough to consider a solution that would allow for consistent gripping despite the surface variations. This constraint led the group to consider soft actuated concepts that could conform to different sizes and contours. Another constraint extracted from the subject is that a lot of the activities mentioned require a sufficiently strong grip. For example, kiting requires a grip strong enough to pull the large kite loaded by wind in order to change the direction of the vehicle. While kiting is the extreme case for grasping activity, even lower loading conditions like grasping a broom for sweeping still has a minimum grip strength requirement.



| Customer Statement | Interpreted Need |
|---|---|
| I need to be able to use my wireless vacuum cleaner or broom to clean up messes. | The device needs to allow grasping for cleaning instruments like brooms and vacuums which have a fairly predictable, cylindrical shape. |
| It would be helpful if there was a convenient way for handling weights for workouts. | The device needs to have the grasping strength to be able to lift hand weights and be able to be locked on and disengaged easily during a workout. |
| It would be great if you could have lateral movement on the wrist for steering the kite. | The device needs to provide the ability pivot about the wrist to allow for a wide range of movements necessary for activities like kiting and sweeping. |
| I have to open one hand using my other hand before I can grasp something. | The device needs to be able to be actuated and released with just one hand without the support of an external actuator or the user's other hand. |

Fig. 1. From this selection of user need statements extracted, we interpreted needs to shows our subject's emphasis on performing one handed power grasping.

Another need found during the interview, was the importance of having a device that was easy and quick to don and doff to make it a high-use device. Thus, ease of use is one of the biggest criteria that was chosen to carry over through the ideation process and into to the final concept. Specifically, we wanted to ensure the hand device can be donned and doffed with just one hand in a matter of seconds as explicitly described by our interviewee. Currently, they need external objects to lock in a grasp or will use their other hand to complete grasping with their grasping hand. They emphasized that it would be beneficial for them to have the ability to complete grasping and release with only one hand, and without having to interact with external objects other than the device itself.

Using the interview data collected from the subject, a user needs chart was generated, which has been summarized by the main user needs demonstrated in (Figure 1). Given these needs, we went through a meticulous process of diverging and converging on our chosen device concept, and this process is described in detail in Appendix B. As such, an IMU control scheme was chosen to enable simple, one-handed actuation, which will be further described below.

## III. METHODS

### A. Device Concept

This work outlines the design of a novel, IMU-based control scheme for power grasp assistance. Our proposed design utilizes a soft pneumatic actuator positioned on the dorsal side of the hand which is wide enough to cover all four fingers as depicted in Figure 2 A). Straight spring steel wires are in the palmar side of the actuator to passively extend the fingers, while the inflation of air causes the actuator to curl in, providing active finger flexion. This design is proposed as our testbed, though our primary focus is the IMU control, as many physical forms of pneumatic actuation already exist.

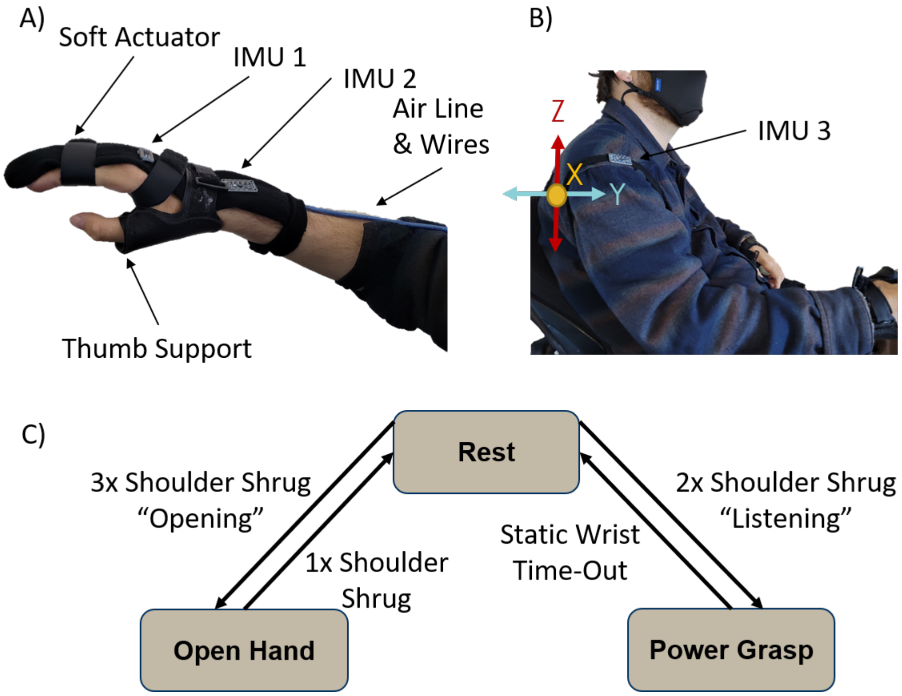


Fig. 2. This figure shows the two primary subsystems. A) shows the hand actuation mitten with thumb support, and IMU 1 and IMU 2 to measure wrist angle. B) illustrates the shoulder IMU control system to change modes C) Illustrates the state diagram for the system. The glove is at rest until it receives 2 shoulder shrugs in rapid succession at which point the hand closes in a power grasp relative to wrist extension. After a set time the wrist angle stays constant, the rest state is entered. With 3 shoulder shrugs, the glove opens until a single shrug or full open hand is detected.

Given the limited hand and arm function of the target user group, there is a very limited number of potential user inputs to allow for seamless, intuitive user-initiated movements. In our current implementation, three IMUs are used, located on the back of the hand, forearm, and shoulder as shown in figure 2 A) and B). The user performs a "quick" 2x shoulder shrug to initialize a "listening" mode, where after a delay, the actuator starts closing the hand, relative to the wrist movement in extension as described in the state diagram in figure 2 C). After the user's wrist position stops changing, the "listening" mode stops, and the hand stays closed in that position. To open, the user shrugs 3x, which then opens until a single shrug is detected or fully open position is achieved. Wrist position is used in this case as intuitive, proportional control, given the user population is already accustomed to using the coupling of wrist motion and grasping with tenodesis [10]. For initial realization and feasibility testing of this device, see Appendix A.

### *B. Hypothesis Testing Protocol*

In order to quantify the efficacy of the IMU-based control, a two-phase test protocols to test the accuracy and feasibility of using a shoulder shrug as the device activation and using wrist flexion to control force through the pneumatic glove will be performed. Completing an in-depth protocol will ensure the device is safe and effective for users and will require submitting a protocol for review to the Institutional Review Board for the Protection of Human Subjects.

*1) Phase I:* The first stage of developing an IMU-control scheme about the shoulder requires collecting shoulder data throughout daily activities. This would give an idea of possible false positive indicators and would help with training the sensitivity of the IMU control scheme. For example, to test the two shoulder shrugs for activation, we can observe whether this repetitive movement also happens in daily life from a series of participants to deduce whether these would cause false positives. We carried out a small example of this test as described in Appendix A.

The next part of this phase is to evaluate the wrist angle measurement using relative hand and forearm movement gathered from two IMUs. A similar experimentation setup to the shoulder shrug motion would be performed with a series of participants. These tests will highlight the accuracy and feasibility of utilizing wrist movement to control the force.

*2) Phase II:* After the feasibility studies in *Phase I* have been completed, a second study would be carried out to compare our device to those currently available. We would have participants complete a series of task using a device controlled by push-button inputs, which would act as our control group. Then the participants would complete the same tasks with our IMU-driven device, which would be our experimental group. Within this study, we would be able to measure accuracy with grasping, further described below, as well as the task speed, which would highlight the device intuitiveness. Doing so would allow us to quantitatively describe the performance of our novel IMU-driven device.

### *C. Experimental Study Analysis*

Our first analysis of the accuracy of the device would be to utilize a confusion matrix. Doing so would allow us to view false positive occurrences, which is the number of times the motion of the shoulder/wrist unintentionally activates the device. Further, the results from the confusion matrix will allow us to calculate the sensitivity, false positive rate, and precision of the control scheme.

We anticipate the testing will highlight areas in which false positives commonly occur. Further, we expect that by measuring the task efficiency, e.g. speed, of participants during *phase II* testing, we would see an increase in efficiency when using our device over push-button devices, which implies that our device provides more intuitive control. Using these protocols and analyses would allow us to optimize the sensitivity of the control scheme in order to create a more accurate, precise, and intuitive device.

## IV. INTELLECTUAL MERIT

The findings of this study, if the hypothesis holds, show the feasibility of providing variable, intuitive control of an assistive hand device for grasping. If the initially proposed IMU thresholds and control scheme are not deemed sufficient or intuitive, the IMUs provide enough flexibility to adjust such parameters to better match the study findings to ultimately provide for a more integrated user experience. By providing this demonstration, research scientists and engineers can implement our IMU control or their own variation to the myriad of research devices currently in development, rather than the over simplified push-button controls currently in use, which some potential users have stated they would not be willing to use [11]. Such an improvement, on the state of the art, will push this field one step closer to moving these research devices out of the lab and into the homes of those who need them.

## V. BROADER IMPACT

For those experiencing significant hand impairment due to SCI, holding a cup of coffee or the broom handle to sweep up the kitchen may feel a long way away. By integrating an intuitive method for these users to control a soft, assistive glove that can open and close their hand, this may be closer than it appears. Having such a device that allows the user to increase their current grasping ability in their daily lives without the need to stop or perform some cumbersome additional activity like having to use their other hand to push buttons, allows for easy adoption and integration to daily life. This leaves the other hand free to grasp a secondary object, stabilize themselves on their wheelchair, and perform bilateral grasping tasks. For these reasons it is imperative to have an intuitive, integrated control of the device, regardless of ultimate physical device architecture.

## REFERENCES

[1] National Spinal Cord Injury Statistical Center, "Spinal Cord Injury Facts and Figures at a Glance 2021," 2021., accessed: 2021-04-10. [Online]. Available: https://www.nscisc.uab.edu

[2] G. J. Snoek, M. J. IJzerman, H. J. Hermens, D. Maxwell, and F. Biering-Sorensen, "Survey of the needs of patients with spinal cord injury: impact and priority for improvement in hand function in tetraplegics," *Spinal cord*, vol. 42, no. 9, pp. 526–532, 2004.

[3] R. A. Bos, C. J. Haarman, T. Stortelder, K. Nizamis, J. L. Herder, A. H. Stienen, and D. H. Plettenburg, "A structured overview of trends and technologies used in dynamic hand orthoses," *Journal of neuroengineering and rehabilitation*, vol. 13, no. 1, pp. 1–25, 2016.

[4] T. du Plessis, K. Djouani, and C. Oosthuizen, "A review of active hand exoskeletons for rehabilitation and assistance," *Robotics*, vol. 10, no. 1, p. 40, 2021.

[5] P. Tran, S. Jeong, S. L. Wolf, and J. P. Desai, "Patient-specific, voice-controlled, robotic flexotendon glove-ii system for spinal cord injury," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 898–905, 2020.

[6] A. C. McConnell, M. Vallejo, R. C. Moioli, F. L. Brasil, N. Secciani, M. P. Nemitz, C. P. Riquart, D. W. Corne, P. A. Vargas, and A. A. Stokes, "Sophia: soft orthotic physiotherapy hand interactive aid," *Frontiers in Mechanical Engineering*, vol. 3, p. 3, 2017.

[7] Y. M. Zhou, D. Wagner, K. Nuckols, R. Heimgartner, C. Correia, M. Clarke, D. Orzel, C. O'Neill, R. Solinsky, S. Paganoni *et al.*, "Soft robotic glove with integrated sensing for intuitive grasping assistance post spinal cord injury," in *2019 International conference on robotics and automation (ICRA)*. IEEE, 2019, pp. 9059–9065.

[8] T. Bützer, O. Lambercy, J. Arata, and R. Gassert, "Fully wearable actuated soft exoskeleton for grasping assistance in everyday activities," *Soft Robotics*, 2020.

[9] J. Guo, S. Yu, Y. Li, T.-H. Huang, J. Wang, B. Lynn, J. Fidock, C.-L. Shen, D. Edwards, and H. Su, "A soft robotic exo-sheath using fabric emg sensing for hand rehabilitation and assistance," in *2018 IEEE international conference on soft robotics (RoboSoft)*. IEEE, 2018, pp. 497–503.

[10] S. Mateo, P. Revol, M. Fourtassi, Y. Rossetti, C. Collet, and G. Rode, "Kinematic characteristics of tenodesis grasp in c6 quadriplegia," *Spinal cord*, vol. 51, no. 2, pp. 144–149, 2013.

[11] Q. A. Boser, M. R. Dawson, J. S. Schofield, G. Y. Dziwenko, and J. S. Hebert, "Defining the design requirements for an assistive powered hand exoskeleton: A pilot explorative interview study and case series," *Prosthetics and Orthotics International*, p. 0309364620963943, 2020.

# APPENDIX A
## INVESTIGATIONAL DEVICE DETAILS

Due to time and resource constraints, a fully realized functional prototype is not possible. However, benchtop testing of the IMU sub-system was demonstrated. To study the feasibility of proportional grasp using two IMU sensors about the wrist, the bench-top setup seen in Figure 3 A) was created. Using this setup, the angle between the IMUs could be varied. This angle corresponds to ”wrist” flexion/extension between the IMUs and was computed by comparing the magnitude of acceleration due to gravity and used as the input to control a series of LEDs. The LEDs mimicked the proportional grasp aperture of the hand ranging from 180 degrees (6 LEDs) to 90 degrees (1 LED). Thus, this demonstration of a pseudo-control scheme from IMU angle to grasp position suggests IMU is a realistic approach. Due to the time constraints, the prototype was limited to the x and y axes being constrained to the horizontal plane. Future work can also incorporate unconstrained x and y axes by adding information from the magnetometer and gyroscope of the IMUs and fusing them with accelerometer information to infer 3D orientation.

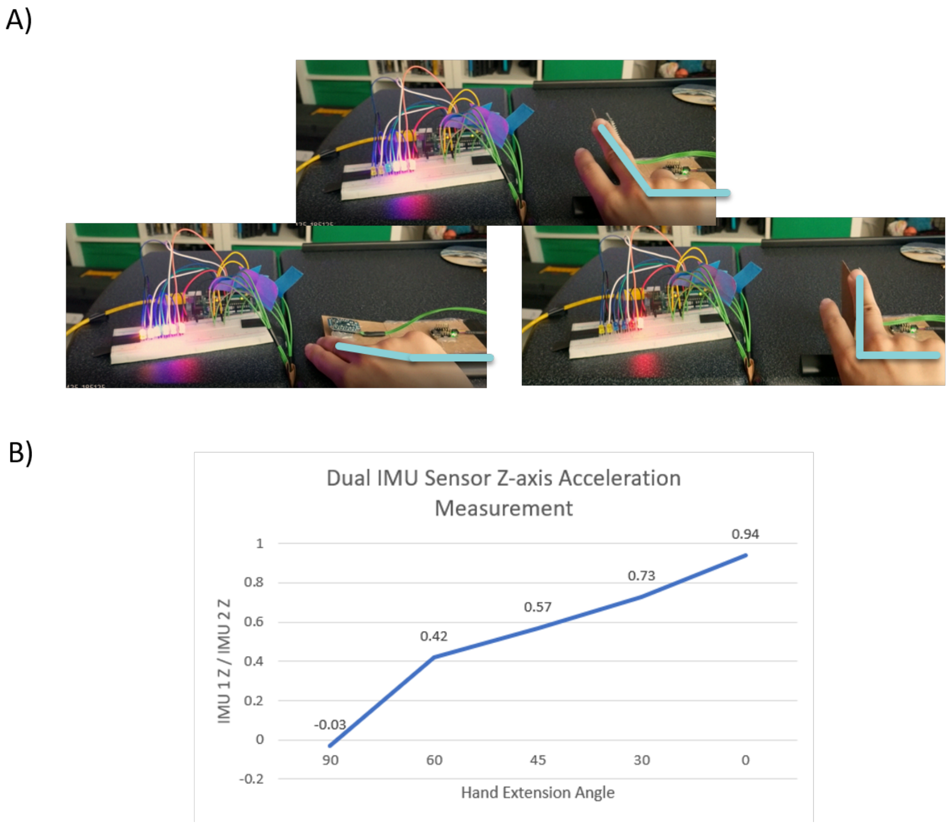


Fig. 3. shows the wrist angle sub-system. A) shows the two IMU setup. As the angle is varied from 180-90 degrees, the number of lit LEDs decreases from 6-1. B) shows example data illustrating how the acceleration changes with wrist angle.

To test the shoulder shrug control, an IMU was placed on the shoulder (as seen in Figure 2 B)). A series of shoulder shrugs, and the common daily task of sweeping and vacuuming as described by the interviewee were performed while collecting IMU data. This data shows that using Y and Z axis motions of the shoulder (see Figure 4 in Appendix A) would be adequate for identifying shrugs and for ignoring other motions in order to avoid false positives. The sweeping motion is just one of many anticipated in daily life, so a more robust testing protocol would collect shoulder motion throughout the day. This protocol is described in further detail in section III-B.

With more robust future testing, the precision and accuracy of the IMU event-driven programming scheme can be assessed and refined.

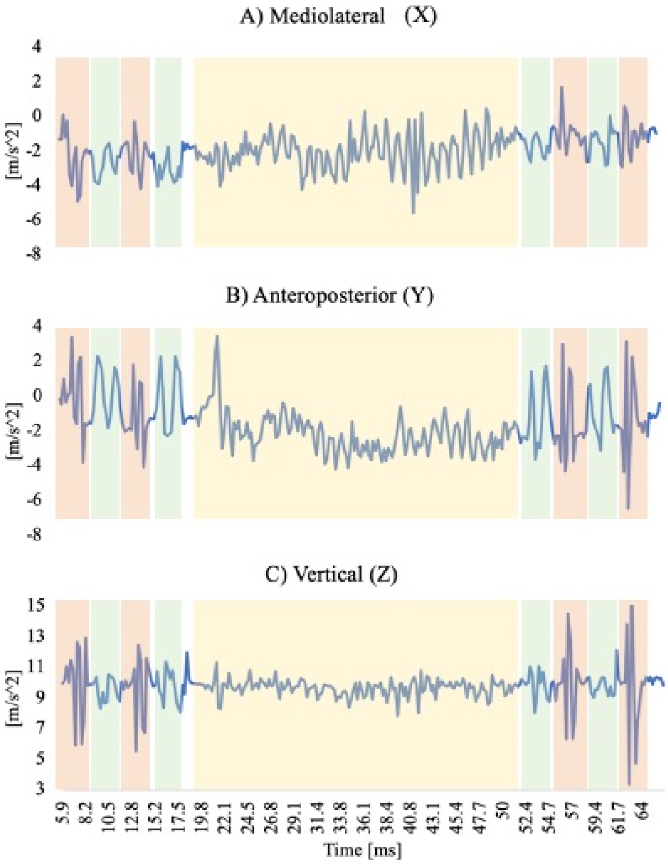


Fig. 4. Data resulting from the shoulder proof of concept exercise. Demonstrated here is shoulder acceleration across the A) mediolateral axis, B) anteroposterior axis, and C) vertical axis over time. More specifically, the red portions are fast shrugs, the green portions are slow shrugs, and the yellow portions show the sweeping motion.

# APPENDIX B
# PRIOR DEVICE CONCEPT PREPARATION

## A. *Brainstorming a Device Concept*

After our interview, described in section II, we carried out a brainstorming session in order to begin creating a device design concept. Our concepts revolved around the activity of cleaning. Specifically, our subject mentioned their desire to use a broom and a wireless vacuum cleaner. Yet he currently does not have the ability to grasp and hold a broom because of his hand impairment.

Our concepts ranged from hand assist graspers to external tools like remote controlled cleaning robots and wheelchair mounted vacuum cleaners with flexible hoses (see Fig. 5). After discussing and debating as a group the results of brainstorming, we converged on concepts that were of a hand assisting nature instead of external tools. Even though some of the external tools met a number of the task specific user needs we extracted from the interview, we felt that as a group, a hand assisting device would provide more capabilities for the user across many tasks, and would allow us develop our skills in orthotic design.

With this in mind, we gravitated to some key features like a ratchet tightening system, wireless electronic control schemes such as IMUs, and universal swivel joints for wide range of motions.

The images below show some of the concepts we brainstormed and discussed during our concept generation process.

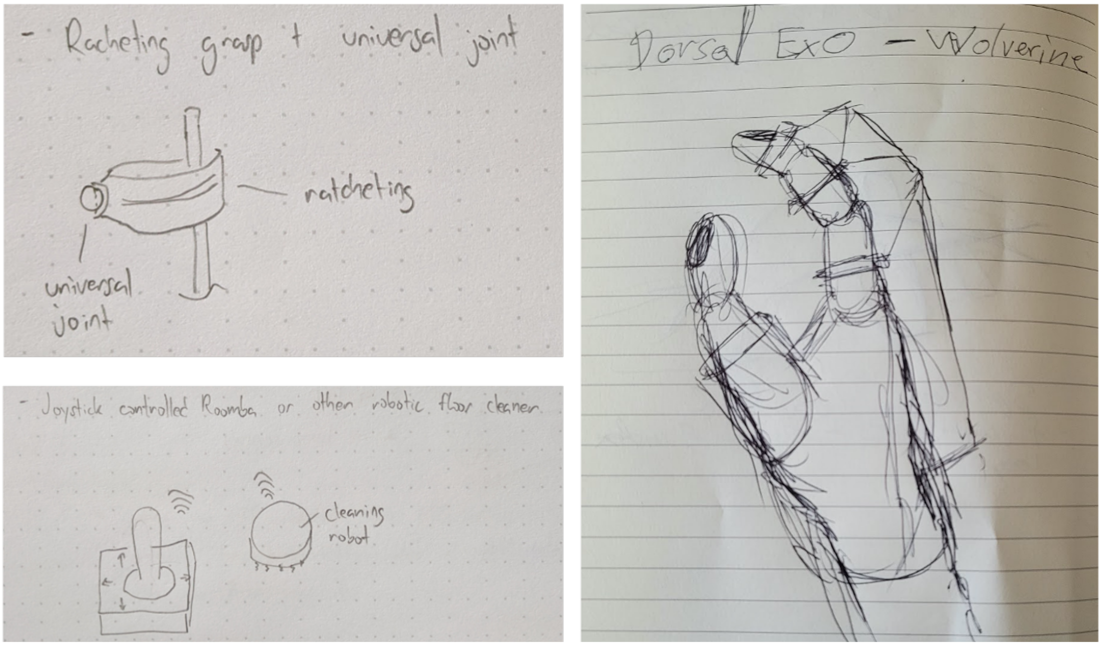
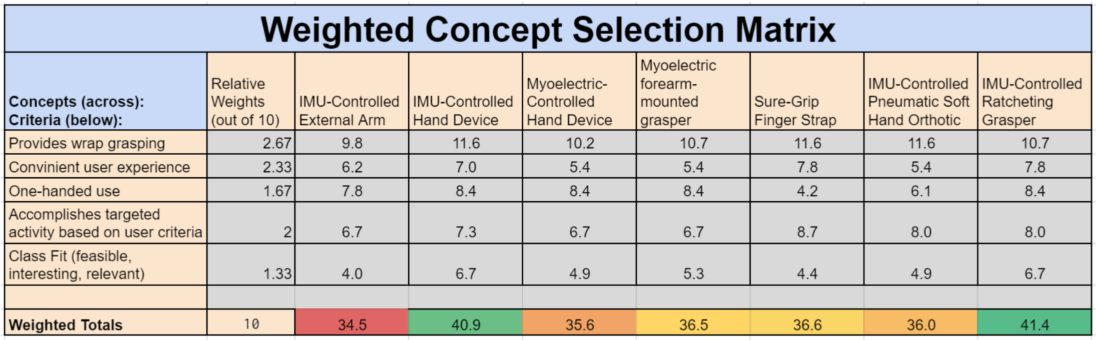


Fig. 5. Concepts show the varying methodologies and technologies we explored.

## B. *Device Concept Selection*

Through a weighted matrix, concept selection process (see Fig. 6), an inertial measurement unit (IMU) controlled soft orthotic glove design was selected (see Fig. 7). A soft pneumatic actuator across the back of the hand closes all fingers at once. The thumb is supported to provide stronger wrap grasp. The soft actuator is inflated and deflated within a closed system to alleviate the need for an air compressor by squeezing an air chamber at the other end of the tube. With a high friction contact surface at the fingertips and palm, the device will provide sufficient grasp strength to hold a broom or vacuum handle.



**Weighted Concept Selection Matrix**

| **Concepts (across):**<br>**Criteria (below):** | Relative Weights (out of 10) | IMU-Controlled External Arm | IMU-Controlled Hand Device | Myoelectric-Controlled Hand Device | Myoelectric forearm-mounted grasper | Sure-Grip Finger Strap | IMU-Controlled Pneumatic Soft Hand Orthotic | IMU-Controlled Ratcheting Grasper |
|---|---|---|---|---|---|---|---|---|
| Provides wrap grasping | 2.67 | 9.8 | 11.6 | 10.2 | 10.7 | 11.6 | 11.6 | 10.7 |
| Convinient user experience | 2.33 | 6.2 | 7.0 | 5.4 | 5.4 | 7.8 | 5.4 | 7.8 |
| One-handed use | 1.67 | 7.8 | 8.4 | 8.4 | 8.4 | 4.2 | 6.1 | 8.4 |
| Accomplishes targeted activity based on user criteria | 2 | 6.7 | 7.3 | 6.7 | 6.7 | 8.7 | 8.0 | 8.0 |
| Class Fit (feasible, interesting, relevant) | 1.33 | 4.0 | 6.7 | 4.9 | 5.3 | 4.4 | 4.9 | 6.7 |
| | | | | | | | | |
| **Weighted Totals** | 10 | 34.5 | 40.9 | 35.6 | 36.5 | 36.6 | 36.0 | 41.4 |

Fig. 6. Weighted concept selection matrix.

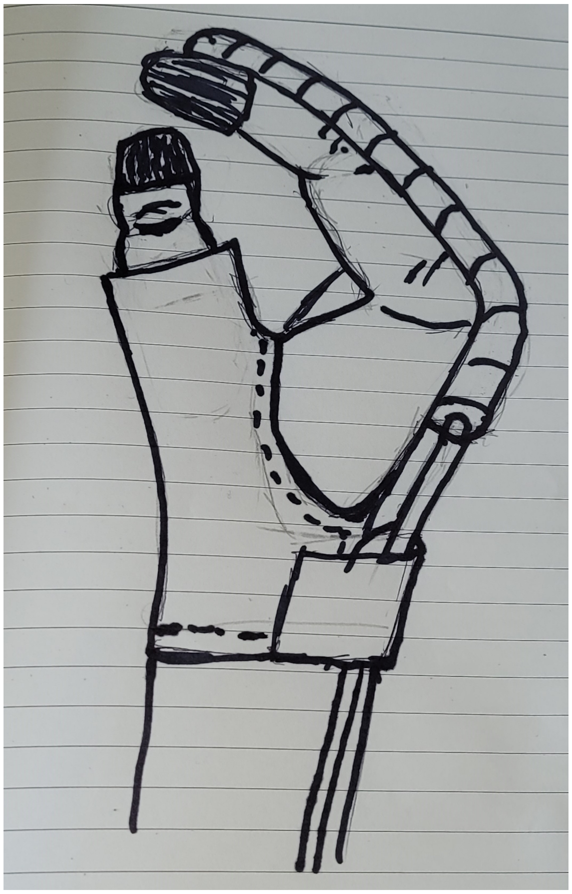


Fig. 7. Sketch of selected IMU controlled, soft robotic actuated, soft orthotic glove.