SmartHub: A Manual Wheelchair Activity Tracking Device for Patients and Clinicians

Undergraduate Honors Thesis

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Abstract

In America, nearly 1.5 million people use manual wheelchairs in their day-to-day lives. These users are typically paralyzed from the waist down after experiencing a spinal cord injury (SCI), stroke (CVA), or diagnosed with cerebral palsy. These patients are fit for manual wheelchairs because their upper extremities are healthy and fully functional. However, the repeated strain of soft tissue in the shoulder and wrist joints from movement in a manual wheelchair leaves these patients highly susceptible to upper extremity injury. Nearly 70% of all manual wheelchair users will develop some form of upper extremity injury eventually leading to increase health costs and discomfort. These injuries can be mitigated by improving sub-optimal biomechanics of wheelchair propulsion. Metrics such as stroke frequency, velocity, stroke force, and stroke distance provide key insights to determine the root cause of these injuries.

SmartWheel is a current legacy product used within assistive technology clinics for collecting and analyzing propulsion metrics. However, due to several factors, the SmartWheel is restricted to clinical settings, leaving data collection to simple tests. This collected data does not form a complete picture of how a patient is using their wheelchair since it is not able to capture a patient’s day-to-day metrics. SmartHub is a concept medical device that aims to serve the capability gaps of the SmartWheel by tracking propulsion metrics inside and outside of the clinic. SmartHub has seen contributions from an Assistive Device Capstone group, and two previous master students creating SmartHub I and II respectively. The goal of SmartHub III is to optimize the internal component layout and existing data collection software to create an unobtrusive form factor. SmartHub III effectively decreased the device width by 30% while improving the overall device experience, moving the device a step closer to its market-ready state.

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To my Dad, I'm sorry you are not able to see the final product, but I know you're watching from a better place now. Thank you for everything, you'll always be my hero.

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Chapter 1: Introduction

1.1 Background

In the U.S. alone, nearly 1.5 million people are manual wheelchair (MWC) users. As the number of elderly in the U.S. is expected to double, reaching 71.5 million by the year 2030, the total number of manual wheelchair users will increase accordingly [1]. Manual wheelchairs are widely used amongst individuals with medical backgrounds such as spinal cord injury (SCI), cerebrovascular accident (CVA), cerebral palsy, as well as other injuries affecting mobility of the lower limbs [2]. Commonly, these patients use a manual wheelchair because their upper extremities are functional. Consequently, repetitive strokes of a manual wheelchair using the push-rim as well as wheelchair transfers place a great deal of stress on the joints and soft tissue of the upper limbs. The susceptibility of developing an upper extremity injury is dependent on the patient's condition and studies have shown between 30-70% of people with paraplegia following SCI are likely to develop an upper extremity injury [3], [4]. These devastating effects cause individuals a great deal of discomfort and increased health support costs [5].

Upper extremity injury while operating a manual wheelchair can be attributed to three main categories: excessive weight, misfit wheelchairs, and propulsion techniques. With regards to wheelchair propulsion, metrics such as stroke length, stroke frequency, wheelchair velocity, and push force provide a great deal of insight into a person's movement patterns. Clinicians can utilize this data to identify the root cause of a patients pain development by altering their propulsion techniques or adjusting wheelchair characteristics such as wheel size, height, and weight [6].

SmartWheel is a current clinical device used in assistive technology centers to diagnose patients for sub-optimal biomechanics by recording and reporting said metrics. The device relays these metrics to a proprietary computer software application where clinicians can analyze and treat patients within the clinic.

1.2 Clinical Treatments and Protocol for Upper Extremity Injury

Manual wheelchair users will receive outpatient care though clinics such as The Ohio State Martha Morehouse Outpatient Care Center. These facilities are led by occupational therapists who provide individualized care to patients as they are outfitted for their wheelchair and modifications to their equipment throughout their life. Additionally, these facilities are equipped with assistive technology product including, ramps, wheelchair accessible treadmills, and other features to assess a patient’s movement.

Patients experiencing upper extremity pain would visit outpatient care and perform a variety of movements in their wheelchair equipped with a SmartWheel. During these activities, the SmartWheel will measure their stroke frequency, stroke length, velocity, and stroke force as well as other metrics. This set of collected data provides key information to the clinician to diagnose corrective measures and decrease the current pain. Upper extremity pain is widely varying depending on the patient’s daily activities, weight, and age. Therapists can utilize the SmartWheel data as well as their expertise to provide the optimal solution. Without the quantitative data produced from the SmartWheel, occupational therapists would not be able to diagnose patients as accurately.

1.3 SmartWheel

SmartWheel is a clinical device used to characterize a patient's movement while operating a manual wheelchair. Designed and manufactured by Out-Front, the SmartWheel can record a patient's propulsion metrics and display this collected data via a proprietary computer software application. The SmartWheel is able to collect crucial metrics including velocity, stroke distance, stroke frequency, and most notably stroke force applied to the hand-rim [7].

1.3.1 SmartWheel Hardware and Design

Figure 1: SmartWheel Attached to Manual Wheelchair [8]

The SmartWheel device, shown in Figure 1 above appears similar to that of a normal wheelchair wheel. SmartWheel is equipped with a controller, digital optical encoder, and an onboard power supply within the central blue "hub" as well as three mechanical strain gauges located near the hand-rim.

The digital encoder is able to measure the wheels angular position to 0.087 degrees (4096 counts/wheel revolution). By measuring this angular position, the embedded software within the controller can calculate the patients distance traveled, velocity, and stroke metrics for a known wheel diameter. The three mechanical strain gauges coupled with the embedded controller measure the patients normal and tangential force on the hand-rim as a stroke is executed. All recorded metrics are calculated by the embedded controller and sent to a propriety software application on a Windows based personal computer connected via WIFI [7].

1.3.2 SmartWheel Constraints

The SmartWheel is considered as the “gold standard” for propulsion metric collection given its legacy presence in the industry. However, the SmartWheel displays limitations from a design prospective. First, the SmartWheel requires the removal of both rear wheels from the patient’s wheelchair using an Allen wrench and installation of two replacement wheels, one with the SmartWheel and the other of equal diameter. This is both time consuming and tedious for therapists working in the clinic as the device cannot be seamlessly transferred from patient to patient. Additionally, the SmartWheel is only available in four standard wheel diameter sizes including 22”, 24”, 25” and 26”, meaning that some patients would be using the device with a wheel size they are not accustomed to leading to skewed data. The SmartWheel battery life is roughly 3 hours and can store 1 hour and 25 minutes of recorded data, restricting the device to a clinical setting. Additionally, due to the short battery life and data storage multiple SmartWheel devices must be purchased for a single clinic and placed in a charging rotation to have at least one SmartWheel available for use. Lastly, the cost of the SmartWheel is $6000.00, which is expensive compared to other activity monitoring devices available to consumers such as a Fitbit or Apple Watch.

1.4 SmartHub Purpose

SmartHub is a concept assistive device aimed to fill the capability gaps of the SmartWheel. The goal of SmartHub is to achieve identical or surmountable accuracy of the SmartWheel data collection including stroke frequency, wheelchair velocity, distance traveled, number of strokes, and push force. Additionally, the SmartHub must be low cost, low weight, and portable such that the device can be seamlessly attached and detached from the wheelchair.

The development of SmartHub began in August of 2014 as an Assistive Device Capstone project. Since the completion of this capstone project, the direction of SmartHub has moved under Dr. Sandra Metzler and Dr. Carmen Digiovine in collaboration with The Ohio State Assistive Technology Center as an area of research within the Department of Mechanical Engineering. After moving under the umbrella of academic research, two previous master's students contributed to the development of the SmartHub. These contributions are explained below.

1.4.1 SmartHub Proof of Concept

In August of 2014, a group of mechanical and biomedical engineering students began to develop the SmartHub device as a Rehabilitation Engineering Capstone project. The team constructed a proof of concept for a wheelchair activity monitoring device. The device hardware can be seen in Figure 2 below.

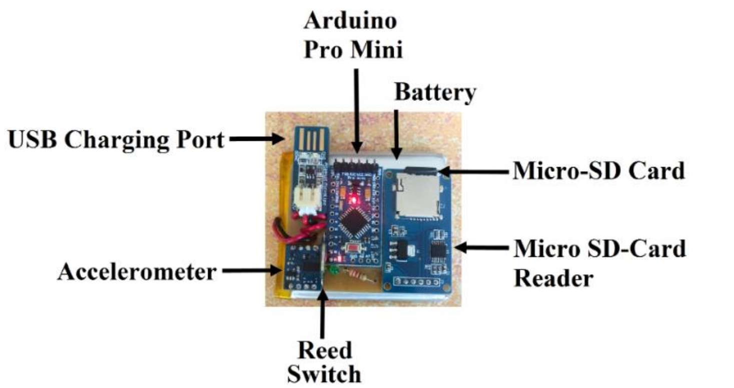

Figure 2: SmartHub Proof of Concept

The key components of this concept were a 3-axis accelerometer, Arduino Pro-Mini, Arduino USB adaptor a 3.7 V lithium-ion battery, and reed switch. The team attached the device directly to the body of the wheelchair near where the patient would rest his/her arms. A magnet attached to the rotating wheel of the wheelchair would activate the reed switch each time that the wheel completed a 360^{o} rotation, enabling distance traveled and average velocity to be calculated. The 3-axis accelerometer provided the team with data to calculate the number of strokes as well as stroke frequency. Hand-rim force was not achieved during this iteration.

While the team wrote algorithms to calculate essential propulsion metrics, these quantities were compared against known values such as distance, speeds, and number of strokes, rather than data collected from the SmartWheel. Additionally, while the device form factor was small, the components lacked a device casing to allow for easy attachment and detachment. While completing data collection trials, the team was securing the device package and magnet to the wheelchair using high strength tape [9].

1.4.2 SmartHub I

From 2015 - 2017, a previous graduate student, Ryan Letcher, made significant changes to the SmartHub hardware. This iteration is labeled as SmartHub I and can be seen in Figure 3 below.

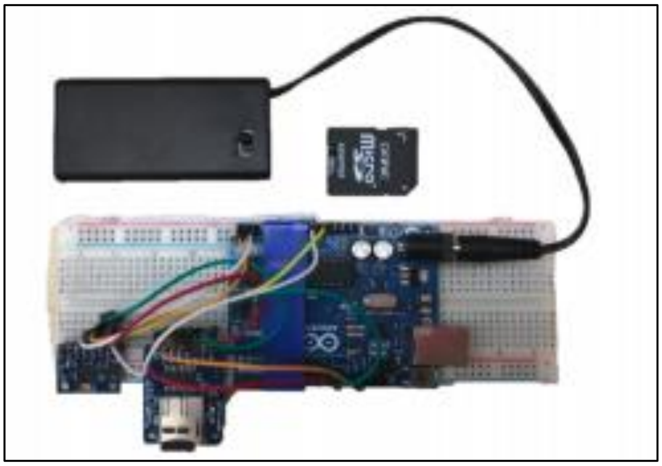

Figure 3: SmartHub I

SmartHub I upgraded the inertial measuring unit (IMU) to a 6-axis accelerometer and gyroscope as well as an Arduino UNO for data collection. A 9-volt battery was used to power the device and stored data locally on a Micro-SD card. Once trails were complete, the Micro-SD card would be removed, and the raw data was processed through a unique MATLAB script. The MATLAB script was able to present the collected metrics similar to that of the SmartWheel yet was restricted to a Windows operating system as well as a MATLAB license. Although this limitation was accepted for prototyping purposes, this manual transfer of data would not be favorable for a patient or in a clinical setting.

The scope of Ryan Letcher's thesis was to collect and compare data from the SmartHub head-to-head with the SmartWheel. Results from these trails showed accurate data collection for number of strokes, distance traveled, and stroke frequency while the stroke length, velocity, and stroke force displayed more significant error margins. However, SmartHub I mounted all hardware to a breadboard that made the device form factor large and obtrusive. During trails performed, the SmartHub I was secured to the wheel using Velcro and high strength tape to keep all components fastened [10].

1.4.3 SmartHub II

Noah Einstein, a previous master's student from 2017 – 2019 made significant changes to both the hardware and software elements of SmartHub. This iteration is labeled as SmartHub II and can be seen in Figure 4 below.

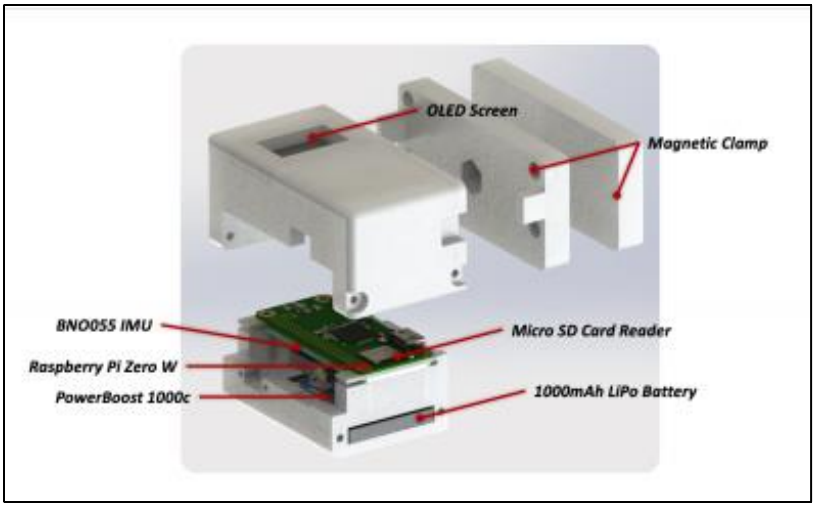

Figure 4: SmartHub II

SmartHub II added a 9-axis IMU (accelerometer, gyroscope, magnetometer), Raspberry Pi Zero W, power boost for micro-USB charging capabilities, and OLED screen to display the device IP address. All data processing and calculations are executed on the Raspberry Pi Zero W and transferred via WIFI to the host machine. This enabled SmartHub II to connect locally to personal machines as well as mobile devices of varying operating systems.

SmartHub II made significant improvements to the device casing than in the past two iterations of the device. This device casing featured a base which contained all electronic components and a lid that fit over the base and was secured in place using screws. This device package was fixed to the wheelchair via a clamping module. The clamping module includes interior and exterior pieces, the exterior sitting on the outside of the wheel spokes while the interior piece attached to the interior of these spokes (between the primary and secondary spokes). The device package connected to the clamping module via a magnetic connection that allowed for easy attachment and detachment to the wheelchair. Figure 5 below aids in the description of this device design.

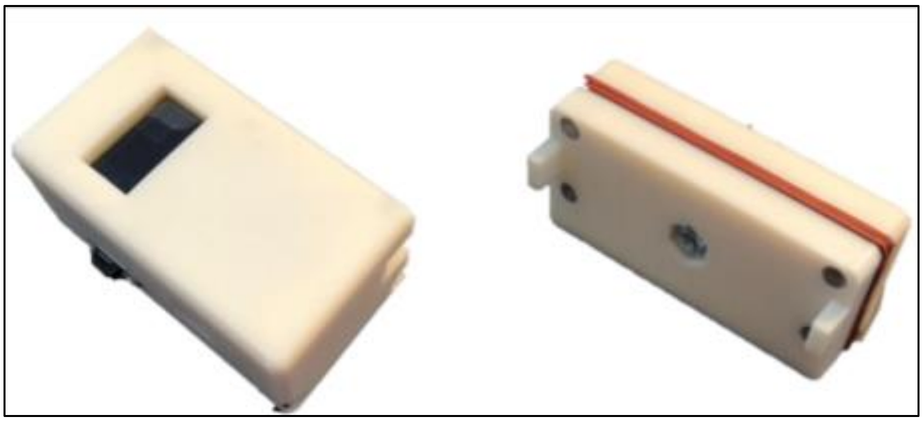

Figure 5: SmartHub II Magnetically Detachable Halves, Data Collection Module (Left), Clamping Module (Right)

Regarding collected metrics, SmartHub II exhibited significant gains in accuracy. The SmartHub II could collect a patient stoke length, stoke frequency, and velocity within 5% error, while the tangential force collected displayed a higher error margin of 20%. This discrepancy is attributed to the SmartWheel using three mechanical strain gauges while the SmartHub calculated this value using classical mechanic equations.

Despite the SmartHub II's smaller size than the previous two iterations, the device form factor presented a few complications since the device extended a significant amount from the wheelchair wheel. This was a concern as the device could be knocked off the wheel and possibly damaged when traveling through tight spaces such as door frames or walls in public settings or within the clinic [11].

1.5 SmartHub III (Current Iteration)

Given the limitations presented from SmartHub II, the scope of SmartHub III was to re-design the device casing and internal component layout to achieve a less obtrusive form factor using the same key electronic components of SmartHub II. Additionally, to improve any hardware elements to elevate the device experience for patients and clinicians who will eventually use this device in their day-to-day lives. Performing these stated improvements will move SmartHub a step closer to its "ready for market" state and serve as a slow-cost and versatile competitor to the SmartWheel, fulfilling the market need for an activity tracking device outside of the clinic.

Chapter 2: Methods

2.1 Design Review of SmartHub II

In order to determine what features the SmartHub III would improve, the SmartHub II needed to be reviewed to determine its critical elements. After speaking with clinical therapists from the Martha Morehouse Assistive Technology Center, it was noted that the SmartHub extended a significant distance from the wheel when fixed into place and would collide with objects both in and out of the clinical setting. Door frames, narrow hallways, and other tight spaces in public facilities risk the device hitting one of these features and potentially break. Figure 6 below illustrates this critical dimension as the device's width or "extension" from the wheelchair, indicated by the yellow/red dimension lines.

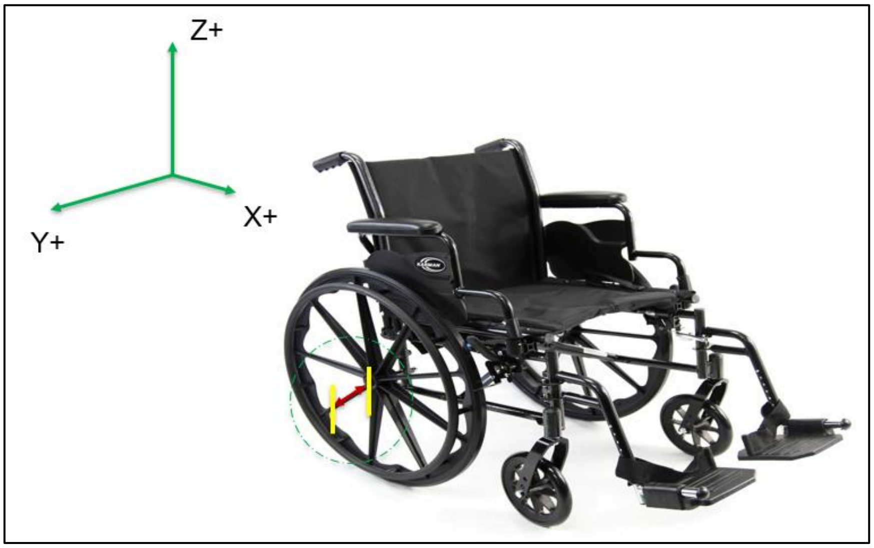

Figure 6: SmartHub Extension Direction

Table 1 below breaks down the elements of SmartHub II to understand the capability gaps of the previous device iteration.

Table 1: SmartHub II Design Analysis

		SmartHub II
Electronic Components	Raspberry Pi Zero W	●
	Rechargeable Battery	●
	OLED Screen	▲
	MicroSD Card	●
	PowerBoost Converter	●
	Inertial Measurement Unit	●
	Slide Switch	▲
Hardware Components and Features	Magnetic Connection	●
	Clamping Module	▲
	Washer + Nut Fastening Type	✖
Size and Orientation	Total Volume	●
	Extension from Wheelchair	✖

Electronic Components

SmartHub II had undergone two "make-overs" of electronic component replacements moving from an Arduino Pro-mini, to Arduino Uno, and finally a Raspberry Pi Zero W that allowed seamless data transfer from the SmartHub to a host machine. Additionally, the SmartHub progressed from a 3-axis accelerometer, to 6-axis, and ultimately a 9-axis accelerometer with SmartHub II to achieve great accuracy shown in head-to-head trials of the SmartHub and SmartWheel. Given the past three component revisions and data collection accuracy, it was concluded that SmartHub III will optimize the space constraints of the existing Raspberry Pi Zero

W, Micro-SD card, rechargeable battery, inertial measurement unit (IMU), and power boost. Effectively, the “brain” of the device will remain identical, while re-arranging component layouts to optimize the device shape given the critical extension from the wheelchair.

Regarding the OLED screen, this component was previously used to display the device IP address while connecting SmartHub II to a host machine. However, given the static IP address of the device, a better method could be used to display this show this information. Lastly, SmartHub II included a slide switch to turn the device on or off. Unfortunately, this switch did not include an LED to indicate the user if the device was on and often led to confusion.

A connected issue of electronic components is wiring these boards together. Given the current SmartHub II design, wires are tucked and bent around other boards to reach the nessesary pin. As a result, repairing the device when a soldered connection was broken proves extremely difficult. In SmartHub II, the internal boards are stacked on top of each other thus repairing a solder connection of one pin often leads to taking the entire assembly apart.

Hardware Components and Features

The SmartHub II hardware consisted of a clamping module fixed to the wheelchair by a washer and fly nut. By turning the nut, the clamping module would firmly hold against the wheelchair spokes. However, the fly nut and washer combo was extremely small and presented a risk of dropping or losing the nut while attempting to attach the clamping module. Thus, this attachment feature was unfavorable. The magnetic connection between the SmartHub II electronic package and clamping device was easy and seamless to attach and remove from the clamping unit. Lastly, gasket sheet was used as a “sticky” material to hold the device in place by friction.

Size and Orientation

The overall volume of SmartHub II is within the target value for a hand-held device that will be fixed to the side of a wheelchair. However, as stated, the SmartHub II extended 2.25” from the wheelchair spokes and risked hitting objects while a patient was completing daily tasks or within the clinic. This risked damaging the device casing or, more consequently, breaking the device completely.

2.2 Design Constraints SmartHub III

Given the analysis shown in Table 1, a few design constraints were determined in order to proceed with brainstorming and prototyping of SmartHub III. In summary, SmartHub III will utilize the core electronic components of SmartHub II to optimize space constraints and minimize the device extension from the wheelchair wheel. Additionally, SmartHub III aims to replace key hardware features to improve the user experience and durability of the device.

A simple analogy of SmartHub III can be compared to a hamburger with multiple toppings. As this burger is pressed into the plate, the contents of the burger spread laterally and the overall height of the hamburger decreases, yet the total contents of the burger remain constant. SmartHub III aims to optimize the internal component layout of the device while improving the user experience.

2.2.1 Electronic Components

The components listed below represent the “brains” of the SmartHub that will remain unchanged.

Raspberry Pi Zero W

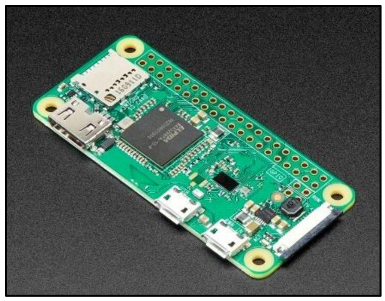

Figure 7: Raspberry Pi Zero W

Shown in Figure 7 above, Raspberry Pi Zero W is a Linux based microprocessor [12]. This compact, low cost board can store multiple programs and communicate with host devices in a variety of ways. The board also includes a Micro-SD card reader which can be used as removable storage. Technical specifications of the Raspberry Pi Zero W include a 1.0 gigahertz processor with 512 megabytes of storage, WIFI connectivity, as well as Bluetooth 4.0 capabilities for wireless data transfer and communication. In SmartHub III, the Raspberry Pi Zero W houses on-board scripts that execute calculations as data is fed from the IMU. This collected data is then packaged and sent to the host machine, providing a key functionality of the device.

Rechargeable Battery

SmartHub is powered by a 1000 mAh lithium-ion rechargeable battery, shown in Figure 8 below [13]. Given the electronic load this battery supports, the SmartHub battery life is roughly 10 hours of constant use, sufficient life for the typical daily use. When the device needs to re-charge, the battery can be fully charged in approximately 1.5 hours.

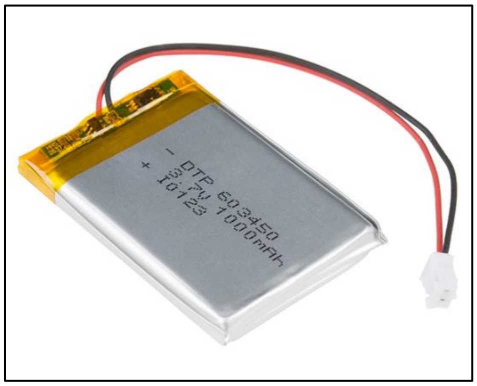

Figure 8: 1000 mAh Rechargeable Battery

Micro-SD Card

The 16 GB Micro-SD card shown below in Figure 9 functions as local storage for the Raspberry Pi Zero W. Python and HTML scripts for data processing and visualization are uploaded to the Micro SD card and then placed into the SD reader on the Raspberry Pi to “upload” written programs [14].

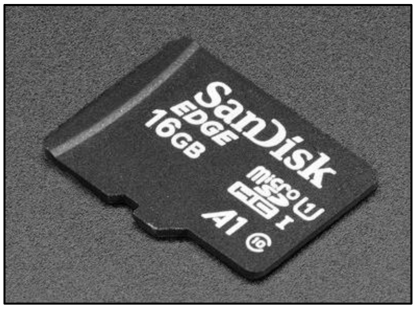

Figure 9: 16 GB Micro-SD Card

PowerBoost Converter

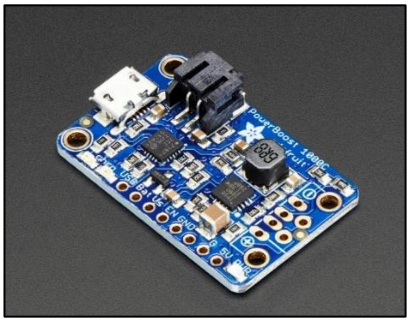

Figure 10: PowerBoost 1000 Charger

Figure 10 above pictures the PowerBoost 1000 Charger [15]. The 1000 mAh battery shown mentioned above in Figure 8 outputs 3.7 volts of electrical power. Thus, a voltage booster is needed to “boost” the voltage of the battery to a constant 5 volts to power the Raspberry Pi. This board also features a micro-USB charging port, a common charging type for consumer products such as headphones, calculators, and video game controllers.

Inertial Measurement Unit

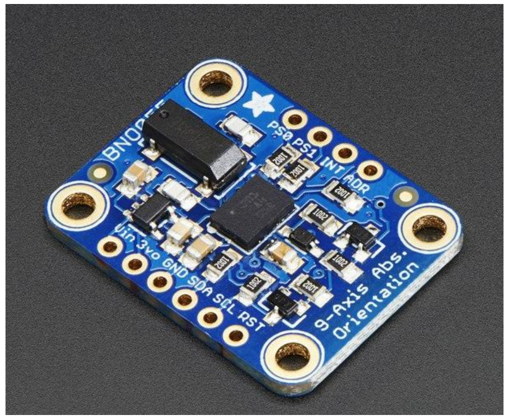

Figure 11: BNO055 Inertial Measurement Unit (IMU)

Besides the Raspberry Pi Zero, the BNO055 inertial measurement unit (IMU) shown in Figure 11 above is the most vital component of the SmartHub. This 9-axis IMU includes an accelerometer, gyroscope, and magnetometer that seamlessly streams this data to the Raspberry Pi Zero W for processing [16]. The IMU records the absolute orientation of the SmartHub, providing roll, angle, and relative location data. As a result, the SmartHub can be placed at any radius from the center of the wheelchair wheel, providing a flexible attachment procedure.

SmartHub III will aim to minimize the device extension from the wheelchair given these internal components while optimizing the internal component layout for repairs and functionality.

2.2.2 Hardware Components and Features

A top view of SmartHub II shown in Figure 12 below exhibits the size and shape of the device [11].

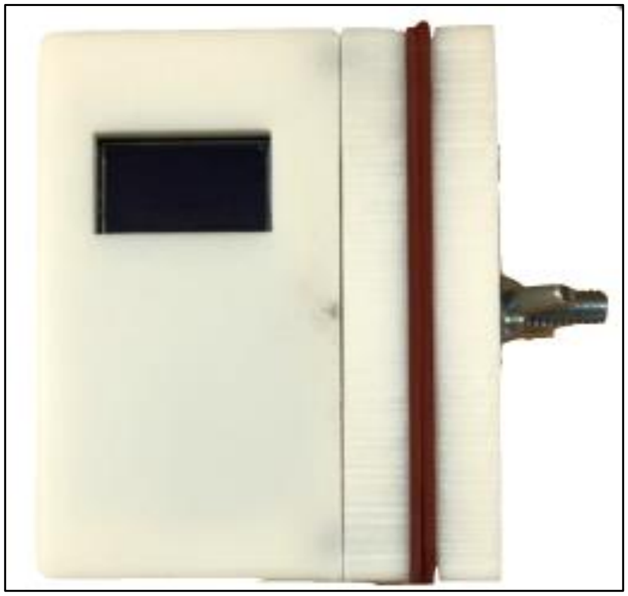

Figure 12: SmartHub II Top View

Also exhibited in the Figure 12 above is the fly nut and washer fastening type. SmartHub III will strive to upgrade this fastening type. However, SmartHub III will also strive to achieve a similar "sandwich" style clamping mechanism as the SmartHub clamping module is "sandwiched" in between the wheelchair spokes.

2.2.3 Size and Orientation

The size and dimensions of SmartHub II are shown below in Figure 13 below.

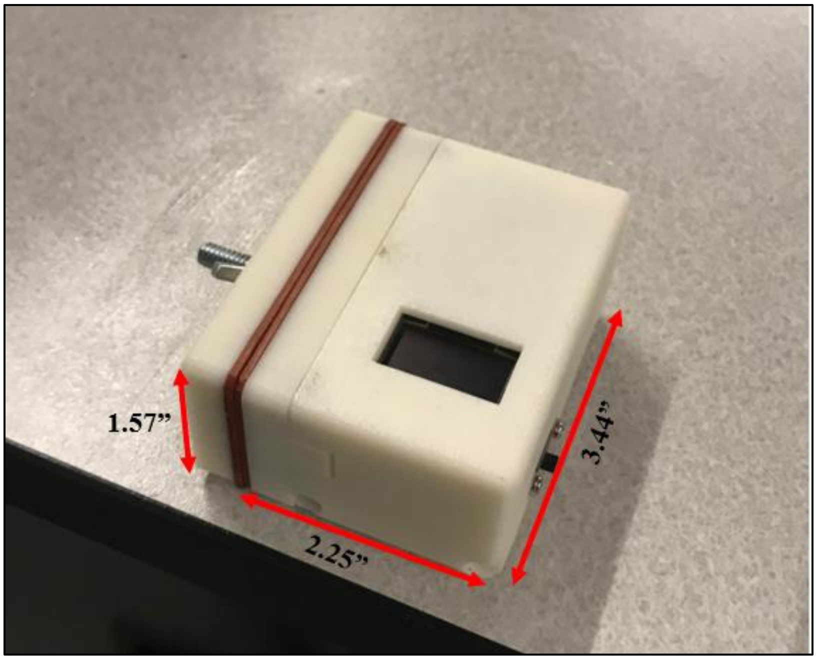

Figure 13: SmartHub II with Dimensions

Note: The 2.25” dimension is not measured to the back of the device as this remaining portion sits behind the spokes of the wheelchair and will not factor into the device width or extension from the wheelchair wheel.

SmartHub II extends 2.25” from the spokes of the wheel and risks colliding with objects. To determine the target dimension for SmartHub III’s extension from the wheel, measurements were taken from manual wheelchairs within the Assistive Technology Center. Figure 14 below was captured facing a wheelchair in front of the wheelchair seat. Pictured is a standard manual wheelchair fit for patients within the clinic.

Figure 14: Typical Distance Between Wheel and Hand-Rim

Shown in Figure 14 above, the distance between the wheel and hand-rim of the wheelchair is approximately 2”. Although varying manual wheelchairs will display different dimensions, this 2” measurement was considered a good average amongst manual wheelchairs. Considering a vertical plane placed coincident with the edge of the hand-rim (at the first tick mark of the ruler), any objects within this plane would be protected from collision of objects such as walls or door frames that would collide with the hand-rim instead of the device. Thus, it was concluded that if the device package did not extend past this imaginary plane, the SmartHub would be free from collision. Therefore a 2” extension from the wheelchair spokes was established as the target dimension for SmartHub III.

2.3 Prusa 3D Printer Build and Formlabs Form 3

As the scope of SmartHub III was determined, it became apparent that 3D printing would be a valuable resource for prototype iterations. At the same time, the research group purchased a

Prusa i3 MK3S, one of the top-line FDM 3D printers for lab and university use. However, this purchase was particularly unique as the printer comes completely disassembled and can be built by following an online instruction guide. Figure 15 displays an assembled Prusa i3 MK3S printer [17].

Figure 15: Prusa i3 MK3S Assembled

The end-to-end process took roughly 30 hours from assembly to testing and the first successful print. This experience provided me with a greater knowledge of FDM printer set-up, assembly, and troubleshooting. At the time this printer was completed, it was expected that this Prusa 3D printer would be used for SmartHub III prototyping given its build volume and 150 microns layer height. However, the research group shortly after purchased a Formlabs Form 3, regarded as a top tier SLA printer within the industry.

The Formlabs Form 3 shown in Figure 16 below was used as the primary prototyping resource for SmartHub III [18].

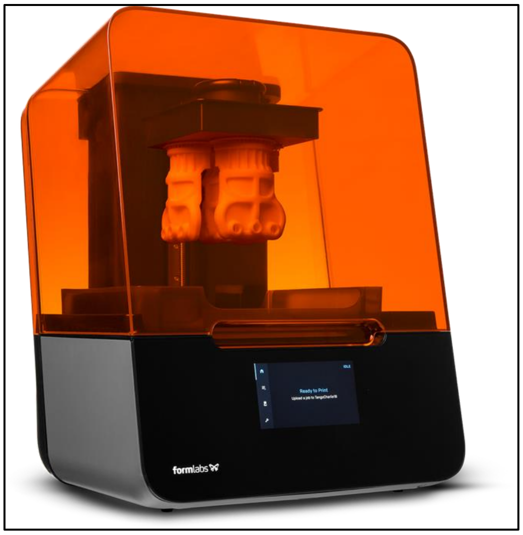

Figure 16: Formlabs Form 3

The Form 3 proved favorable over the Prusa i3 MK3S due to its 25 microns layer height capability and continuity of bonds within the printed structure versus an FDM printer that will display small discontinuities between layers of extruded plastic. This feature was critical as mechanical fasteners were expected to be used this continuous body from an SLA printer would maximize the strength of the print. The Form 3 also features a variety of resins including tough and durable mechanical properties that could be utilized for SmartHub III.

Additionally, as this printer was a new resource to the research group, SmartHub III prototypes acted as a pilot to discover and document printing capabilities and best practices. During the SmartHub III prototyping phase, all prints were evaluated for mechanical properties such as tolerances and surface finish, then communicated to the research group as these discoveries could benefit other on-going research within the group.

2.4 SmartHub III Design Iterations

The strategy for SmartHub III stemmed from the concept that if electronic components were placed on the same plane, the overall extension of the device would be minimized. This strategy is opposed to that of SmartHub II where the electronic components are stacked on top of each other shown in Figure 4. Mounting the electronic components side-by-side would optimize the size of the device as all printed circuit boards (PCB) are roughly 0.2" in size and additionally simplify the wiring between components as the resultant wiring path from pin to pin would decrease.

2.4.1 SmartHub III Iteration 1

SmartHub III's first iteration set to prove this principle of laying all electronic components on the same plane in order to better understand how the device would look. Figure 17 below displays the first rudimentary model of SmartHub III. This concept placed the electronic components side by side, keeping connected pins as close as possible to minimize the wire length between boards.

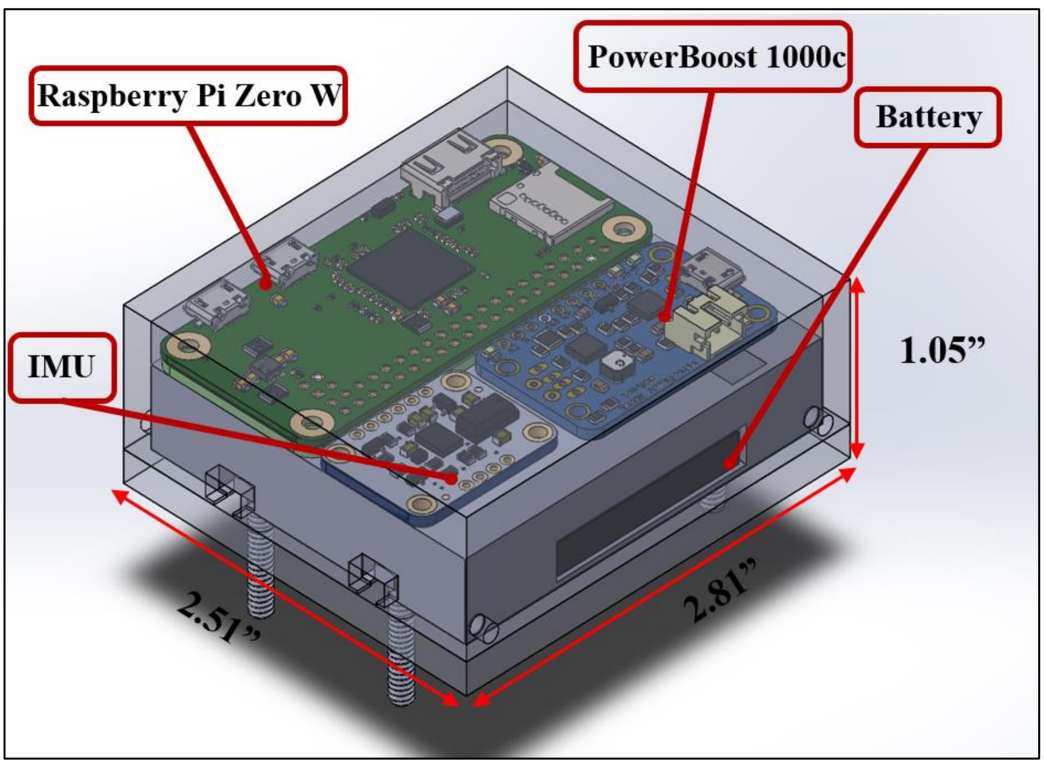

Figure 17: SmartHub Iteration 1, Transparent Device Lid

Although this iteration was not a polished and complete design, it served as a benchmark to support the concept of placing all electronic components on the same plane. Additionally, the rechargeable battery was placed under the "bed" of mounted boards. At this time, a replacement switch for the slide switch had not been determined. As for the attachment type to the wheelchair, four hex head screws were designed to be fit into the base of the device and wingnuts would be used to fix the device into place. Although it was expected this attachment type would be improved, this feature was input to identify space constraints of the future fastening type.

Figure 17 displays the model dimensions of this iteration. 2.51" represents the height, 2.81" represents the length, and lastly 1.05" represents the width or extension from the wheel of the wheelchair. Given the width of 1.05", this iteration proved that mounting the electronic components on the same plane would lead to a decreased extension from the wheelchair. Although these dimensions were subject to change, with this concept confirmed, SmartHub III continued to pursue this strategy.

2.4.2 SmartHub III Iteration 2

The second iteration of SmartHub III greater solidified the dimensions and overall design of the device. Based on the positive feedback received from clinicians regarding the magnetic attachment and detachment, SmartHub III aimed to re-create a clamping module that would reflect similar features. Figure 18 below displays SmartHub III iteration 2.

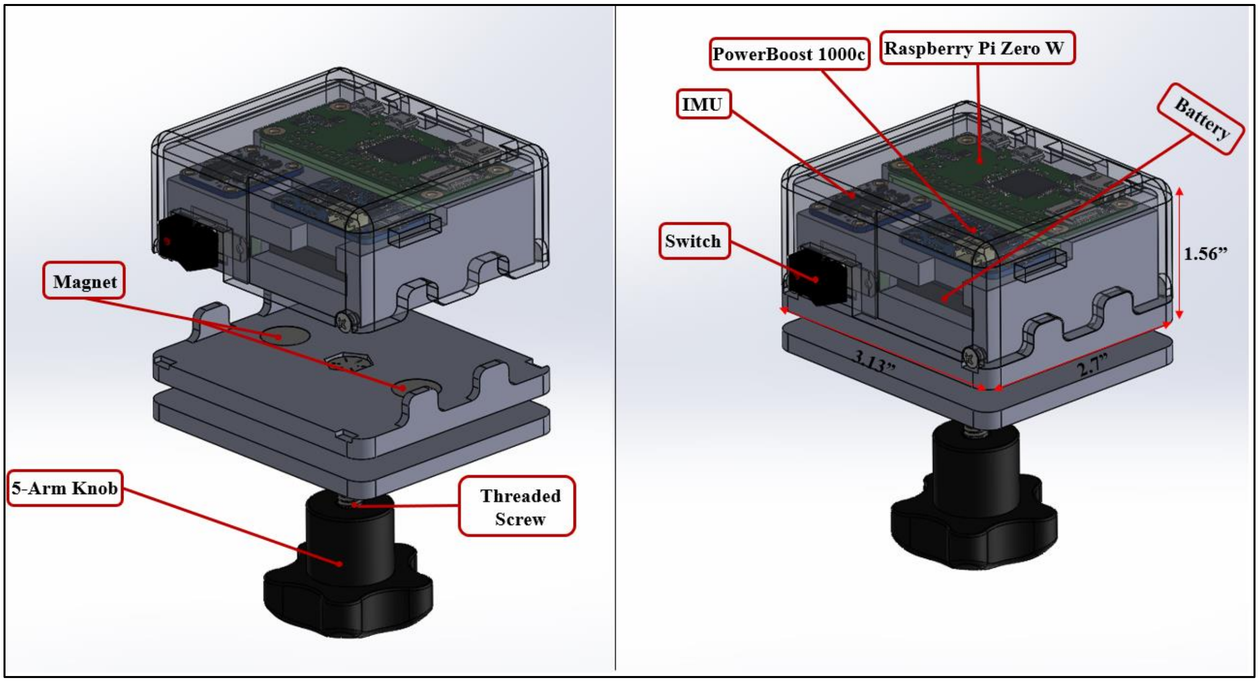

Figure 18: SmartHub III Iteration 2, Data Collection Module Detached from Clamping Module (left), Data Collection Module Attached to Clamping Module (Right)

Seen in Figure 18 (Right) the dimensions of this iteration are as follows: length of 3.13”, height of 2.7”, and width or extension of 1.56”.

Electronic Components

SmartHub III iteration 2 made a few changes to electronic components within the device. The first decision was to remove the OLED screen used in SmartHub II. The OLED screen had previously been used to display the device IP address. However, since the Raspberry Pi Zero W has a static IP address this information could be label printed and stuck to the device. Additionally, removing the OLED screen allows the device width to be smaller as the device casing includes one less component.

A second component altered was the previous slide switch used to power on and off the device. This iteration included a rocker switch with an embedded LED within the body of the switch. This feature would provide the user with visual feedback if the device was active or not. Unfortunately, this particular rocker switch was in short stock and not expected to re-stock until after the conclusion of this thesis. As a result, this switch type was later changed and shown in the SmartHub III Final Design section.

Hardware Components and Features

A few changes were made to the clamping module in order to improve its performance and functionality. First, two half inch diameter magnets were added to each half of the data collection and clamping module. The magnets used in SmartHub II were significantly smaller (one eight inch in diameter) and provided a weaker hold between the two device halves. Further details of these magnets are explained in the SmartHub III Final Design section.

A significant change of this iteration is the 5-arm knob added. This feature replaces the need for a washer and nut combo used in SmartHub II and could be easily dropped or misplaced. The knob fastening type can be tightened until the device is secured in between the spokes of the wheel. This features greatly improves the user experience as the larger knob is easier to grip for all sized hands.

Lastly, two “channels” were added for the data collection and clamping module to fit together. These channels can be seen in Figure 18. By adding these supports the data collection module will be firmly secured to the clamping module and eliminate the device wobbling or rattling while the patient is moving the wheelchair.

Size and Orientation

As more hardware was selected and space constraints were discovered, the width or extension of the device increased to 1.56”. However, this dimension is within the target extension of 2.00”. Thus, iteration two moved onto prototyping using the Form 3 SLA printer.

Prototyping, Takeaways, and Modifications

To start, the bottom case of this prototype iteration was printed and post processed. This post processing procedure included sanding down surfaces of the part that had support material and drilling holes using a drill press to clear out any material due to hole shrinkage from the printer. When the print was complete, the base-lid connection holes were drilled to size. This hole is for a thread-forming screw to connect and fasten the lid of the device over the base. After drilling these holes, it became clear that there was too little material in between the diameter of the hole and the sides of the part. As a result, major cracking occurred displaying that these holes needed to be moved to a new location where the strength of the part would be maximized. This cracking can be seen in Figure 19 below indicated by the red circles.

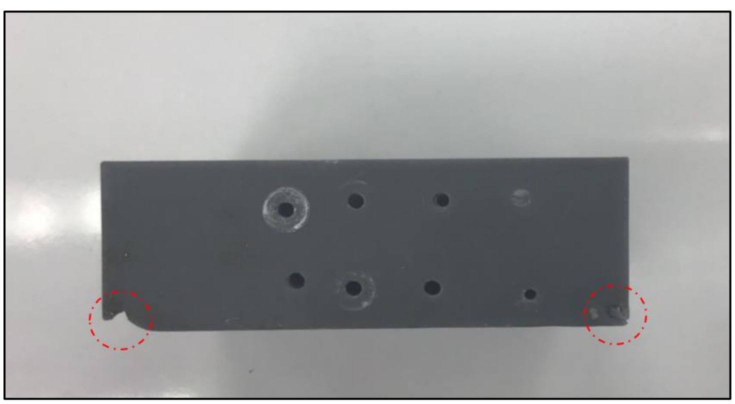

Figure 19: SmartHub III Iteration 2, Cracked Base Holes

Note: Please ignore additional holes as they were used for hand drilling practice.

After seeing this result, the remainder of SmartHub III iteration 2 was printed to determine other features of the design that need to be re-worked. The fully assembled (without fasteners) prototype can be seen in Figure 20 below.

Figure 20: SmartHub III Iteration 2, Assembled

From this print iteration, it was determined that the connection and magnet dimensions fit great for the connection between the data collection and clamping unit. A few additional adjustments were recognized concerning the internal layout of electronic components, shown in Figure 21 below. In this image specifically, a few electronic mounting screws were input to test mounting the components to the case.

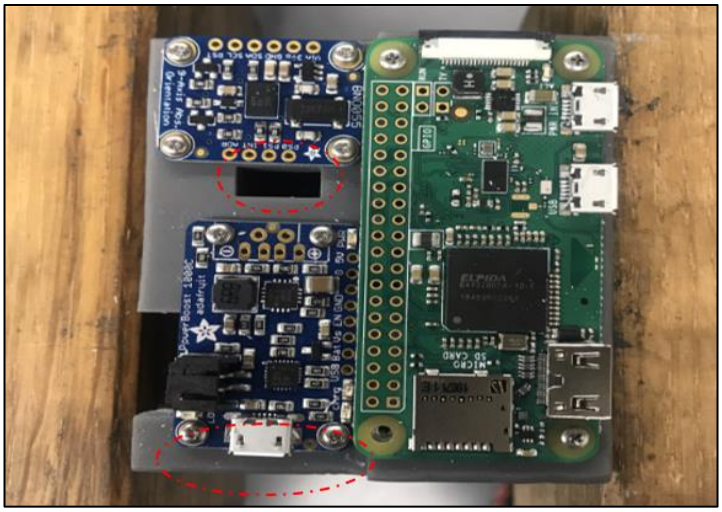

Figure 21: SmartHub III Iteration 2, Internal Component Layout

By laying mounting these components, it was recognized that the wire channel (top red oval) would need to be increased to attach wires through this hole to the on/off switch of the device. Additionally, the PowerBoost needed to be moved closer to the edge of the base (bottom red oval) to provide easier access to the micro-USB charging port.

All adjustments including electronic components, hardware components, and size were documented and reflected in the SmartHub III Final Design.

2.5 SmartHub III Final Design

SmartHub III iteration 3 represents the final design for SmartHub III. This final design satisfies all design constraints and addresses complications presented by SmartHub II. The final design can be seen below in Figure 22. Additionally, Figure 23 displays an exploded view of the data collection unit.

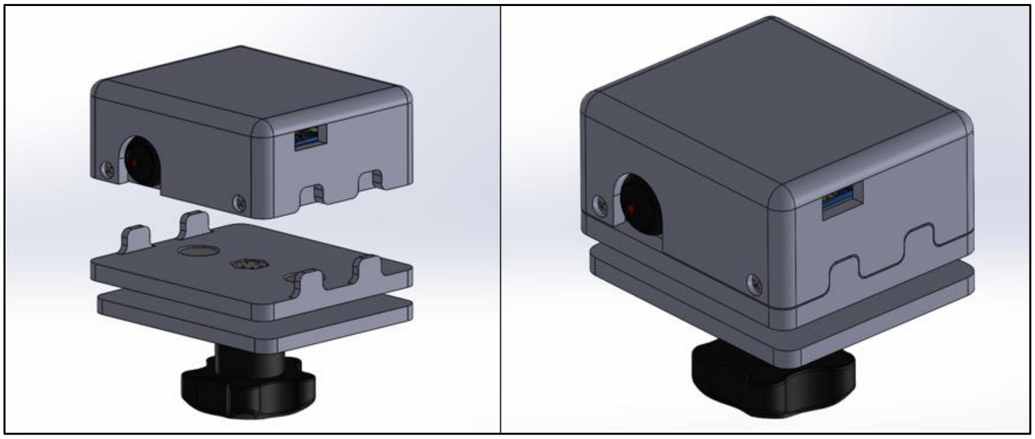

Figure 22: SmartHub III Final Design, Attached to Clamping Module (Left), Detached from Clamping Module (Right)

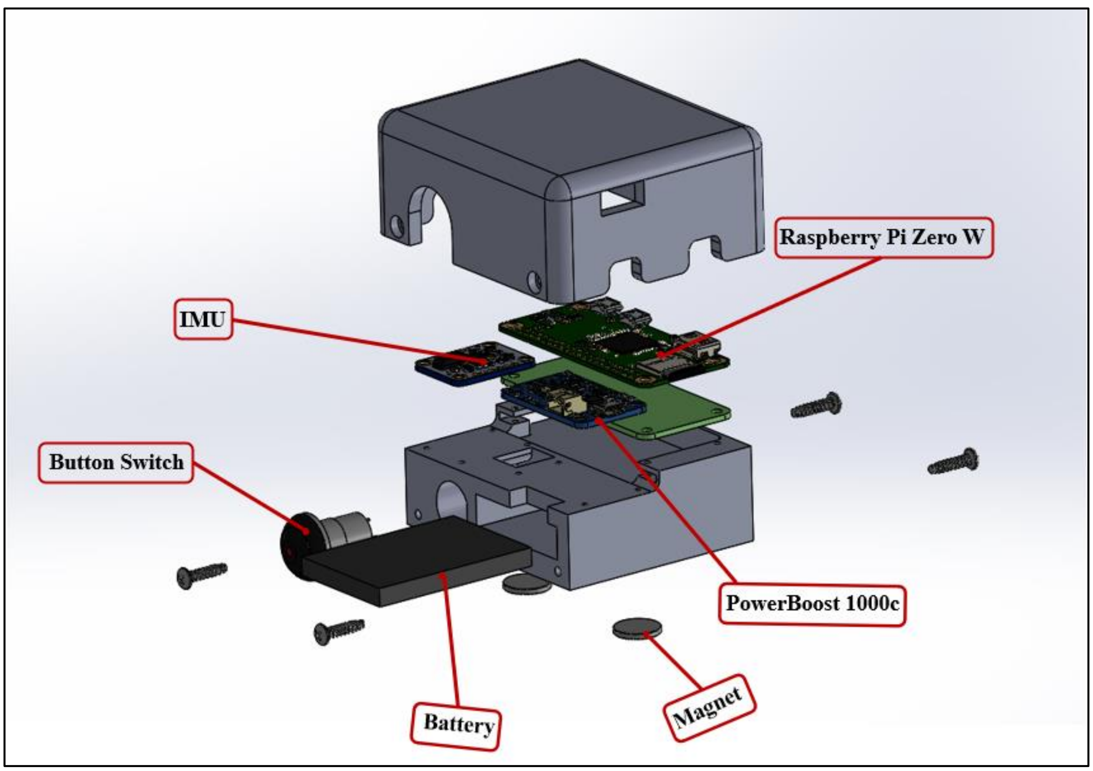

Figure 23: SmartHub III Final Design, Exploded Data Collection Unit

Details of this design are explained below in the New Electronic Components, New Hardware Components and Features, and New Size and Orientation sections.

2.5.1 New Electronic Components

The SmartHub III data collection unit contains the same “brains” of the SmartHub II with an additional feature. A push button switch was added with an internal LED that will activate when the button is pressed and turn on the device. This push button is shown below in Figure 24 below.

Figure 24: Pushbutton Switch

The push button switch is a single pole single toggle (SPST) switch meaning that the switch has one off and one on position, current rating of 1000 mA and voltage rating of 24 volts [19]. Panel mounted to the side of the base, the geometry of the switch snap-fits into the 3D printed case, allowing for easy assembly. The location of this switch can be seen in Figure 25 below.

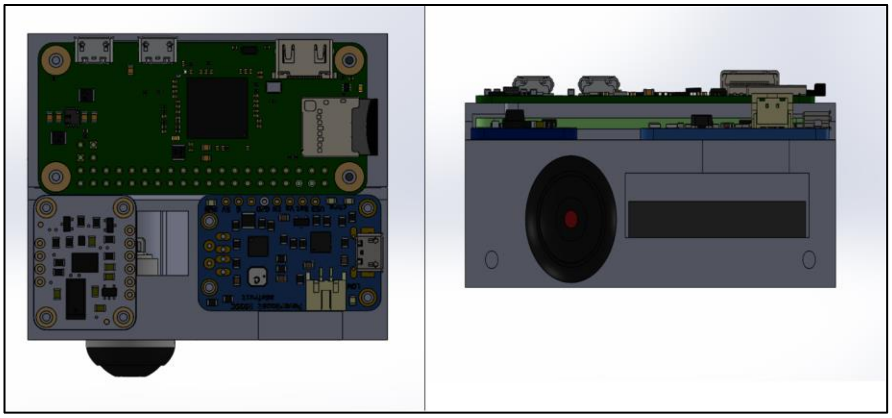

Figure 25: SmartHub III Electronic Component Layout (Left) Top View, (Right) Front View

The wires connected to the switch will be fed through the wiring channel seen in the center of Figure 25 (left) and connected to the PowerBoost. Re-arranging the electronic internal layout of the electronic components optimized wiring for the device. Since connected pins were placed the closest distance possible, making wiring and repairing the device if needed greatly simplified. The complete wiring diagram for SmartHub III can be seen below in Figure 26.

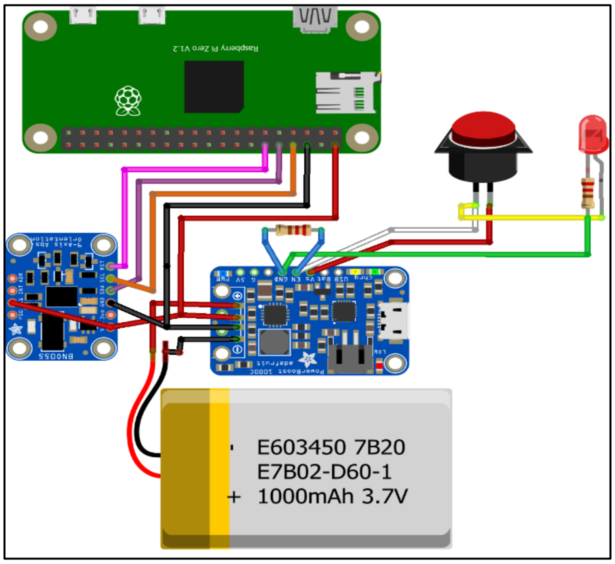

Figure 26: SmartHub III Wiring Diagram

Note: The LED in Figure 26 represents the internal LED within the push button switch.

2.5.2 New Hardware Components and Features

The major changes in hardware components for SmartHub III include the clamping module. Both side and isometric views of the lamping module can be seen below in Figure 27.

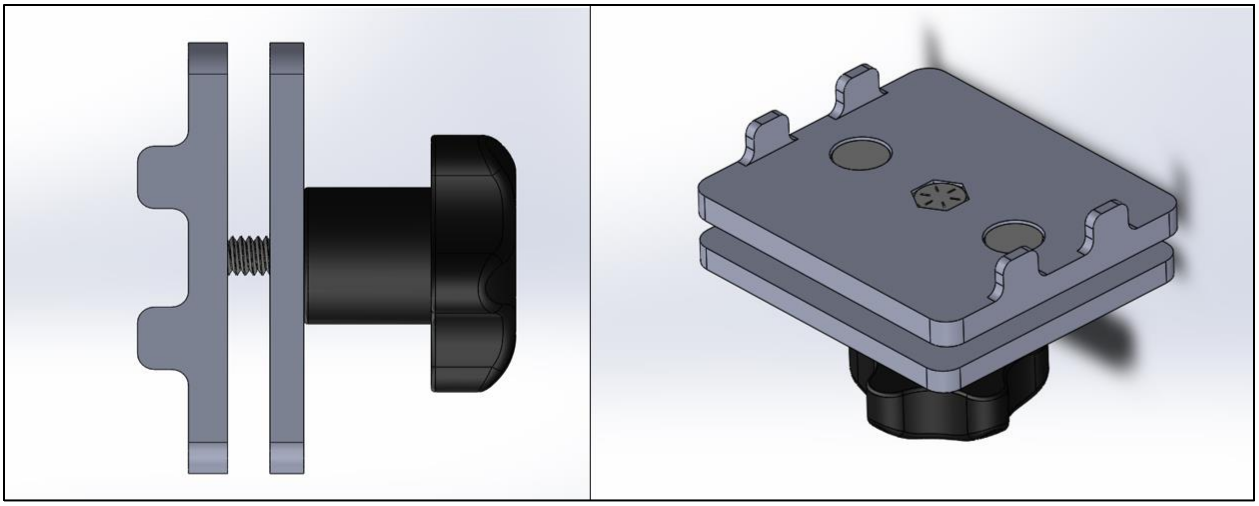

Figure 27: SmartHub III Clamping Module

The clamping module “sandwiches” between the spokes of the wheelchair wheel and fastened using the 5-arm knob displayed in Figure 28 [20].

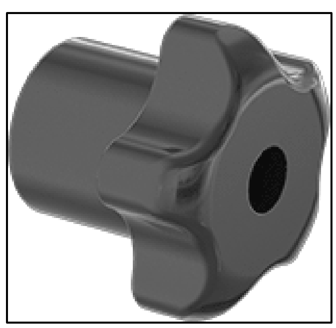

Figure 28: SmartHub III 5-Arm Knob

The front piece of the clamping module includes the two sets of guided slots that face outward on the wheel of the wheelchair (in the positive y-direction with respect to Figure 6). The secondary piece is fits in between the first and second sets of spokes on the wheelchair. Then, the

5-Arm knob fastens the clamping module by applying retention force to keep the device fixed while the patient is performing tasks.

Additionally, the data collection unit is attached to the clamping module by two high strength magnets shown on Figure 27 and guided by the “channels” on the clamping module. These magnets require a maximum pull force of 3.6 lbs. and feature a 3M adhesive VHB (very high bond) backing for easy assembly when fitting the magnets into the case, requiring no superglue or other materials [21].

2.5.3 New Size and Orientation

A complete isometric view of the SmartHub II is shown below in Figure 29. This view shows the device attached to the clamping module, where the device would be seated during operation. The dimensions shown in Figure 29 are tabulated in Table 2 on the next page.

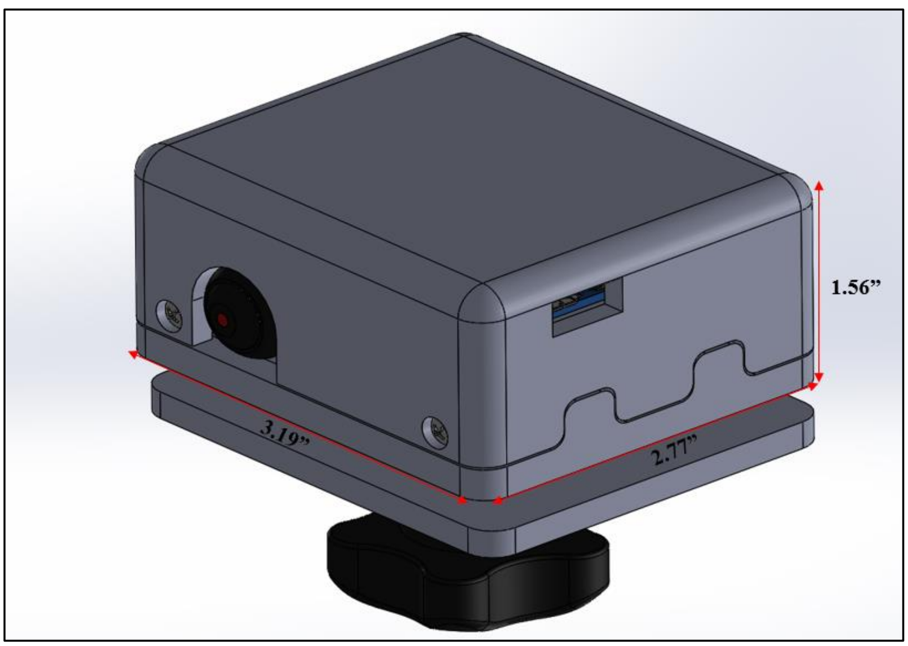

Figure 29: Final SmartHub III Design with Dimensions

Table 2: SmartHub III Final Design Dimensions

SmartHub III	
Length [in]	3.19
Height [in]	2.77
Width [in]	1.56
Total Volume [in^3]	13.78

Unfortunately, the progress of this research was cut short due to the COVID-19 outbreak and immediate closing of all university facilities and mandated quarantine. As a result, the SmartHub III Final Design was unable to be printed and wired with the electronic components mentioned above. As a result, the Figure 30 below is the SmartHub II iteration 2 mounted onto the wheelchair, taken just before departing from the university. However, SmartHub II iteration 2 featured the same device width as the final design and can be used to display what the final design looks like in physical form. The technical drawings for SmartHub III Final Design can be found in Appendix B, while Bill of Materials can be Found in Appendix A.

Figure 30: SmartHub III Connected to Manual Wheelchair

On the left, the SmartHub III is attached to the primary set of wheelchair spokes and seated in the clamping module. This image additionally displays the scale of the SmartHub III in comparison to the total diameter of the wheel. On the right, the device is shown from the front side of the wheelchair. Given the device width (extension) of 1.56”, the device fits completely between the 2” space of the first wheelchair spokes and the hand-rim with respect to Figure 6

Chapter 3: Results

3.1 SmartHub III Overview

SmartHub III leveraged existing electronic components from SmartHub II to create a small and unobtrusive form factor that can be easily attached and detached from a manual wheelchair. More specifically, the OLED screen and slide switch of the previous SmartHub II were adjusted to create a more favorable experience for a patient or clinician using the device. The clamping module and attachment mechanisms to the wheelchair were improved to create seamless and firm connection to the wheelchair. Lastly, the overall form factor of SmartHub III was improved as the devices extension from the wheelchair was decreased by 30% shown by Eq. 1 below while the volume increased slightly. However, the total volume of SmartHub III is adequate for that a hand-held device while decreasing the devices critical dimension, its width.

$$Percent\ Decrease, Device\ Width = \frac{W_{SmartHub\ III} - W_{SmartHub\ II}}{W_{SmartHub\ II}} * 100 = 30.6\% \quad \text{Eq. 1}$$

3. 2 SmartHub II vs. SmartHub III

SmartHub III improved elements of SmartHub II including electronic components, mechanical hardware, as well as size and orientation. As, stated the vision for SmartHub III was to utilize the pre-existing hardware and associated processing scripts of SmartHub II, yet improve the device size and functionality to create a superior user experience. SmartHub II and SmartHub III are compared in Table 3 below.

Table 3: SmartHub II vs. SmartHub III Comparison

		SmartHub II	SmartHub III	Comments
Electronic Components	Raspberry Pi Zero W	●	●	
	Rechargeable Battery	●	●	
	OLED Screen	▲	●	Eliminated and replaced with label printed IP address
	MicroSD Card	●	●	
	PowerBoost Converter	●	●	
	Inertial Measurement Unit	●	●	
	Slide Switch	▲	▲ / ●	Replaced by button switch with internal LED
Hardware Components and Features	Magnetic Connection	●	●	
	Clamping Module	▲	●	Improved connection and hold of data collection unit
	Washer + Nut Fastening Type	✖	●	Replaced by 5-arm knob
Size and Orientation	Total Volume	●	●	
	Extension from Wheelchair	✖	●	Total width or extension of device from the wheelchair decreased by 30% (decreased from 2.25" to 1.56")

As seen in the chart above, SmartHub III improved many aspects of SmartHub II that were observed as unfavorable. Most substantially, the device extension of SmartHub II was reduced by 30% while increasing in total volume only slightly, however still of appropriate size for a hand-held device. The side by side dimensions of SmartHub II and SmartHub III can be seen in Table 4 on the following page.

Table 4: SmartHub II vs. SmartHub III Dimensions and Volume

Dimension	SmartHub II	SmartHub III
Length [in]	3.44	3.19
Height [in]	1.57	2.77
Width [in]	2.25	1.56
Total Volume [in^3]	12.15	13.78

This improvement displayed in the width column is substantial because it moved the width or extension of the device within the bounds of the wheelchair hand-rim (refer to Figure 14), effectively shielding the device and mitigating risk of collision with objects. This was the primary concern from clinicians after evaluating SmartHub II.

Unfortunately, as stated above, due to the COVID-19 outbreak and immediate closing of university facilities, the final design of SmartHub III was unable to be fabricated and assembled.

3. 3 SmartWheel vs. SmartHub III

While SmartHub III based its improvements off the previous iteration of SmartHub II, the end goal of SmartHub III is create a device with superior performance to that of the SmartWheel and allow for data collection outside of clinical settings. This is a key functionality of the SmartHub as the collected data will paint a complete picture as to how patients are using their wheelchair day-to-day. The improvements made for SmartHub III strengthen the device profile as the alterations of electrical components and mechanical hardware enhance the device experience for both the patient and clinician. These features make the device seamless and easy for all users while the SmartWheel required tedious attachment and detachment of the device as well as data collection that can only be viewed on a personal computer. Additionally, to use an activity monitoring device outside of the clinic, it must be hand-held and unobtrusive to create the optimal experience for the user. SmartHub III serves this capability given its dimensions, the device does not extend past the wheelchair hand-rim and therefore is protected from collisions with objects such as doorframes and hallways in public facilities or in a patient’s home.

Chapter 4: Discussion

4.1 Device Feedback

To gain feedback on the SmartHub III design, a survey was conducted with three clinicians from the Ohio State Martha Morehouse Assistive Technology Center. Plans for this identical survey included feedback from The Ohio State Buckeye Blitz Wheelchair Rugby team as well as members of Creating Living, a Columbus Disabled Living Residency. However, due to COVID-19 circumstances unfortunately these future participants could not be surveyed.

4.1.1 Survey Feedback

As stated, a five-question survey was completed by three clinicians in The Ohio State Martha Morehouse Assistive Technology Center. Participants got the opportunity to hold the SmartHub III device in their hands, attach and detach it from the manual wheelchair, and perform any other tasks with the device they felt would be necessary to accurately answer the questions posed. The five questions as well as their results can be seen in Figures 31-34, with addition feedback listed in question 5. For each question, the prompt is listed above the bar chart and the key can be found below this chart.

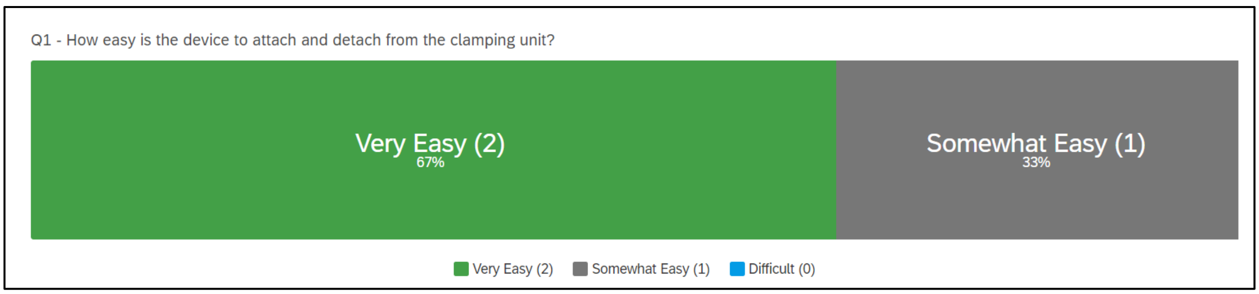

Figure 31: Question 1, Survey Results

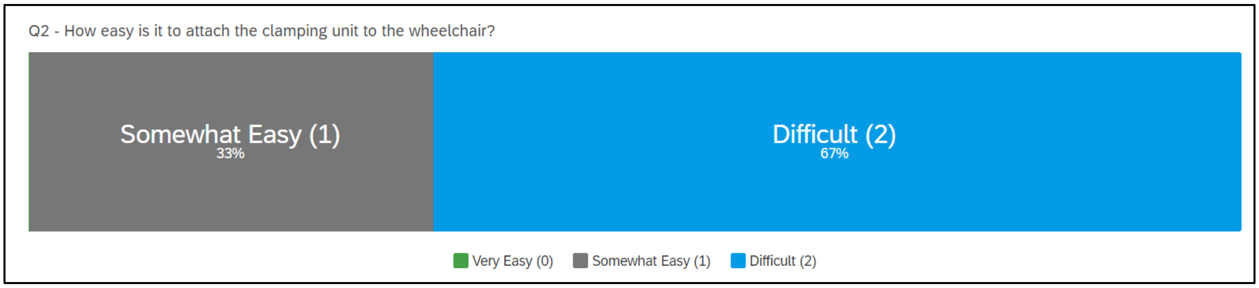

Figure 32: Question 2, Survey Results

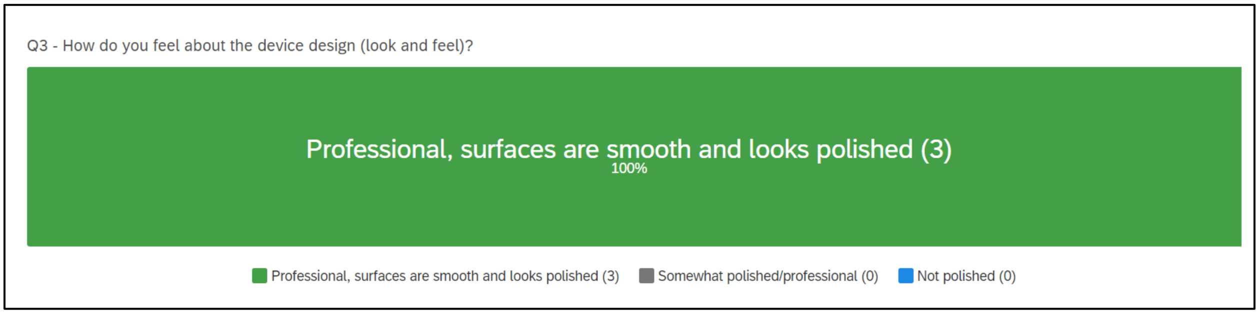

Figure 33: Question 3, Survey Results

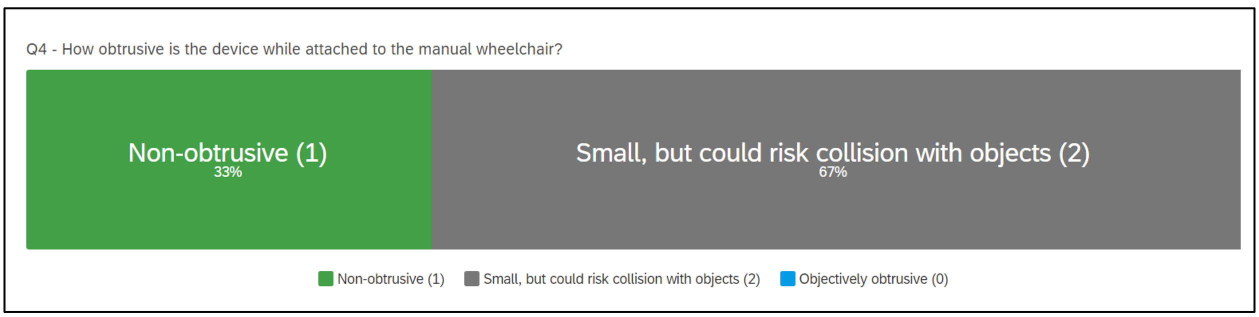

Figure 34: Question 4, Survey Results

Q5 - Please provide any additional feedback you of the device you feel is nessesary.

Participant 1:

"Talked about potential for easier way to fasten to Smart Hub from and exterior approach due to lack of ability to reach between spokes; feedback provided in clinic and notes taken on ideas"

Participant 2:

"Interior screw making contact with frame-too deep. Suggestion to screw from exterior of chair due to inner spoke restricting access"

Participant 3:

"If possible to be smaller, it would be great to fit between the spokes. The device may get to be a bit heavy over time, especially if one side would be heavier than the other. Doesn't necessarily need to be easily removable from the spokes, could require a tool"

4.2 Insights Gained

Based on the results, the SmartHub III device features a profession aesthetic that is easy to attach and detach from the clamping module. The SmartHub III can safely secure to the manual wheelchair, but the mechanical elements used to fasten the device to the wheelchair could be improved. When attaching the device, the user must reach through the secondary spokes (from the back of the wheel) and turn the 5-arm knob while holding the device in place from the front of the wheel. Based on the spacing of the spokes, this can be a troublesome task. Figure 35 aids in this description.

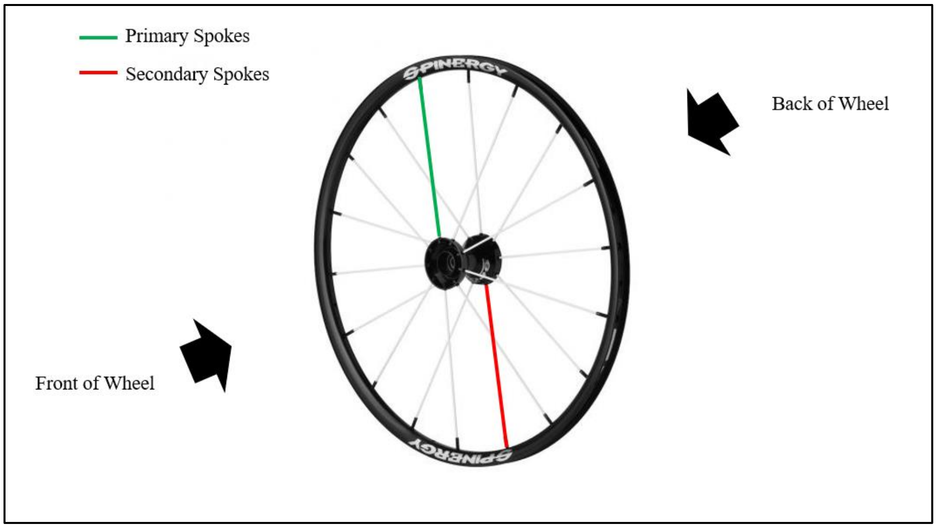

Figure 35: Primary and Secondary Spokes of Manual Wheelchair Wheel [22]

Participant 1 and 2 suggested moving the fastening feature of the device to the front of the wheel, so the user does not have to reach in-between the spokes of the wheelchair. However, this would likely introduce a tool to the installation procedure which the SmartHub team was initially advised against. Lastly, the size of the device improved with recent revisions, however this total volume could still be decreased to provide a better solution. With regards to size, participant 3 suggested making the device small enough that it could fit between the primary and secondary wheelchair spokes so the device would be held on the interior of the wheel and completely unobtrusive. The feedback gained from participants 1-3 proved useful as this group represents and end-user of the product.

Chapter 5: Conclusions

5.1 SmartHub III Summary

The scope of SmartHub III was accomplished as the device width or extension from the wheelchair wheel was decreased by 30% (within the 2” threshold) by re-arranging the key internal components to optimize wiring layouts within the device and upgrading electrical and mechanical features. The SmartHub III is polished, compact, and presents a straightforward design addressing the capability gaps of SmartHub II. The software scripts previously written to execute dynamic calculations with great accuracy compared to the SmartWheel can still be used since SmartHub III utilizes the same key electronics components. Thus, the data accuracy of the SmartHub II is now housed by an un-obtrusive and seamless device casing, with select mechanical and electrical improvements. These advancements bring the SmartHub device a step closer to its “ready for market” state to help patients and clinicians collect and optimize the biomechanics of a wheelchair stroke to prevent upper extremity injury. A device comparison summary is shown in Table 5 below.

Table 5: Device Comparison Summary

		SmartWheel	SmartHub III
Device Design	Unobtrusive	●	●
	Portable	✗	●
	Adaptable	✗	●
	Light Weight	✗	●
	Easy Attachment to Manual Wheelchair	✗	●
Electrical Components	Indicates When Device is Active	●	●
Look and Feel	Professional Aesthetic	●	●
	Durable	▲	●

The results displayed from the feedback survey confirm that the SmartHub III made significant improvements from a design standpoint. While these serve as milestones, the device has great room for improvement. The main concerns addressed by the clinician feedback addressed the size and attachment of the device to the wheel.

5.2 Limitations

The size of SmartHub III is limited by the size of its components as well of number of components contained in the data collection module. Within this unit there is three "off the shelf" PCB's, a battery, and a button switch, all connected by 14 total wires. As a result, the size of SmartHub III is limited by the dimensions of the PCB components as well as battery since the device casing cannot be any smaller than the components themselves. Although the components can be re-oriented, SmartHub II and SmartHub III exhibit the most logical and tightly packed configurations possible given the size constraints of the components and design constraints of the device. As a result, further re-arrangement of the device components will yield limited improvement to the device size, and in turn sacrifice stability and durability of the casing by decreasing wall thickness and similar features.

5.3 Future Work

Electronic Components and Device Size

Given the limitations presented, the most pressing next step is to combine the three "off the shelf" electronics, Raspberry Pi Zero W, IMU, and PowerBoost, into one custom board. This would greatly decrease the device size as all ports and functionality of the device will be combine onto one compact board. As a result, the design constraints for the device casing will change dramatically, allowing for a thinner and sleeker design. However, this is no small feat, the current PCB components are optimized for the function of the board, the combine PCB must also maintain accuracy and functionality of the current SmartHub.

Hardware and Fastening Type

Given the suggestions from the clinical feedback, fastening the SmartHub from the front of the wheel instead of between the primary and secondary spokes would provide the best experience for clinicians and patients. A future concept of SmartHub could feature a similar clamping module that is secured by two thumb screws, turned into place from the front of the wheel. These thumb screws will secure the clamping module to the wheel however the user will now fasten this piece from the front of the wheel instead of reaching from the back side of the wheel in between the wheelchair spokes to secure the device.

Creation of a Biomechanical Model

Although the short-term goals of the SmartHub are to continue to develop a portable, unobtrusive, and seamless propulsion feedback for personal use as well as within the clinic, a larger goal for SmartHub is to combine the propulsion data with biomechanical modeling software's such as OpenSim. OpenSim is a widely used musculoskeletal modeling and simulation software to study the biomechanics of physical disabilities [23]. This software can use data from physical IMU's placed on the patient's body to record the motion of the patient as they move through space. Creating an OpenSim model of wheelchair biomechanics in conjunction with propulsion metrics from the SmartHub can be used to address and characterize sub-optimal biomechanics as well as greater research studies to mitigate upper extremity injury.

While the next steps for SmartHub include a custom PCB and improved fastening to the wheelchair, shifting the device into a "ready for market" state, the greater purpose of SmartHub is to provide useful metrics for patients and clinicians to address and improve wheelchair biomechanics using the propulsion metrics output from the device. Looking forward, SmartHub can be combine with other computational software's to eliminate upper extremity injury for the greater community of manual wheelchair users.

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Appendix A: SmartHub III Bill of Materials

Table A1: SmartHub III Bill of Materials

Part Name	Description	Quantity	Cost	Subtotal
Raspberry Pi Zero W	Microprocessor	1	$10.00	$10.00
IMU	BNO055, 9-axis gyro, accelerometer, magnetometer	1	$34.95	$34.95
PowerBoost	PowerBoost 1000 Charger, Rechargeable 5V Lipo, Micro-USB Charging	1	$19.95	$19.95
Battery	1000mAh Power Source	1	$9.95	$9.95
Micro-SD Card	Storage Drive for Raspberry Pi Zero W	1	$19.95	$19.95
Push Button Switch	Push Switch SPST (Single Pole Single Toggle) 0.1A, 24V	1	$7.05	$7.05
Raspberry Pi Zero USB Add-on	USB Type-A Connector for Raspberry Pi Zero	1	$7.99	$7.99
Raspberry Pi Zero W Mounting Screws	Phillips Rounded Head Thread-Forming Screws, 18-8 Stainless Steel, Number 1 Size, 3/8" Long	4	$0.26	$1.02
IMU & PowerBoost Mounting Screws	Phillips Rounded Head Thread-Forming Screws, 18-8 Stainless Steel, Number 1 Size, 1/8" Long	8	$0.25	$2.00
Case Attachment Screws	Phillips Rounded Head Thread-Forming Screws, 18-8 Stainless Steel, Number 4 Size, 1/2" Long	4	$0.27	$1.08
5-Arm Knob	Plastic 5-Arm Knob, Vibration-Resistant, 1/4"-20 Threaded Hole, 1-3/8" Wide Head	1	$1.10	$1.10
Threaded Bolt	Zinc Yellow-Chromate Plated Hex Head Screw Grade 9 Steel, 1/4"-20 Thread Size, 3/4" Long	1	$0.12	$0.12
Gasket Sheet	Rubber Material to Provide Friction on Wheelchair Spokes	1	$1.00	$1.00
Formlabs 3 Grey Resin	3D Printing Resin	1	$20.00	$20.00
			Total	$136.16

Appendix B: SmartHub III Technical Drawings

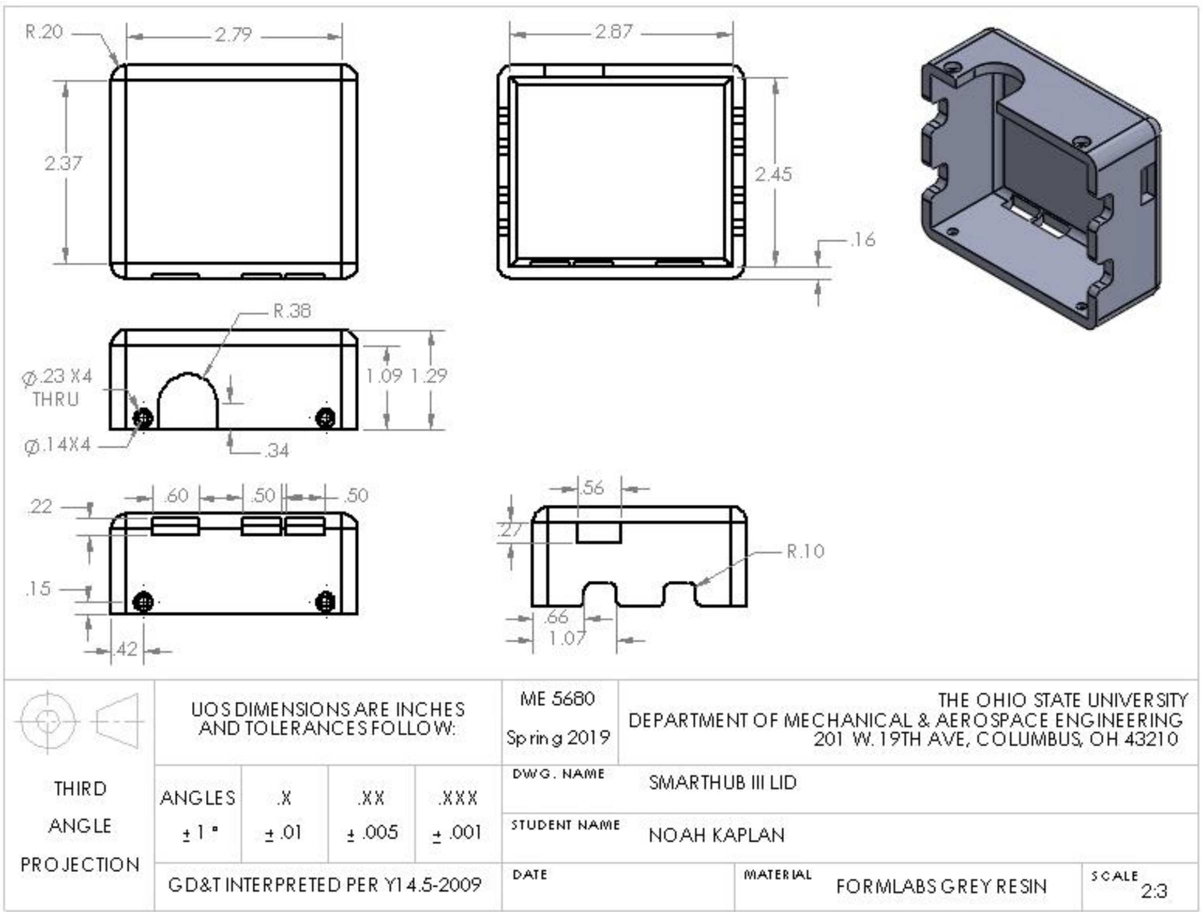

Figure B1: SmartHub III Case Lid

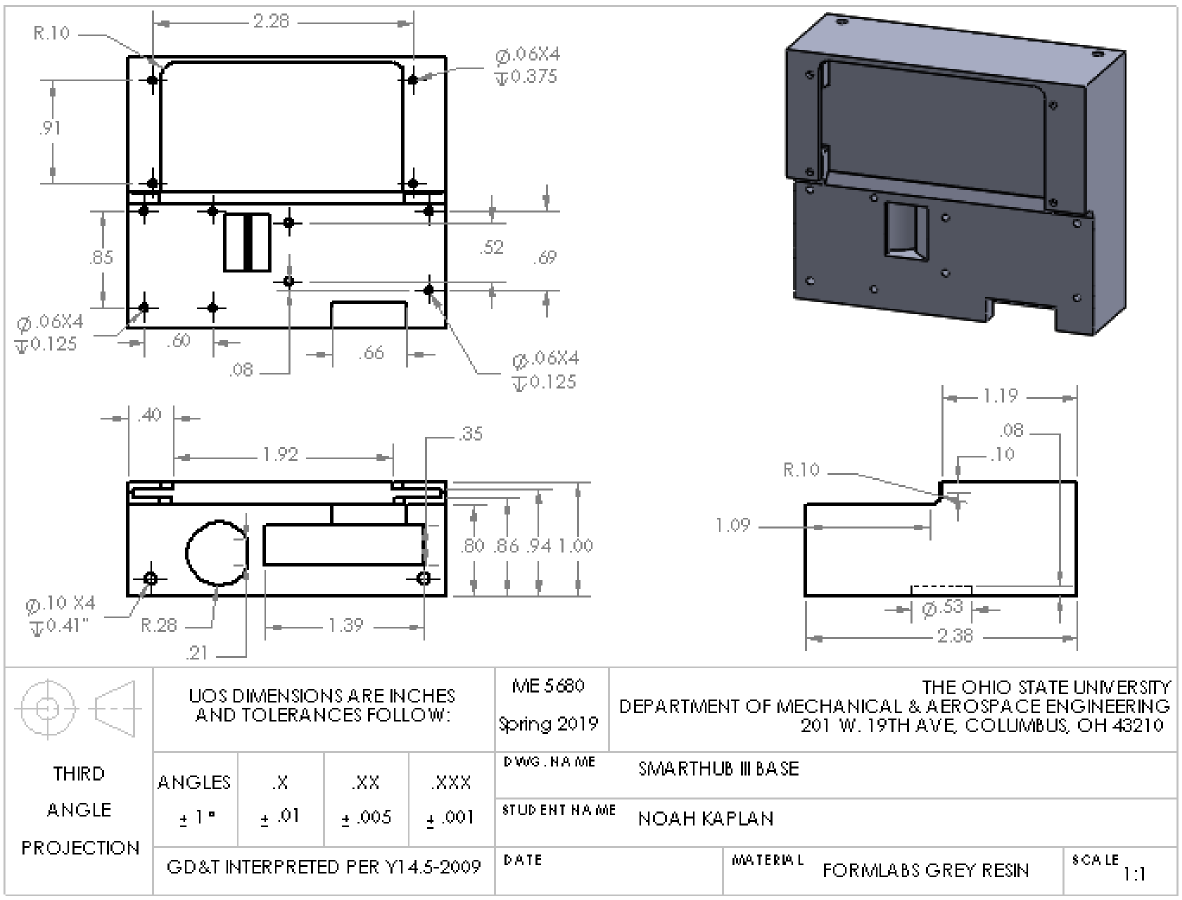

Figure B2: SmartHub III Case Base

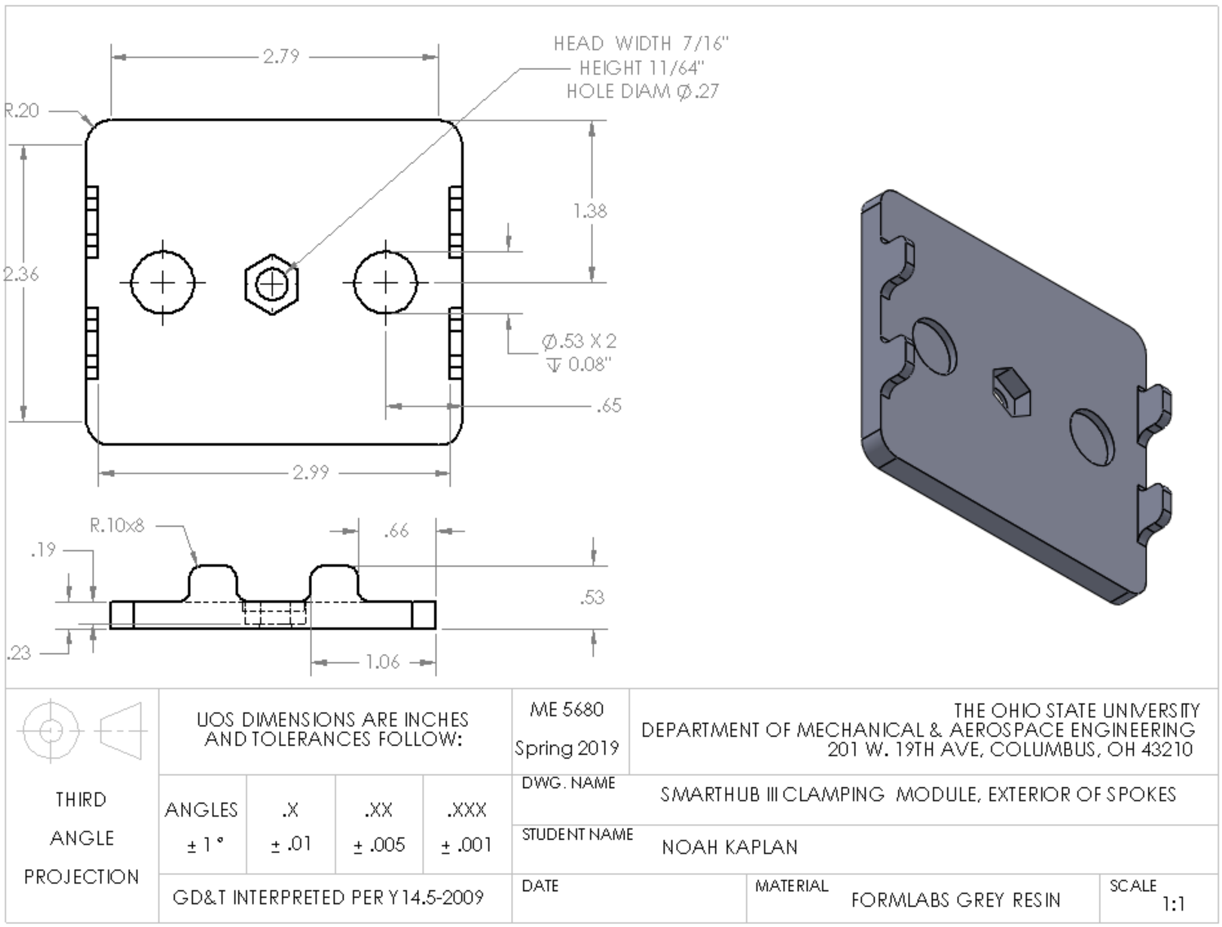

Figure B3: SmartHub III Clamping Module, Exterior of Spokes

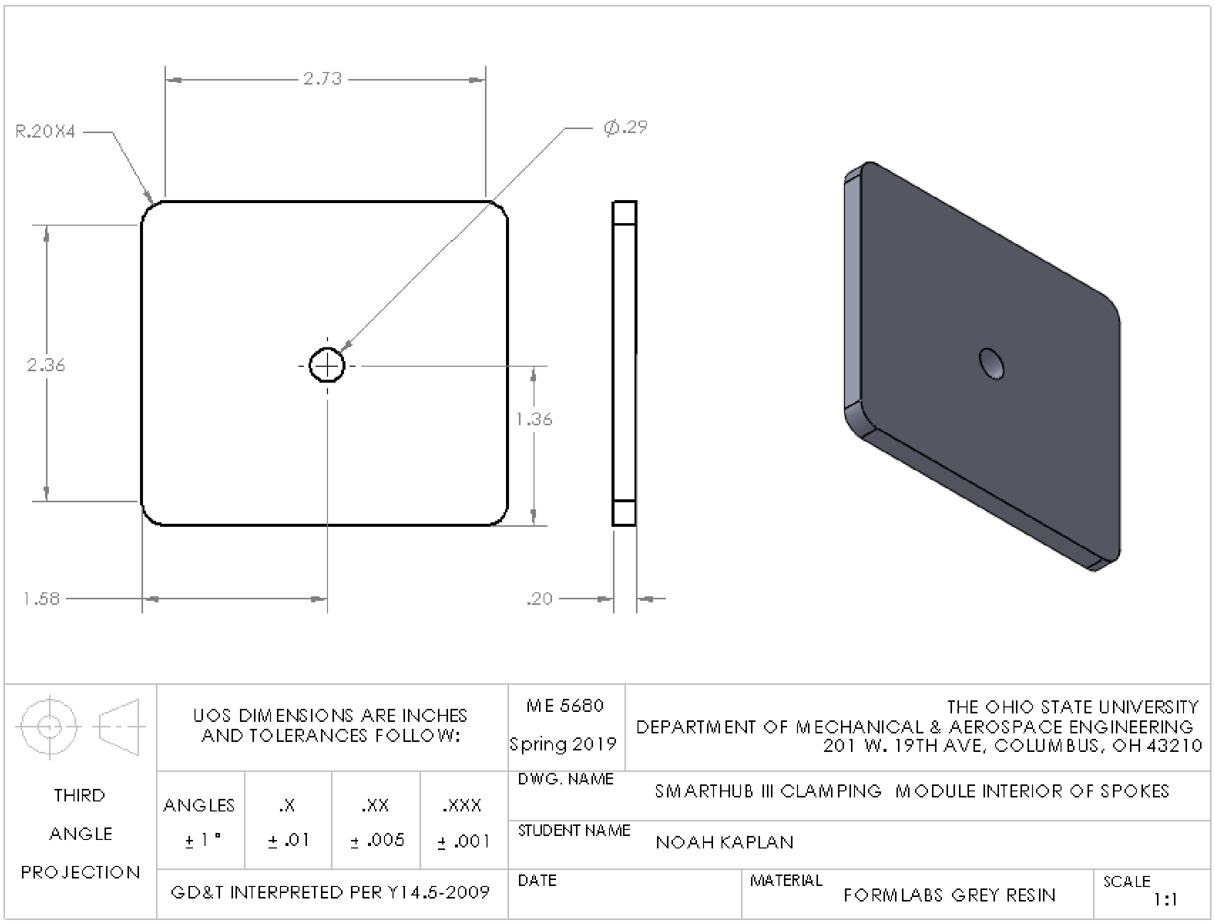

Figure B4: SmartHub III Clamping Module, Interior of Spokes