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# Autonomous Exoskeleton for Paraplegic Assistance

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# Abstract

Paraplegia is a condition that occurs after a spinal cord or brain injury. When someone suffers this injury, they are either partially or completely paralyzed from the waist down. Since there is no cure for the injury, patients have to undergo a process of treatments (usually involving physical therapy) to improve their function and motion capabilities. One type of assistive device that has been recently developed are exoskeletons. Exoskeletons are devices designed to aid or improve human movement, and can be of great help to people with paraplegia. They can be used both for therapy and everyday life, improving living conditions for people. Since current exoskeletons are very expensive (~$80,000), our team decided to create our own design that is more accessible to the general population. Our group's exoskeleton is capable of lifting a 200lb human, and supporting the motions of walking, sitting, and standing.

# Executive Summary

## Introduction

Paraplegia is defined as either partial or total paralysis affecting the legs and pelvic areas (1, 2). It is estimated that approximately 7,200 individuals have spinal cord injuries that result in paraplegia yearly (4). Robotic exoskeletons are machines that are designed to aid or improve human movement. Uses can range from strength enhancement to injury rehabilitation to movement assistance (5). The design of exoskeletons usually consists of joints and components that correlate to those found in the human body (6).

There are a few lower limb assistance exoskeletons like our design currently on the market including the ReWalk, the Indego Personal Exoskeleton, the Ekso exoskeleton, and the Hal for Medical Use (Lower Limb Type) all of which cost upwards of $80,000. Three of the most noticeable physical benefits of exoskeletons are improved circulation, reduced muscle atrophy, and maintaining a healthy bone density (8,9,10).

## Methods

We began our design process by laying out six objectives. We were able to lay out the first three objectives through our background research on exoskeletons in the market and paraplegia. These objectives were that the exoskeleton must be able to support the motions and forces of standing, sitting, and walking. Then, we conducted interviews with Physical Therapists, Occupational Therapists, and Spinal Cord Injury experts to gather more insight into the rehabilitation process of people with paraplegia as well as the role of exoskeletons in it. This allowed us to come up with the fourth of objective, ensuring that the exoskeleton has a reasonable cost. The fifth objective was that the exoskeleton must be safe to use. The sixth and final objective was that the exoskeleton must be easy to put on and operate. Using our objectives as a guide, we decided on a single piece assembly using a joystick for user control of the exoskeleton. Once we chose a design, we evaluated the constraints such as cost, human safety, FDA and IEEE standards, and IRB approval. Taking all of these factors into account as well as our objectives we created a client statement to guide our project: “the objective of this project is to design and build an individualized lower limb exoskeleton to assist paraplegic individuals in standing and walking that costs less than $10,000 to produce.”

We then expanded on our design using SolidWorks for the framework of the exoskeleton, Altium for the hardware, and Arduino for the software development. The final design of the frame is an exoskeleton with a motor at each hip and knee with gearboxes on each motor to increase torque, a battery/electronics pack at the back of the hips, springs at the ankle to control rotation, and straps at the thighs and calves. The final design of the hardware includes a 48V power supply, two microcontrollers, a pulse oximeter, an emergency stop button, several relays, motor speed controllers, and other smaller components. The software design uses timer-based interrupts to constantly measure data from the joystick, motor positions, and safety sensors and a case statement to control the motor position by changing the motor speed of each joint based on its angle. The motor speeds and positions for each movement type were determined from motion capture data of one of our group members walking with crutches.

Each of the electronic components were tested for accuracy and reliability and the battery capacity was measured with a multimeter. The batteries lasted about 15 minutes which was expected. Before we tested our device on a human participant, we tested all the mechanical and electrical safety features of our design.

Once we ensured that all the aspects of the exoskeleton were working properly, we were able to test the full exoskeleton with a human participant in the apartment style PracticePoint lab at 50 Prescott. This lab has a harness running around the apartment so all types of movement can be tested while the user is supported by the harness in case of failure. We then tested the motions of sitting, standing, walking, turning left, and turning right.

## Results

The interviews that we conducted largely agreed with much of the study data that we found during our literature review. Exoskeletons on the market are difficult to purchase due to their high cost and poor coverage from insurance. They also have psychological benefits for their patients. We also learned the details behind the importance of safety in these exoskeletons, due to other health challenges that come with paraplegia. Once constructed, the exoskeleton was able to support all of the relevant motions we laid out. The user was able to successfully sit up, walk forward, turn left, walk forward, turn right, and sit down.

The user, also a member of our group, described using the exoskeleton as “Pretty different from walking normally but definitely possible with some practice”.

## Conclusion

In conclusion, we were able to meet all six of our original objectives. Our first three objectives were confirmed during our user testing at PracticePoint when our group member was able to perform the motions of walking, sitting, and standing and the exoskeleton supported his weight and did not sustain damage. Our fourth objective, the exoskeleton bust have a reasonable cost, was confirmed during a cost analysis where we determined that the total cost of the production of the device was $10,080 which is much less than current devices on the market. This was an important aspect, as it was one of the main limitations from current exoskeletons that came up from our interviews and background research. Our fifth objective, the exoskeleton must be safe to use, was confirmed when we did our user testing the user reported no adverse effects of the device. Our sixth and final objective, the exoskeleton must be user friendly, was confirmed during user testing when the user described putting on and taking off the device as “Fairly easy to remove. The supports are pretty comfortable”.

We were constrained by our budget and one-year deadlines so there is further work that can be done by future MQP teams. Overall, the Autonomous Exoskeleton for Paraplegic Assistance was a success and met all of the objectives laid out at the beginning of the project.

# Introduction

Paraplegia is defined as either partial or total paralysis affecting the legs and pelvic areas (1, 2). Paraplegia can have many causes but is most often associated with a traumatic injury to the spinal column (3). There are about 291,000 people with spinal cord injuries in the United States, with an average of 18,000 more yearly. Of these spinal cord injuries, it is estimated that approximately 39.5% result in paraplegia (4). Robotic exoskeletons are machines that are designed to aid or improve human movement. Uses can range from strength enhancement to injury rehabilitation to movement assistance (5). The design of exoskeletons usually consists of joints and components that correlate to those found in the human body (6).

There are a few lower limb assistance exoskeletons similar to our design currently on the market. The first one approved was the ReWalk Personal Exoskeleton. This exoskeleton costs about $85,000 (7). Currently, there is not a consistent way of getting aid through insurance companies. As of right now, there is only one insurance in the U.S. that has adopted a policy change to cover the cost of personal exoskeleton devices. The ReWalk was designed to assist users in their daily life. It has motors on the hip and knee joints and is controlled by changes in the center of gravity of the user, basically moving in the direction that the user leans. It is not self-balancing, so the user must use forearm crutches with the device (7). There are several other assistance devices on the market including the Indego Personal Exoskeleton, the Ekso exoskeleton, and the Hal for Medical Use (Lower Limb Type). Three of the most noticeable physical benefits of exoskeletons are improved circulation, reduced muscle atrophy, and maintaining a healthy bone density (8,9,10).

# Literature Review

## Paraplegia

Paraplegia is defined as either partial or total paralysis affecting the legs and pelvic areas (12, 11). Paraplegia can have many causes but is most often associated with a traumatic injury to the spinal column (14). Specifically, a lumbar spinal injury to the L1 to L5 vertebrae shown in Figure 1 (13). Although this is the most common cause of the condition, it is also possible for paraplegia to result from stroke, cancer, and congenital or genetic disorders (14). The most common method of injury is motor vehicle accidents. There are about 291,000 people with spinal cord injuries in the United States, with an average of 18,000 more yearly. Of these spinal cord injuries, it is estimated that approximately 39.5% result in paraplegia (15).

*Figure 1: L1 to L5 Vertebrae*

## Exoskeleton Overview

Robotic exoskeletons are machines that are designed to aid or improve human movement. Uses can range from strength enhancement to injury rehabilitation to movement assistance (16). The design of exoskeletons usually consists of joints and components that correlate to those found in the human body (17). Most exoskeleton designs utilize battery-powered electric motors to power the movements of joints, for example the hip, knee, or ankle (18).

Exoskeletons can have many health benefits for people who have walking disabilities, especially those who are paraplegic. Benefits of exoskeleton usage can include improving community mobility and socialization, as well as reducing secondary medical issues from lack of movement such as osteoporosis, urinary tract infections, and pressure sores (19).

There are two main types of exoskeletons: stationary or mobile. Stationary systems are primarily used for high-intensity gait training (20), because their stationary nature allows for higher-spec motors and increased power capacity. An example of a stationary exoskeleton is shown in Figure 2. Mobile exoskeletons are designed to operate under battery power and allow the user to walk and move more freely than a stationary device would allow.

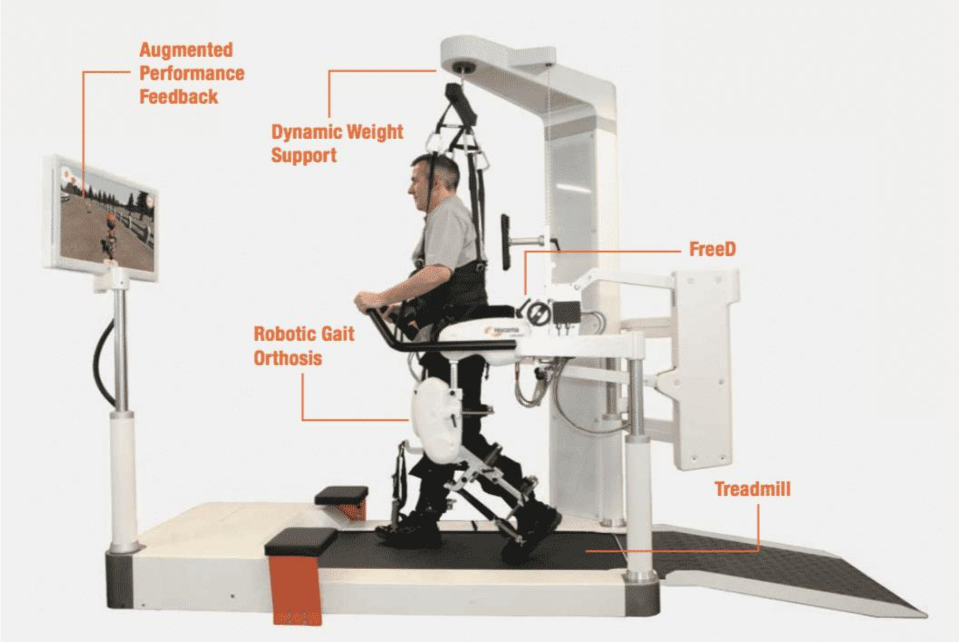

*Figure 2: Hocoma Lokomat (10)*

Exoskeleton devices are devices that have brought people with Spinal Cord Injuries (SCI) more opportunities to expand their day-to-day capabilities. Our device will be focused for people that are paraplegic, or those that have “impairment or loss of motor and/or sensory function in the thoracic, lumbar or sacral (but not cervical) segments of the spinal cord, secondary to damage of neural elements within the spinal canal.” (21) This means that they have arm mobility, but torso, legs, and pelvic organs are affected, depending on the extremity of the injury.

**Competitors**

There are a few lower limb assistance exoskeletons for daily use currently on the market. The first one approved was the ReWalk Personal Exoskeleton (Figure 3). This exoskeleton costs about $85,000 but ReWalk is committed to helping their customers afford this exoskeleton including a dedicated reimbursement team and a relationship with the Veterans Association (VA) so that all qualifying veterans will be able to use the exoskeleton (27). Currently, there isn’t a consistent way of getting aid through insurance companies. As of right now, there is only one insurance in the U.S. that has adopted a policy change to cover the cost of personal exoskeleton devices.

*Figure 3: ReWalk Exoskeleton (10)*

The ReWalk was designed to assist users in their daily life. It has motors on the hip and knee joints and is controlled by changes in the center of gravity of the user, moving in the direction that the user leans. It is not self-balancing, so the user must use forearm crutches with the device (27). The ReWalk also contains a battery pack on the back of the hips as shown in Figure 3.

*Figure 4: Indego Exoskeleton (19)*

Another assistance exoskeleton currently on the market is the Indego Personal Exoskeleton (Figure 4) which costs about $80,000. This exoskeleton features a quick connect design which can easily be taken apart and transported. It also weighs only 29 pounds making it the lightest weight exoskeleton on the market today (29). Like the ReWalk, the Indego features motors on the knee and hip joints and is controlled by extremely sensitive sensors that measure position and tilt (30). The system can be programmed to do anywhere form 10%-100% of the work of walking (31). The Indego is not intended for stair climbing or sports. This system is also included in the VA program to provide exoskeletons to veterans with spinal cord injuries (31).

There are also several exoskeletons that are focused for use in therapy or rehabilitation as opposed to daily use. The Ekso exoskeleton (Figure 5) supports the legs, hips, and torsos during walking and uses a handheld interface to specify and initiate steps. This must be used in combination with crutches or a walker and a physical therapist to supervise the patient. (32). A study was conducted with three physiotherapists using the Ekso as a tool for rehabilitation of patients with spinal cord injuries and they had very promising results. Patients found that they could take many more steps with the exoskeleton than without “allowing much more opportunity to work on balance, gait, and core strengthening than would otherwise be possible” (35, par. 29). Physiotherapists involved in the testing also noted significant psychological benefits to the use of the exoskeleton with one stating of one patient, “As soon as you would put him up in the Ekso his face would just light up. He would just be so happy” (35, par. 33). There were also some challenges to working with the Ekso. Most notable was the amount of time required for physiotherapists to learn how to use the device as well as the longer patient sessions given that

*Figure 5: Ekso Exoskeleton (23)*

the device must be put on and programmed (90-120 minutes for initial assessment and 60 minutes for a normal session). Some patients also experienced anxiety since they were giving up some motor control to the exoskeleton. Some patients also experienced discomfort when the exoskeleton was not fitted properly. The Ekso also only comes in one size which excludes many patients, giving a negative psychological effect (33).

One of the newest lower limb exoskeletons is the Hal for Medical Use (Lower Limb Type) (Figure 6). This exoskeleton is also meant for therapy and has assistive torque at the knee and hip joints. Unlike the other exoskeletons, the Hal is controlled by residual movement in the patient's legs so it cannot be used by people who no longer have any control over their movement. Several studies were done using the Hal exoskeleton as a gait training therapy tool and compiled in a literature review. It was found that “the HAL system is feasible when used for gait training of patients with lower extremity paresis in a professional setting” (36, para. 4). Benefits included both physical and psychological benefits like those seen while using the Ekso. The only adverse effects reported from the studies were small complaints about the pressure of the suit, skin irritation, or training related pain. There were no serious adverse side effects or injuries reported.

*Figure 6: HAL for Lower Limbs (24)*

### Exoskeleton Use in Therapy

Paraplegia is a condition that can be hard to treat, as it can affect many bodily functions in addition to the obvious mobility restrictions. People with paraplegia can suffer from "neurogenic bladder and bowel, urinary tract infections, pressure ulcers, orthostatic hypotension, fractures, deep vein thrombosis, spasticity, autonomic dysreflexia, pulmonary and cardiovascular problems, and depressive disorders," among other things (23, para. 1). The recuperation process is a long, expensive one, requiring a lot of patience from both the patient and therapists involved.

Exoskeletons are a relatively new technological advancement and as such, they have lots of limitations and room for improvement. This means that there is not extensive research in the area, so the therapeutic practices with these newly designed devices still have room for development. As of right now, there are not any specific types of robotic aid that have been definitively proven to work better than others (22).

### Usefulness for Therapists

Exoskeletons can be very helpful in therapy. In the introduction of an article from the Journal of Orthopaedic Translation, the benefits of exoskeletons in therapy are highlighted: "Compared to traditional physical therapy, exoskeleton assistive rehabilitation has the advantages of reducing the work of therapists, allowing intensive and repetitive training, and it is more convenient to use for quantitatively assessing the recovery level by measuring force and movement patterns" (41, para. 5). This is confirmed with the positive experience that the hospital UH St. John Health Center has had when using an Indego Therapy Exoskeleton with their patients (23). Pam Lanter, a PT at UH Saint John, commented that "In just one session with the Indego Therapy exoskeleton, we're able to accomplish what may have taken 5-10 sessions without it." (25, para. 4). She also mentioned that "The device lessens the burden on both the patient and the therapist."

## Patient Experience with Exoskeleton Use

Life with paraplegia can have its obstacles, as many normal day-to-day activities become exhausting, time consuming, or even impossible to do without any assistance. This increased difficulty can be very discouraging and have a significant emotional toll. Exoskeletons are not readily available for public use. There is an overall lack of accessibility, which comes from high prices and lack of approved devices. Usually, this happens because the technology is expensive to make, but also because of the very strict FDA rules (38). Typically, it is most commonly used in research settings rather than in day to day life. Still, this doesn't hinder the great benefits that exoskeletons bring to the table. In a study where participants shared their experiences with robotic Locomotor Exoskeletons, the responses highlighted that there were several benefits of using them in different aspects of life (37).

## Mobility Improvement Through Exoskeletons

For our purposes, our exoskeleton focused on controlling the legs and hip region, granting paraplegic individuals with mobility that they wouldn't normally have. A lot of studies on the benefits of exoskeletons have been conducted, and three of the most noticeable physical benefits are improved circulation, reduced muscle atrophy, and maintaining a healthy bone density (24,25,26). Circulation is a significant problem for paraplegics since most of the time they are not active but are generally restricted to sitting in their chair or laying down in their bed. This causes excess blood to pool in their legs and feet. This is one reason exoskeletons are important for paraplegics: it gets them active, on their feet improving circulation throughout their body. Improved blood flow to the feet means their body will also have improved cellular activity (24). Muscle atrophy, the loss of muscle, is also common in paraplegics due to the inactivity of many muscles in their body (26). Similarly, paraplegics will also have this problem with their bone density (26). This can start to occur with as little as four weeks of not using their muscles. An exoskeleton will allow the user to be back on their feet causing all their bones to be able to bear the weight of their own body in between the joints while being held up by the suit at these joints.

While exoskeletons are becoming more popular, many options are still not ready for daily use. Most exoskeletons on the market require assistance from others as they cannot be put on by the user themselves and are hard to use in tight spaces. Tasks in simulated home environments showed that many kitchen tasks were feasible, but maneuvering in tight spaces remains challenging, as stopping and turning require considerable space (37). Two examples of exoskeletons having a hard user interface are ReWalk and Indego. Both exoskeletons require the user to have multiple physical therapy sessions to be able to use the exoskeletons. Both products also do not work in small areas due to the long walking sticks they use to stabilize the upper portion of the user. These walking sticks in combination with their design, make it impossible for these exoskeletons to enable the user to open a pull door (25). Not only is it difficult to use an exoskeleton for daily use, they also can cause harm to the user if not operated properly. Every new exoskeleton user needs to have physical training sessions to operate this new system, but they need to be careful how often they do this training. A group of researchers from Ekso Bionics have developed their own exoskeleton, and from their testing they found that if the user does not get accustomed to their exoskeleton they will have abrasions at their joints and feet (26). This adds to the cost as well as the time required for users to get acclimated to the exoskeleton

Another drawback to exoskeletons currently on the market is the high cost. For most people spending up to $80,000 for an exoskeleton is not an option since insurance does not cover these purchases. Therefore, our goal was to make our design available for a much lower price. This has been achieved by simplifying the design, operating systems, and the material choices. Currently, most exoskeletons have a very complex design and operating system. For example, the ReWalk user interface is controlled by body movements from the user which takes the user time to adjust to this counterintuitive control mechanism (25). The design of our exoskeleton will tackle this issue, aiming to have a more user-friendly control mechanism to control movements. Other exoskeletons use different methods of walking like using sensors which detect directional leaning. The ReWalk platform is made of lightweight composite materials and is powered by a battery that runs motors at the hip and knee joints (36). This is similar to our design as we are using a combination of metal alloys and PLA plastic. There are steel supports for the linkages bearing the full weight of the user and the exoskeleton, PLA plastics for all the waist connections and electrical housings, and polystyrene for securing the suit to the user. This makes the manufacturing process easier and cheaper making our exoskeleton more accessible for more people. All the steel linkages will be CNC machined on a small milling machine while the PLA plastic parts will be 3D printed.

Increasing the mobility of paraplegic patients will improve their life over time by increasing their freedom and their confidence. The National Rehabilitation Centers 2019 report said Robotic exoskeletons may be highly motivating for people with SCI (Spinal Cord Injuries), and they may offer several physical and psychosocial health benefits. Exoskeletons allow people with paraplegia to perform tasks easier, as it provides them with support in these activities. Moving around freely without the assistance of others and completing simple household chores are two examples of freedoms paraplegic individuals would get from using an exoskeleton. Also, the extra freedom from being able to move freely around at their own pace will boost their confidence because they will now be able to communicate at (or around) eye level with people that are standing up. Users from a study published in the Journal of NeuroEngineering and Rehabilitation reported some mental health and confidence benefits from exoskeleton use (39).

## Lower Limb Exoskeleton Design

There are some basic principles that govern the design and operation of an exoskeleton. Primarily, there are the two types of interactions between the exoskeleton and the user: cognitive human robot interaction (cHRI), and physical human robot interaction (pHRI). cHRI is the method or methods for the user to control the exoskeleton (8). This can include many control methods, such as a joystick, keyboard input, voice commands, and movement, or others. With the rapid advancements in technology, these options are expanding greatly. pHRI is the application of the forces between human and exoskeleton, which mainly pertains to the way that the device is attached to the user, and which parts are machine powered and which are powered by the user. (18).

Those are some examples of the benefits, drawbacks, and principles behind exoskeleton design and operation. However, these are purely design considerations, the final exoskeleton must conform to regulations to be suitable for commercial sale.

## Standards

The FDA defines a lower limb exoskeleton (product code PHL) as “a prescription device that is composed of an external, powered, motorized orthosis that is placed over a person's paralyzed or weakened limbs for medical purposes” (37, para. 1). There are several special controls for lower limb exoskeletons. Any elements that come into contact with the patient must be biocompatible, testing must validate electromagnetic compatibility/interference (EMC/EMI), battery performance and safety, wireless performance, mechanical safety, electrical safety, and thermal safety. Non-clinical performance testing must demonstrate device performs as intended through mechanical bench durability testing, simulated use testing, validation of manual override controls, accuracy of device features and safeguards, flame retardant material validation, liquid/particle ingress prevention, sensor and actuator performance, and motor performance. Clinical testing must demonstrate safety and effectiveness and include considerations for the level of supervision necessary for intended use of the exoskeleton and the environment of use. Lastly, the labeling must be detailed and contain all warnings and instructions (35).

There are also some international standards that need to be considered when designing an exoskeleton to ensure that it meets the legal requirements for safety. This protects the consumer by ensuring that they receive a reliable product while also providing the company with clear guidelines while designing and producing their product. ISO 13482:2014 has guidelines for the safe design, protective measures, and information for use of personal care robots including exoskeletons. These standards are meant to provide human care related hazards as well as domestic animal or property damage. ISO TC299 WG2 contains general standards for many aspects of devices including, consumer warranties and guarantees, healthcare services, the ergonomics of human-system interaction, preparations for instruction for use, robotics, and 3D printing. All of these will have to be considered when designing and building an exoskeleton. ISO 12100:2010 specifies procedures for general design of machinery including identifying hazards and estimating and evaluating risks during relevant phases of the machine life cycle. Lastly, ISO 14971 specifies principles for risk management of medical devices and is applicable to all phases of the life cycle of a medical device. Since the exoskeleton is intended to treat paraplegia it falls under the purview of medical devices as defined by the FDA and therefore must follow ISO 14971. In addition to the research stated above, we conducted interviews with several physical therapists to ensure that our design would be useful.

## Interviews

Given that there are limited firsthand accounts of experiences with exoskeletons in past research, it was important to find people that had direct involvement in the matter. Also, since the team did not have experience with people that have Spinal Cord Injuries (SCIs), it was important to speak with experts in the area. The team interviewed physical therapists, spinal cord experts, and a physiatrist that have had experiences with people with Spinal Cord Injuries (SCIs) as well as with the use of exoskeletons in therapy. The interviews explored the benefits, limitations, and dangers of using exoskeleton devices in physical therapy or for daily use in patients with paraplegia. Also, the interviews provided feedback for the current designs in the market, which will be helpful to future teams that are involved in this project.

## Method

### Participants

We conducted interviews with 6 individuals (4 female participants and 2 male participants) that are involved in physical therapy or rehabilitation facilities in New England. The participants consisted of 3 physical therapists, 1 physiatrist, 1 occupational therapist and 1 spinal cord therapy student. The participants had varied experiences working with individuals in physical therapy; 3 of them had between 0 and 5 years working in PT, and the remaining 3 had above 25 years of experience in PT or rehabilitation. Several of the participants had experience working with exoskeletons in therapy. Participants were recruited through convenience sampling from personal contacts and snowball sampling from referrals. All participants gave informed consent prior to participating.

### Design & Materials

We conducted semi-structured interviews with these participants to gain insight and feedback on the use of exoskeleton devices for individuals with spinal cord injuries. The participants provided information about their experiences with individuals with paraplegia in their day-to-day jobs as well as their opinions and experiences (or lack thereof) with exoskeleton devices in therapy. Participants also provided feedback on the current exoskeleton designs in the market. This was a semi-structured interview because the interviewer followed the same script of questions for all participants (Supplemental Materials A), but also deviated from the scripted questions when the participant discussed something that seemed important and relevant. When topics that were outside of our predetermined questions that appeared to be helpful to our project were mentioned, we inquired about these topics. The interview results were analyzed through thematic analysis, in which we identified patterns in themes that appeared throughout the interviews (41).

### Procedure

Participants were first contacted by email to see if they had an interest in participating in our interviews. If they were, participants booked a time for their interview session based on their availability and were provided with the Zoom information to access the interview. At the start of the interview, participants were given the informed consent form, which included a general description of what the study was about, as well as the risks, benefits, and purpose associated with the study. Once signed, the interview continued with a brief introduction of the purpose of the study, followed by a verbal reminder of the participant's right to leave the study at any time. Also, they were asked for permission to record the interviews for the transcription process only. These recordings were only accessible to our team and were deleted once they were transcribed and any identifiable information was removed. The transcription can also be found in Supplemental Materials A. The participants answered questions about their experience with individuals with paraplegia, followed by their experiences (or lack of) with exoskeletons. A sample question from the interviews was: "Based on your experiences in therapy with exoskeletons, do you have any recommendations for things that work well or do not work well in the current designs?" which helped participants address their opinions and judgements on these devices. To finish off, we asked the participants if they knew about any one in their profession that could help us any further. This included any patient that they knew that would be interested in participating. After finishing the interview, participants were thanked and debriefed about the purpose of our study, which was to get their input on the best uses for our device, potential dangers, and overall concerns.

## Results

The responses from the interviews with the 6 participants provided great insight into the benefits and limitations of current exoskeletons, as well as feedback into the design features of exoskeletons in the market.

## Benefits of Current Exoskeletons

When asked about the overall benefits that exoskeletons have in therapy or everyday use, 5 out of the 6 participants (83%) had a strong positive response. This confirmed the information found during our background research regarding the benefits of exoskeletons in therapy. They also felt that the benefits extended into several components of the patient's life that were beyond the obvious physical benefits.

> *Exoskeletons can provide the patient with huge emotional and psychological benefits. They see the ability to walk as part of their identity and personality. It has helped some patients achieve their goal of walking in the short term while working towards recovering walking in the long term.*
>
> Participant 2

Our interviews revealed that one of the benefits of using an exoskeleton for patients is assisting with neuroplasticity which is "the brain's ability to modify, change, and adapt both structure and function throughout life and in response to experience" (34). Using an exoskeleton can facilitate rewiring in the brain because the exoskeleton helps individuals with the entire mechanics of walking rather than individual movements. Some of our participants who have experience with exoskeletons indicated that exoskeletons can also add a fun component into the therapy for many patients. Being able to be supported by these devices allows patients to do therapy in different settings bringing variation into what can be a boring and repetitive experience.

> *They [Exoskeletons] provide patients with a more fun experience. They can use them in different terrains rather than just a treadmill.*
>
> Participant 4

### Limitation of Current Exoskeletons

While many of the participants saw the benefits of exoskeletons, participants also provided insights into some limitations of the existing exoskeletons that are available.  The most notable limitation that 5 out of 6 participants (83%) noted was that the exoskeleton needs to be removed prior to using the bathroom. Since removing the exoskeleton usually requires assistance and can be time consuming and exhausting, many patients are unable to use the currently existing exoskeletons in their daily lives. Thus, our participants highly recommended either making the device easy to take off/put on or to somehow allow the patient to use the bathroom while wearing it. One participant stated:

> *Something very important that isn't obvious from the outside is that these exoskeletons need to be easy to take off to allow the patient to go to the bathroom. This is a big limitation that the current ones have.*
>
> Participant 4

Another limitation that emerged from our interviews was the weight of the current exoskeletons, particularly since the exoskeletons they have used are the heaviest of the competitors (ReWalk and Ekso models). Most of the participants (5 out of 6; 83%) indicated that current models are too heavy (about 80 pounds) for a patient to use and handle on their own. The participants noted that it usually takes one or two additional people to help the individual put the exoskeleton on and take it off. When asked about their thoughts on the weight of current models, one participant said:

> *The lighter you can make it the better. The ones we currently use [ReWalk] weigh a lot, around 80 pounds. Something like 30-50 would be excellent.*
>
> Participant 2

When asked about pricing, most participants (5 out of 6; 83%) felt that the current prices are too expensive. Some had experiences with the ReWalk and Ekso Exoskeletons, and they felt like their pricing was too high for patients to consider.

> *The cheaper it costs, the better. Usually, the patients are very low income, and they live off state insurance. These spinal cord injuries cost millions and insurance companies almost never cover them.*
>
> Participant 1

Even though most of the participants had a strong inclination towards a cheaper pricing, there was also an opposite viewpoint. One of the participants believed that the technology was worth the price, as there was not anything else that does something similar. Also, this participant believed that a big reason for the high pricing is that exoskeletons were new, so inevitably they would drop in price with time when they become more common.

> *The price seems right for what they [exoskeletons] currently are and what they can do. Right now, these devices are not very common, so once they become more useful and popular, like wheelchairs, the price will drop.*
>
> Participant 6

### Feedback from Current Designs in the Market and Recommendations for Future

Given that several participants (4 out of 6) had experiences with exoskeletons during therapy, we inquired about their experiences, particularly if they had any specific feedback for design aspects that currently work or do not work well. The participants had experience with two models that are in the market, the Ekso and the ReWalk Exoskeletons. They provided their thoughts on the design choices that we had and with things to watch out for based on their experiences with the ReWalk and Ekso exoskeletons such as “the highest place of friction that causes irritation is the long bone along the femur. Also, you must be careful not to apply torque along that bone because paraplegics tend to have low bone density and can easily fracture.” For the locations where skin irritation is most common, they recommended adding extra padding and adapting to the patient’s feedback.

Another important recommendation was regarding muscle spasms. Several participants warned us that “something you also have to watch out for is muscle spasms. This can happen at unexpected times and can make the patient work against the exoskeleton and can easily lead to injury.” They warned that these spasms sometimes make the patient work against the exoskeleton, which can be very dangerous.

Lastly, another source for feedback was regarding how the speed of the device is determined. The participants were very insistent on making the device speed very adjustable stating “You can’t make a one speed fits all device. Each patient is different. It [speed] needs to be adjustable. It will probably start off very slow since they [patient] isn’t used to these movements, then with time the speed might increase.”

The interviews were very helpful towards learning more about Spinal Cord Injuries as well as the current benefits and limitations of exoskeletons and their role in treating paraplegia.

# Project Strategy

## Initial Client Statement

The original goal of this project was to design and build an individualized lower limb exoskeleton to assist paraplegic individuals in standing and walking that we could prototype for less than $1250, with a commercial cost of roughly $10,000. The budget was selected based on the amount of funding provided to us by WPI, as well as comparison to existing products on the market.

## Objectives and Constraints

Based on the research and interview results summarized in the previous chapter, we determined the following design objectives:

1. The exoskeleton must be able to support the motion and forces of standing from a sitting position
2. The exoskeleton must be able to support the motion and forces of sitting (on a chair or similar height surface) from a standing position
3. The exoskeleton must support the motion and forces of walking
4. The exoskeleton must have a reasonable cost
5. The exoskeleton must be safe to use
6. The exoskeleton must be user friendly (the client should not need any assistance putting the exoskeleton on or using it)

These objectives were ranked using the Pugh Matrix in Table 1. Safety was found to be the most important objective while cost and supporting the motion of sitting were found to be the least important. The rest of the rankings can be seen in Table 1.

*Table 1: Objectives Pugh Matrix*

| | **Support Standing** | **Support Sitting** | **Cost** | **Safety** | **Walking** | **User Friendly** | **Total** |
|---|---|---|---|---|---|---|---|
| **Support Standing** | X | 1 | 1 | 0 | 1 | 1 | **4** |
| **Support Sitting** | 0 | X | 0.5 | 0 | 0 | 0 | **0.5** |
| **Cost** | 0 | 0.5 | X | 0 | 0 | 0 | **0.5** |
| **Safety** | 1 | 1 | 1 | X | 1 | 1 | **5** |
| **Walking** | 0 | 1 | 1 | 0 | X | 1 | **3** |
| **User Friendly** | 0 | 1 | 1 | 0 | 0 | X | **2** |

These rankings were then used to compare four design options. The first design option was a single piece assembly with a joystick to control the movements of the exoskeleton. The user would move the joystick depending on the direction they wish to go and the joystick would feed back to the motors. The second design option was a multi piece linkage assembly with a joystick control. The multi-piece linkage consists of an upper and a lower segment that are fastened together to act as a single beam. The benefits of this design being that it can easily be modified should length adjustability be required in the future. However, this design also increases the possibility of error as the relevant pieces will have to be machined more exactly for them to work as expected. The third design option was a single piece assembly with an Electromyogram (EMG) to control the movements. The EMG would read the muscle movements of the user and use those to determine how the motors should move. The single piece design would be a less complicated structure that would make it easier to design attachments, however it would have required specialized equipment to produce because of its length. The final design option was a multi piece linkage assembly with an EMG control. The designs were compared using the weights found in Table 1 and the comparison is shown in Table 2.

*Table 2: Design Comparisons*

| | **Weight** | **Joystick Control Single Piece Assembly** | **Joystick Control Multi Piece Linkage Assembly** | **EMG Control Single Piece Assembly** | **EMG Control Multi Piece Assembly** |
|---|---|---|---|---|---|
| **Safety** | 5 | 0 | 1 | 0 | 1 |
| **Support Standing** | 4 | 1 | 1 | 1 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| **Walking** | 3 | 1 | 1 | 0 | 0 |
| **User Friendly** | 2 | 1 | 1 | 0 | 0 |
| **Cost** | 0.5 | -1 | 1 | -1 | -1 |
| **Support Sitting** | 0.5 | 0 | 0 | -1 | -1 |
| **Total** | | **8.5** | **15** | **3** | **3** |

In Table 2, a score of 0 represents a design meeting the requirement, 1 represents a design exceeding the requirement, and -1 represents a design not meeting the requirement. The multi piece linkage assembly with the joystick control received the highest score so we proceeded with that design.

There were several mechanical constraints that needed to be kept in mind when designing this exoskeleton. The first consideration was the restriction of the degrees of motion that the suit can achieve. As the human legs cannot rotate in three hundred and sixty degrees as a motor can, a physical limiter was necessary to prevent hyperextension of the joints. These limiters will allow for movement within the following angles. The knees will be allowed to rotate 110 degrees, the ankles will be allowed to rotate 90 degrees, and the hips will be allowed to rotate 130 degrees. These angles are based on the angles calculated during the motion capture study that our team conducted. Full details of our motion capture study can be found in Supplemental Materials B.

An additional concern was what the exoskeleton will do if things go wrong. To solve this problem, all of the main motors would be equipped with an emergency kill switch, mocked out in Figure 7 below. This switch operates by having the switch retracted by a servo as soon as the power is turned on. The switch will, at the same time be held under tension by a spring, then the power is cut, the servo will stop pulling and the spring will pull on the switch, intermeshing its end with the gears at the beginning or the drive train, stopping all motion and freezing the suit in place.

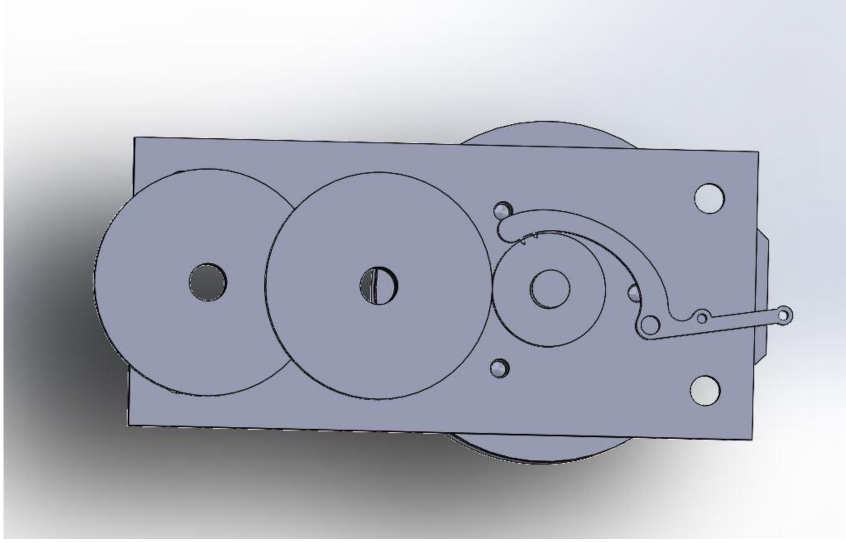

*Figure 7: Initial Emergency Stop Design*

To complement the kill switch, the exoskeleton will also include a power kill switch. This switch will operate on a similar principle and will directly cut off the power from the battery if the users vital signs reach an unsafe level or if they want to use it as a manual stop. This loss of power will then engage the mechanical kill switches, freezing the suit in place.

Given that the intended use of the exoskeleton will be for paraplegic individuals, the motors will be programmed to move at a limited speed to reduce the risk of injuries. This means keeping the output at a maximum of 7.5 RPM in order to maintain the sitting to standing motion in the 2 second range.

## Function Blocks and Specifications

A high level functional block diagram was created using these objectives and constraints as seen in Figure 8. The design includes a pulse oximeter which will be constantly measuring oxygen levels and heart rates and will trigger an emergency shutdown if the levels reach an unacceptable range. There will also be an ultrasonic sensor that is turned on during the action of sitting and detects when the user has fully sat down based on the distance from the sensor to the chair. Lastly, there will be a joystick controlling the motors so the user can move forward, turn left or right, stop moving, or sit down based on the joystick position.

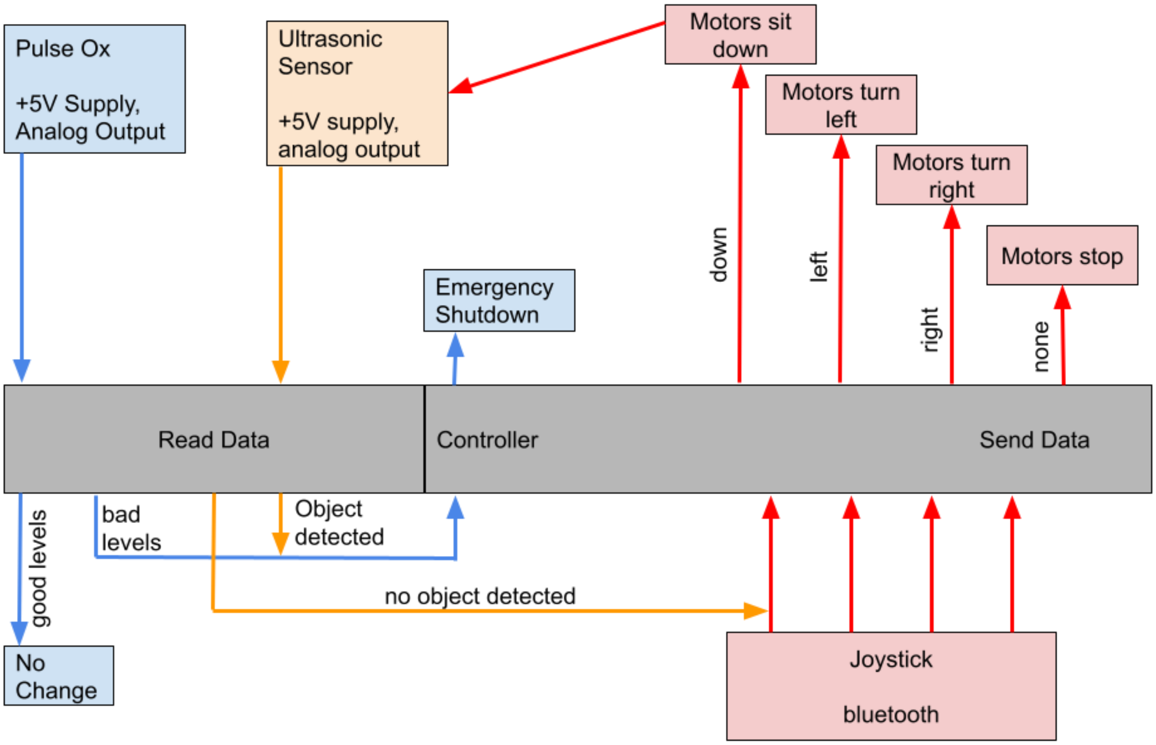

*Figure 8: Initial Block Diagram*

The pulse oximeter must have a tolerance range of ±5% or less. The ultrasonic sensor must have a range from at least 10 cm to 2 m and a tolerance of ±5% or less. The motors should produce a torque of 100 Nm and spin at a minimum of 20 RPM. These motor specifications were determined by mathematical analysis of our test participant’s weight and leg geometry, then verified that value with a motion capture study in WPI’s PracticePoint Lab. The motion capture study included analyzing walking, stand-to-sit, and sit-to-stand motions at various speeds in order to record the various speeds and forces through those motions. The full results of that study can be found in Supplemental Materials B. Ideally the battery life will be 10-12 hours.

## Standards

Along with the ISO standards listed in the previous chapter, ISO 10328 on the structural testing of lower-limb prostheses was followed. This standard is completely accepted by the FDA and includes testing standards for relevant components including principal static and cyclic tests for all components, static tests in torsion for all components, static ultimate strength test in maximum knee flexion on knee joints and associated parts for all knee units or knee-shin-assemblies and adjacent components that normally provide the flexion stop on a complete prosthesis, and static and cyclic tests on knee locks (44). These qualities were tested during bench testing using the fully assembled exoskeleton. They were also tested with simulation software that ensured strong enough materials were chosen before the device was built.

All mechanical design was done in SolidWorks and the ISO compliance setting was enabled to ensure that all designs followed ISO standards. Material selection was done following the American Society for Testing and Materials (ASTM) guidelines. An ASTM test method typically includes a concise description of an orderly procedure for determining a property or constituent of a material, an assembly of materials, or a product (45).

The device also follows the IEEE standards for the testing of wearable robotics. As these were created in conjunction with ISO there was no additional testing required to be compliant with these standards. This device is battery powered and all batteries comply with FCC power regulations.

The exoskeleton contains two microcontrollers both programmed using the Arduino IDE. All standards for this IDE, such as syntax standards, were followed during programming. Basic programming guidelines such as functional block diagrams and clear commenting were also followed throughout the creation of this code.

Each component of the exoskeleton was tested individually (as well as the exoskeleton as a whole) before any human testing to ensure safety. The ultrasonic distance sensor was tested for accuracy for distances between 46 and 5 inches. The pulse oximeter was also tested for accuracy for a period of five minutes to ensure consistency and under multiple conditions (movement, after exercise, standing still). Each of the motors were tested to ensure that the torque, speed, and amperage draw are consistent with the specifications provided by the supplier. Motor stop speed in the event of an emergency power shutoff were also tested. Once the exoskeleton was fully assembled, the joystick function was tested to ensure the motors move in the correct direction at the correct speed to support walking. After all of these tests were passed, human testing began.

The Health Insurance Portability and Accountability Act (HIPAA) established guidelines for keeping individuals' medical information confidential. In an effort to comply with this policy, the data from the pulse oximeter was not stored, only read in order to determine if the user was still at healthy levels, then deleted. This is the only medical data that the device collects. Furthermore, an IRB application was submitted prior to testing to ensure that all consent forms are acceptable, and anyone involved in testing will be able to revoke consent at any time.

## Revised Client Statement

Considering all of the information in this chapter, the new objective of this project was to design and build an individualized lower limb exoskeleton to assist paraplegic individuals in standing and walking costing less than $10,000 to produce.

## Management Approach

A Gantt Chart, shown in Figure 5, was created at the beginning of the project to keep the team on track. In addition to the Gantt chart the group will meet three times a week; once with the advisors, and two additional meetings that are just the project group so that the members can better hold each other accountable and keep up the pacing of the project.

*Table 3: Gantt Chart*

| WBS NUMBER | TASK TITLE | TASK OWNER | START DATE | DUE DATE | DURATION |
|---|---|---|---|---|---|
| 1 | Project Conception and Initiation | | | | |
| 1.1 | Write Literature Review | Team | 8/25/21 | 10/1/21 | 36 |
| 1.1.1 | Write Project Strategy | Dina | 10/2/21 | 10/8/21 | 6 |
| 1.2 | Develop CAD Models | Alek | 8/25/21 | 10/25/21 | 60 |
| 1.3 | Research Components | Team | 8/25/21 | 10/13/21 | 48 |
| 1.4 | Complete Consent Form and IRB | Ricardo | 8/25/21 | 10/13/21 | 48 |
| 1.5 | Begin Ordering Components | Team | 9/15/21 | 11/10/21 | 55 |
| 2 | Further Development and Initial Assembly | | | | |
| 2.1 | Machining Parts | Team | 10/25/21 | 11/10/21 | 15 |
| 2.2 | 3D Printing | Team | 10/25/21 | 11/10/21 | 15 |
| 2.3 | FInd Participant(s) | Alek | | | 0 |
| 2.4 | Interview Participant(s) | Ricardo | 11/1/21 | 12/16/21 | 45 |
| 3 | Assembly | | | | |
| 3.1 | Mechanical assembly | Team | 10/25/21 | 11/10/21 | 15 |
| 3.2 | Electrical assembly | Dina | 9/15/21 | 11/10/21 | 55 |
| 3.2.1 | Programming | Dina/Alek | 9/15/21 | 4/8/22 | 203 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 4 | Testing and Presentation |  |  |  |  |
| 4.1 | Power on and systems check |  |  |  | 0 |
| 4.2 | Walking |  |  |  | 0 |
| 4.3 | Sitting |  |  |  | 0 |
| 4.4 | Present MQP |  |  |  | 0 |

# Design Process

## Needs

In the beginning of the design process, it was necessary for us to determine what goal we wanted our exoskeleton to achieve. Given that this was the project's first year, there was a limit on what we could achieve given the timeframe and budget. Our team decided that the ability to walk and sit would represent many of the basics of everyday necessary movement and were the priority during the design process.

## Wants

The next thing we determined was range of operation. Ideally, we wanted the machine to be able to operate all day, as the average person would likely want to use it for the day and recharge during normal sleeping hours. This was unrealistic; however, given a sixteen-hour window of operation and the relative cost of batteries with this amount of power. Our team decided to aim for a 1 hour active time frame, as this would allow us time to test the machine as needed and would be enough time to commute or to perform everyday tasks around the house.

## Concept Map

We started our design process with the concept map shown in Figure 9.

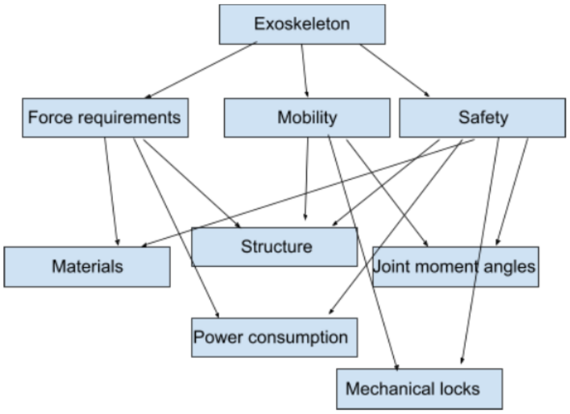

*Figure 9: Concept Map*

## Frame Concepts

The original concept for the Exoskeleton, shown in Figure 10, was designed to operate on the outside of the legs, over clothes and shoes, and could be equipped by a single person. The concept for putting on the exoskeleton was that the operator could lay it down before entering, attach the straps, then pull themselves up with the help of a bar of cane. An alternative method would be to leave the exoskeleton in a sitting position, and then equip it from a chair and stand up using the power of the exoskeleton. The exoskeleton could then be maneuvered using a joystick. The supports for this model were located at the hip, thigh and shin. This design focused mainly on points of contact and mimicking a human's range of motion.

*Figure 10: Original Conceptual Design*

We then attempted to add a motor and gearbox as shown in Figure 11.

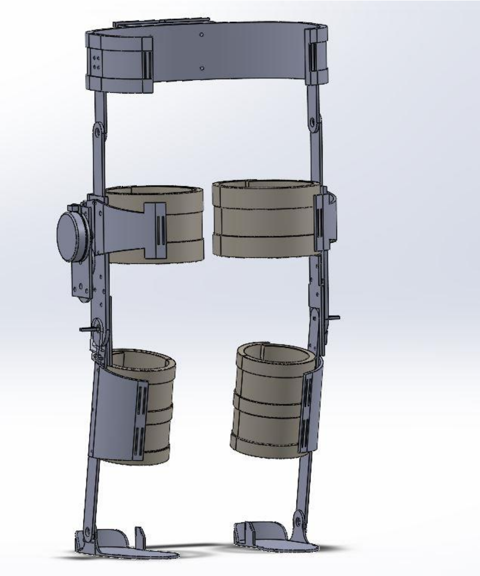

*Figure 11: Second Conceptual Design*

We then selected the final gearbox design and added a protective covering to prevent damage. We also realized the original foot idea would not work so we replaced it with a more sturdy design centered around a tough bracket that could support the system's weight. The changes can be seen in Figure 12.

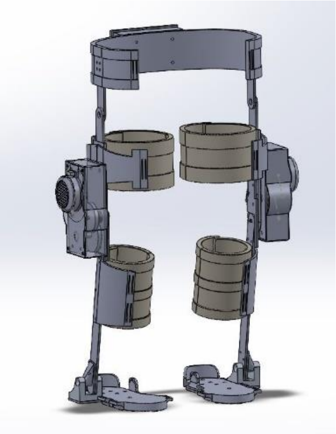

*Figure 12: Third Conceptual Design*

In our next concept, shown in Figure 13, we added the gearbox and motor design to the hip and changed them slightly to attach more efficiently. The previous hip design was not strong enough for this application and was changed from fully 3D printable plastic to having metal inserts that could absorb more of the force from human movement. The new design also features better body support for the person as it is secured snuggly around the rib cage instead of the hips. This makes lifting the operator more comfortable.

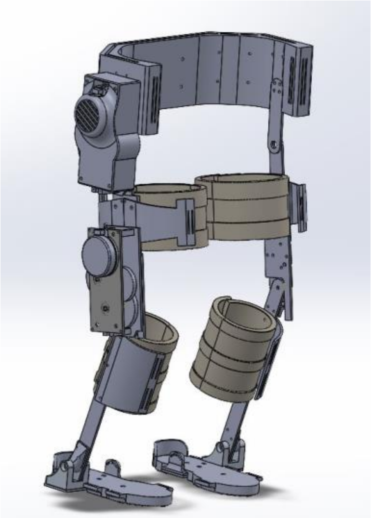

*Figure 13: Fourth Conceptual Design*

In our next conceptual design we added springs at the ankles to replicate the appropriate foot and ankle movement during walking as seen in Figure 14. The resistance from the springs gives the user more stability in order to avoid a potential collapse. Springs were selected to replace a motor, significantly reducing the power requirements of the exoskeleton.

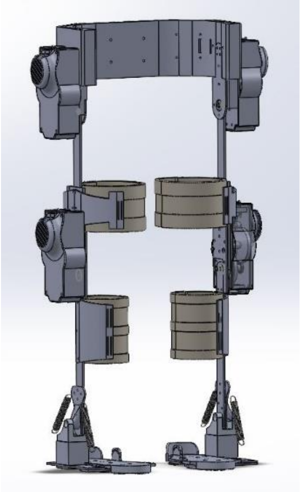

*Figure 14: Fifth Conceptual Design*

**Circuit Concepts**

The original design for the electronics of the exoskeleton used one controller board, an Arduino, to control a pulse oximeter and an infrared distance sensor as shown in Figure 15. The pulse oximeter would be used to measure the heart rate and oxygen level of the participant to ensure that it is in a safe range. The infrared sensor would be used to measure the distance from the hip to a surface when sitting. Sitting would stop when the distance reached a certain level.

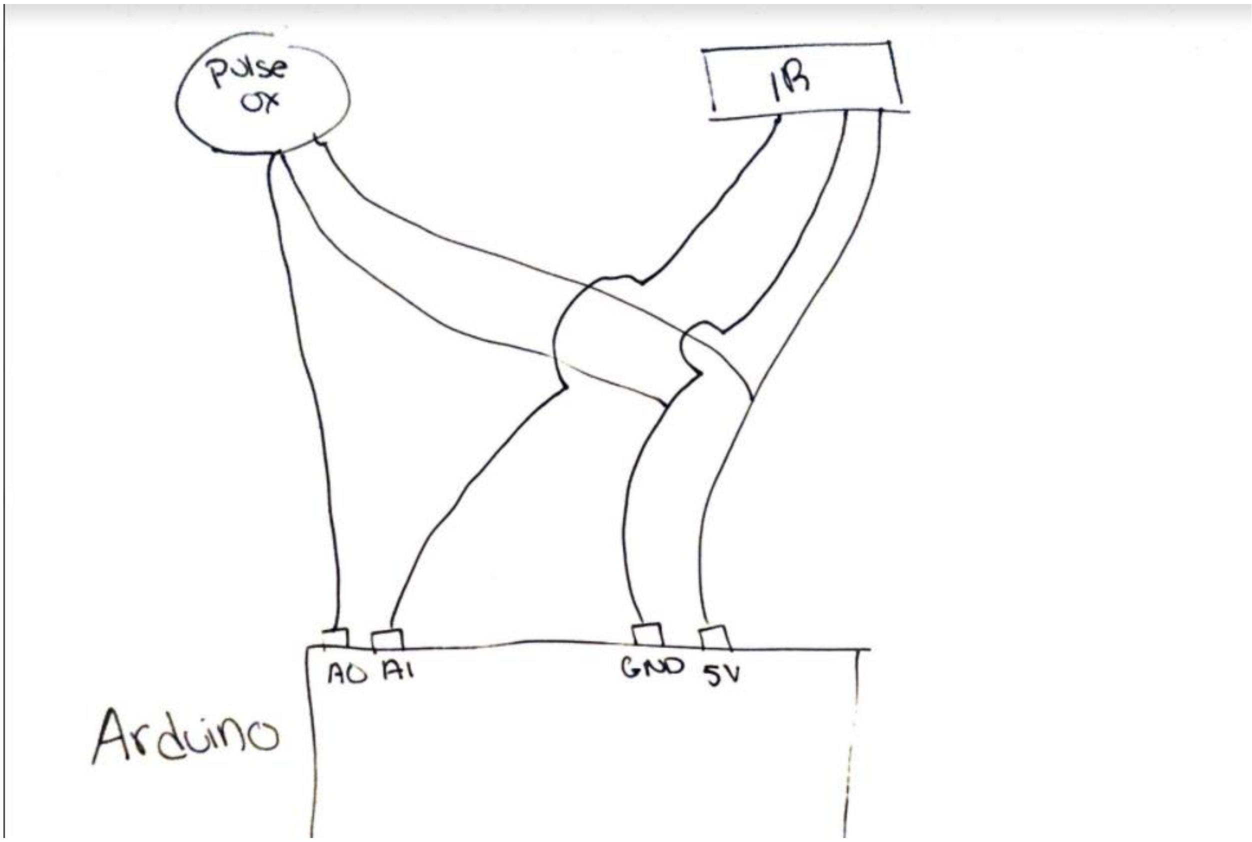

*Figure 15: Original Circuit Concept*

The next concept, seen in Figure 16, used an ultrasonic sensor instead of an infrared sensor because it was more accurate and would not be affected by heat. We also added a second board, an ESP32, to connect with the joystick via bluetooth and control the motors through motor controllers that we planned to design. The motors we selected were Maxon motors that used a 48V power supply so we also added voltage regulators to power the control boards. A 48V to 5V voltage regulator was used to power the Arduino and a 5V to 3.3V voltage regulator was used to power the ESP32. A relay was added before the power supply to the motors that was controlled by the Arduino so the Arduino could cause a shutoff of the motors if the pulse or oxygen level of the patient reached emergency levels or when the participant completed the motion of sitting or wanted to power off the device.

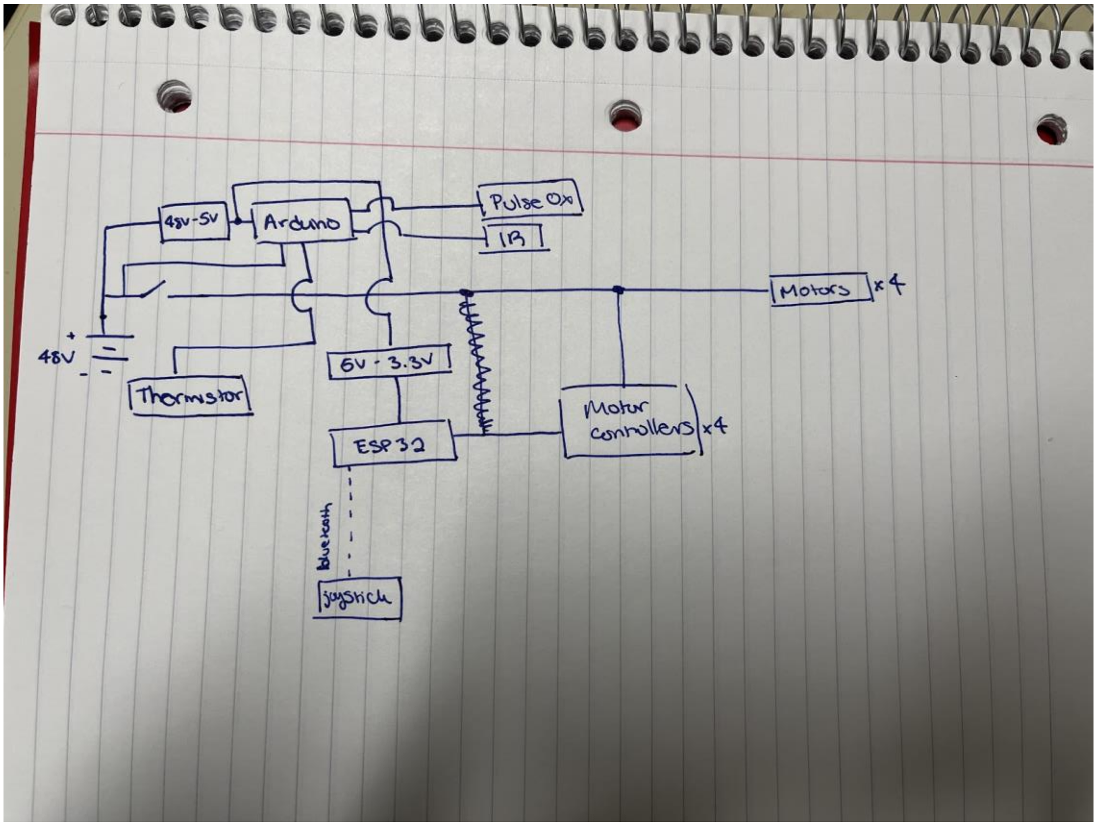

*Figure 16: Second Circuit Concept*

The next circuit design, shown in Figure 17, used a thermistor to measure the heat of the power supply to ensure it did not reach dangerous levels. In this concept we also decided to go with an off the shelf motor speed controller with a potentiometer that we “hacked” instead of creating our own controller. We controlled these parts with an analog signal from the Arduino, instead of the ESP32 in the previous design, to mimic the signal from the potentiometer and control the speed percentage of each motor. One controller was required for each motor.

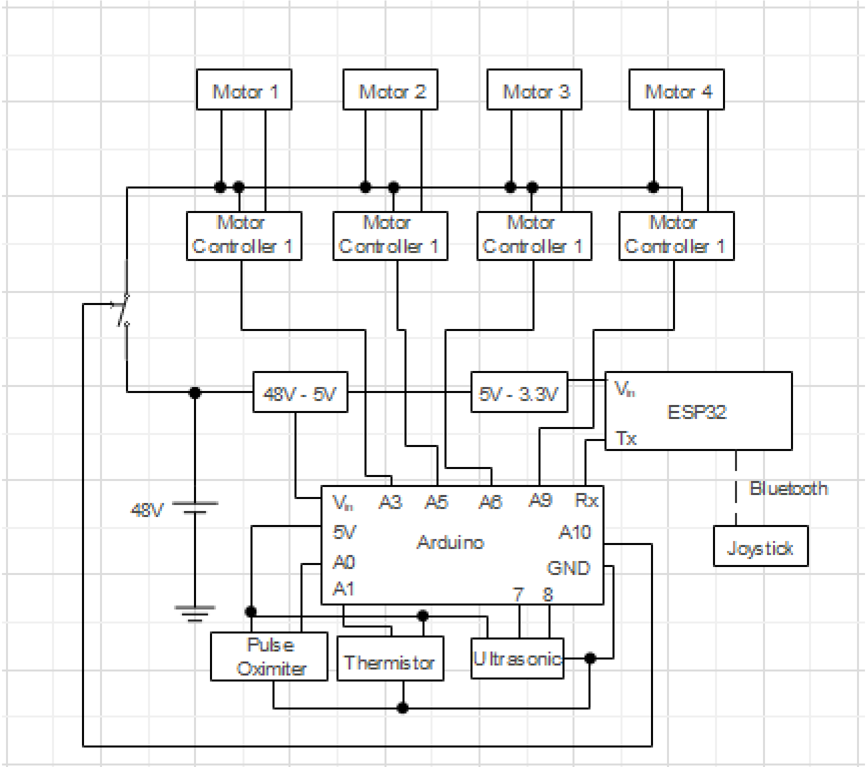

*Figure 17: Third Circuit Concept*

**Battery Concepts**

There were three main battery technologies that we researched and compared for our use in this project: lithium-ion batteries, lithium-polymer batteries, and lead-acid batteries. These three types are each used in different mainstream applications. Lithium-ion batteries are the most widely used technology for smartphones, laptops, and other portable electronic devices, as well as electric vehicles (Manthiram, 2017). They have higher energy density than other battery technologies, which is why they are dominant in these markets. Lithium-polymer batteries are very similar to lithium-ion, but have slightly different technologies. These batteries are most often used in remote-control cars, drones, or other such applications (*Lithium Polymer (Lipo) Battery Guide*, 2015). Finally, lead-acid batteries are the technology that are used in car batteries, and are generally considered to be very reliable, but tend to have a shorter life span than other technologies (*BU-201*, 2010).

**Lithium Polymer:**

We first looked into Li-Po batteries as an option for this project due to the wide-spread use and availability of the cells, as well as the compatibility with many different types of systems. There is even documentation for harnesses that can be used to harness multiple packs together to increase overall capacity and voltage of the system. Despite these aspects, we were unable to find a package that would have the capacity and voltage output required for our project while staying within the cost, size, and weight constraints.

**Lead Acid:**

Lead acid batteries are very common, and can be found on many automotive websites. They also often can be found in 24V configurations, which is much higher than many Li-Po or lithium ion battery cells. The downside of these batteries is that they're very large, heavy, and would require two or more of these large packages to adequately power our system. We found the minimum weight of the lead-acid system to be around 6 pounds, which would be roughly 30% of our estimated weight at the time. It would also require two car batteries, which would make movement rather challenging when strapped to the hip area as our design required.

**Lithium Ion:**

Lithium Ion batteries are another very common type of battery. They usually come in cylindrical form, similar to the shape of AA, AAA, or C batteries, for example. They generally come in 3.7V and ~9.6A configurations, with the main distinction between models being capacity. They have a much lower voltage than we need, but they are frequently arranged in parallel or series configurations to increase voltage and capacity for different use cases. Their design allows them to be easily put in holders such as those found in remote controls or calculators, as well as tack welded together for a more permanent battery solution. The tack welded solution requires the use of a battery balancer to charge each of the cells to full capacity, but by using a holder that allows for the removal of the batteries we were able to save our limited budget and reduce the wiring for our prototype.

When we began our design process, we wanted our design to have enough battery power to last through a full day of use, allowing the user to freely move about their home as needed, and then have the exoskeleton charge overnight. We calculated our necessary battery capacity assuming that the motors would draw the most significant portion of the power, and the other electronics would be essentially negligible. The specifications of the EC-90 Flat motors that we acquired from Maxon Precision Motors stated a nominal power draw of 260 watts per motor at 48 volts. Assuming each motor is running at the nominal speeds and drawing that amount of power, reaching 12 hours of battery life would require a total battery capacity of 260 amp-hours, while outputting 48 volts. We also wanted to keep the battery design as small and lightweight as possible to reduce the strain added to the joint motors. This also allows the exoskeleton to be more easily manipulated by the user in an unpowered state.

**Code**

The initial concept for the code was for the ESP32 code to read the joystick and send a serial message to the Arduino board. The Arduino code would then read the message and move accordingly. The movements of the motors would be decided by the motion capture study we conducted in PracticePoint. The motors move at a speed we calculated until it reaches a position determined by the motion capture study. Each time the speed or direction of a motor changes a new position begins. Each position is coded using a while loop where the while statement is while each motor is between the previous position and the next position and the content is the speed of the motors.

**Feasibility Studies**

The knee and hip joints are designed to be driven by a ⅜’’ square titanium shaft which are press fit into the bearings and limbs of the exoskeleton. We ran multiple equations on this shaft to ensure it would be able to withstand the forces the exoskeleton will be experiencing. The equations we performed were the maximum shear stress, the torsional stiffness constant K, and the angle of twist.

$$\text{Maximum Shear Stress (T): } Tmax = (0.601*T)\ \ a^{3}$$

$$Tmax = (0.601*60N/m)\ \ (0.00476m)^{3} \qquad Tmax = 334.35\ MPa$$

$$\text{Torsional Stiffness Constant (K): } = 2.25a^{4}$$

$$K = 2.25(4.76mm)^{4} \qquad K = 1{,}157.5\ mm^{4}$$

$$\text{Angle of Twist } (\theta) = TL\ \ KG$$

$$\theta = (60N/m*0.127m)\ \ (1{,}157.5mm^{4}*44GPa) \qquad \theta = 8.38\ \text{Degrees}$$

The speed of the final gear was an important variable because this determines how fast the exoskeleton will stand up and walk. The max speed of the motor is 1670 RPM and there is a 100:1 gear reduction. This results in a final gear speed of 16.7 RPM, 0.278 RPS. This means the exoskeleton is capable of standing up in 1 second at 100% motor effort, 2 seconds at 50% motor effort, and so on.

### Final Design

The first final design we chose was the foot component which can be seen in Figure 18.

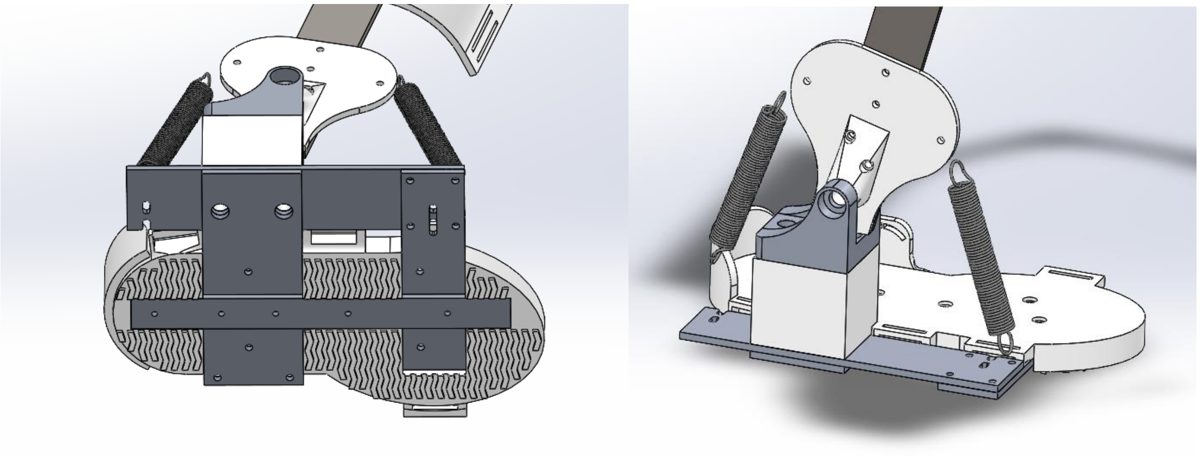

*Figure 18: Final Foot Design*

This design was chosen mainly due to funding issues, as the ideal design would have been to place another gearbox (the same as those used for the knees and hips) at the ankle to control the motion. We initially wanted the foot to be another metal piece. However, based on the size and our manufacturing limitations, we were forced to create a design that is primarily 3D printed plastic but is reinforced with machined aluminum. When it first became apparent that the budget would not allow for ankle motors, we were going to rigidly fix the foot and ankle so that the ankle would not be able to rotate at all. However, when reviewing the data collected from the motion capture study, it became apparent that this would impede the machine's stride by possibly causing the toe area to dig into the ground while walking. Because of this, we moved to a design that used two opposing springs that would hold the toes slightly up while in the air so that they wouldn't touch the ground. These springs would then allow for rotation to happen while the foot was on the ground, but would restrict the motion, slowing it down long enough for the stride to be completed.

To determine the strength of the springs, we reviewed the data collected from the motion capture study and chose an amount that approached the readings for how much force the ankles were experiencing.

For sitting, the end of the tibia link extends past the fulcrum point for the ankle and is angled at the end so that it will stop against the bottom of the joint at angles of 15 degrees on either side in order to transfer the force directly into the ground rather than through the ankle as shown in Figure 19 below. This angle was chosen after reviewing the motion capture study, which determined the positioning of the ankle while sitting.

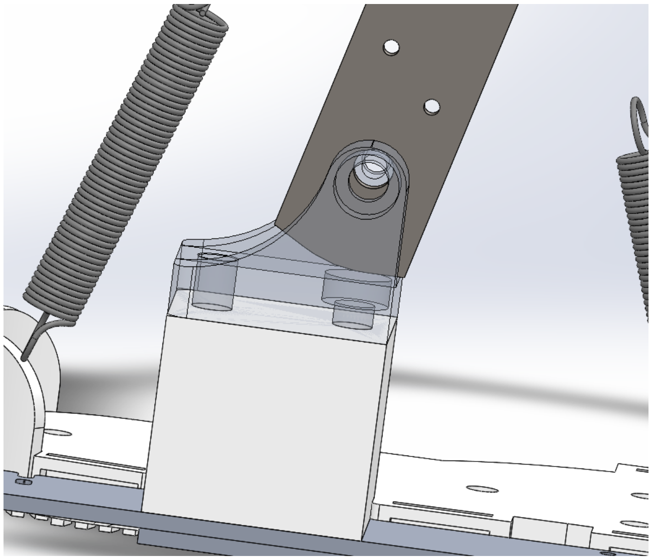

*Figure 19: Tibia Link*

The next final design we chose was the lengths for the thigh and shin sections, shown in Figure 20 below, were decided by taking measurements of the participant. These measurements were taken from the center of rotation between the hip and knee for the thigh section, and between the centers of rotation for the knee and ankle for the shin section.

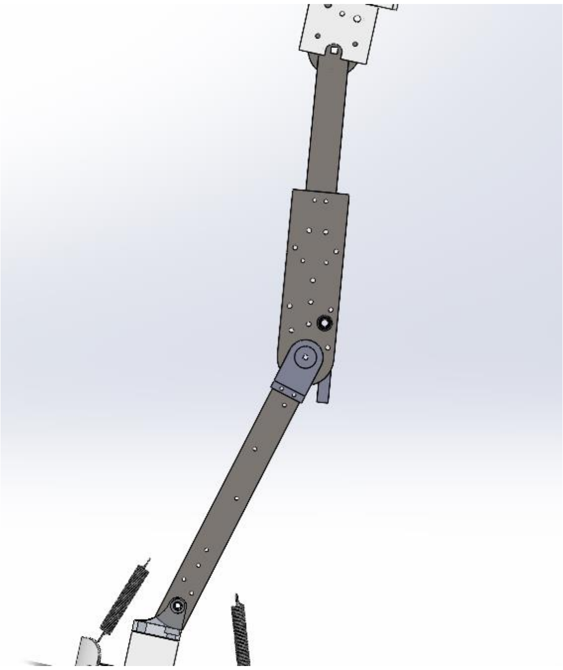

*Figure 20: Final Leg Length*

The third final design we chose was the waist fastener design and is shown in Figure 21.

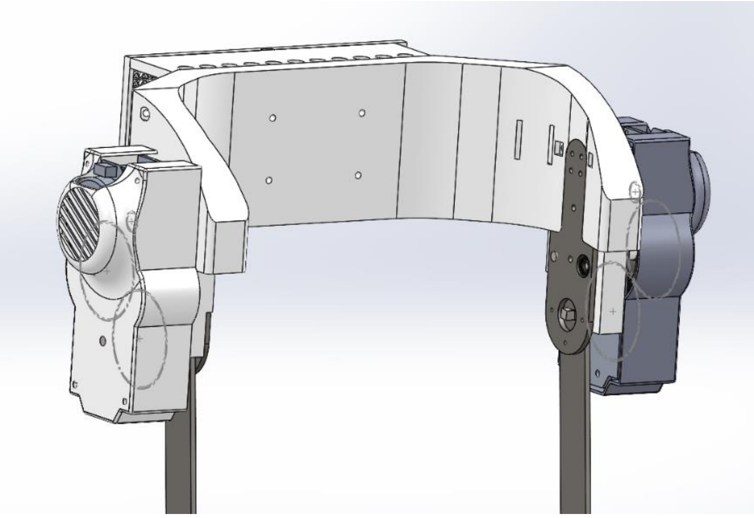

*Figure 21: Final Waist Fastener Design*

This design started out to be a singular metal piece which would have been manufactured out of aluminum by an outside source, Zometry. Since this part would have been very difficult and costly to manufacture, we made a new design to have it 3D printed in 5 different pieces. This way they can all be bolted together allowing the person to be strapped in from the back. This option is more affordable and is lighter than the aluminum option. Foam is wrapped around the inside of the plastic prints making the user more comfortable. The original design did not have as much padding, but based on our initial design feedback we realized that adding more foam would ensure proper blood flow and vastly increase the comfort of the user.

The fourth final design we chose was the foam connections shown in Figure 22.

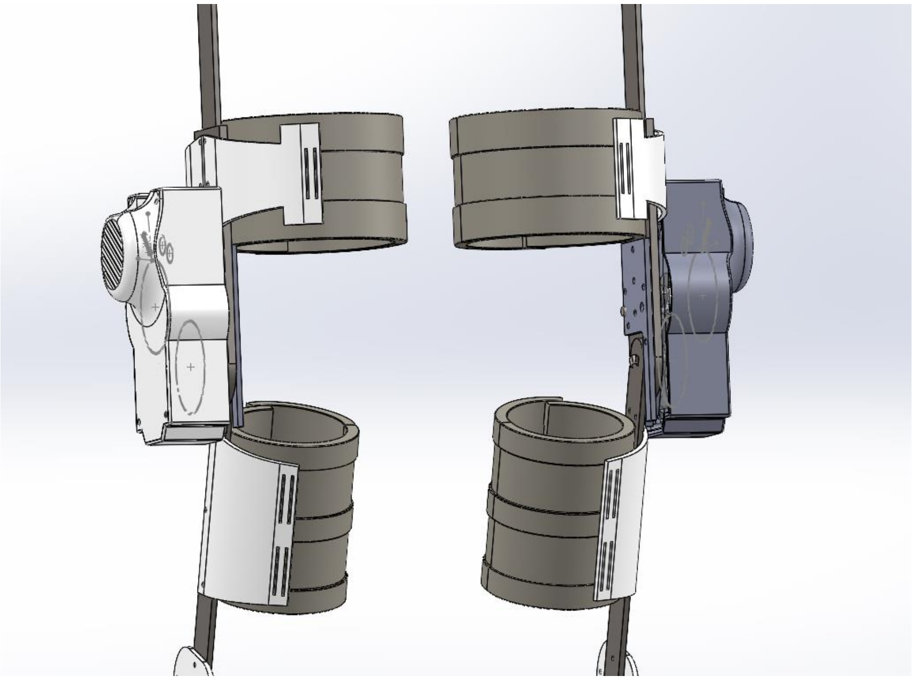

*Figure 22: Final Foam Connection Design*

The final design for this component was chosen after giving thought to a balance between comfort and ability to support the passenger. Strapping a person into the suit directly would likely result in loss of circulation, so it was decided to add a foam buffer between the person and the straps as a means of distributing the force across a larger surface area. Also, this would allow the muscles and skin to shift while still being supported.

The fifth final design we chose was from the gearbox and is shown in Figure 23.

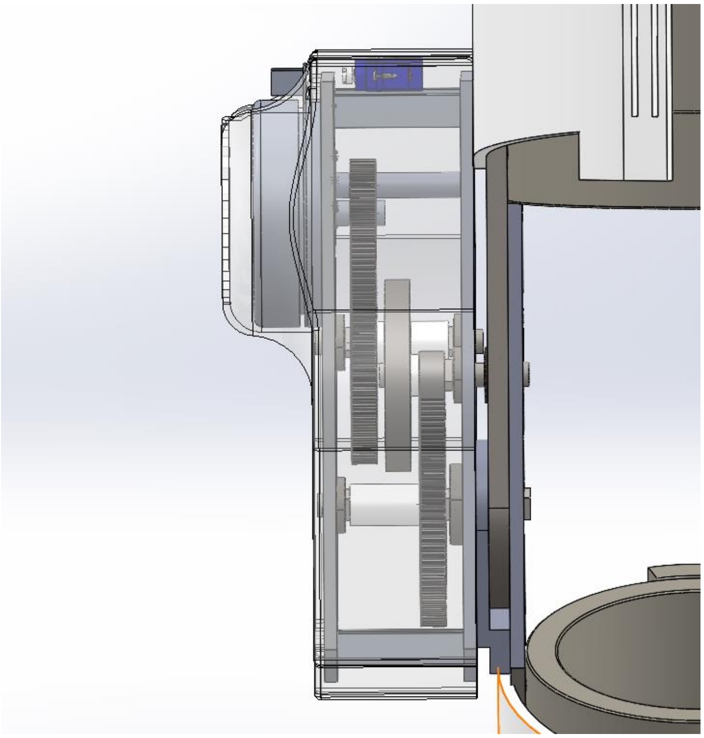

*Figure 23: Final Gearbox Design*

Our design has four gearboxes, two at the hips and two at the knee joints. This allows for actuation at the knee and hips to allow the suit to walk forwards. As stated above, we completed a motion capture to study the torque requirement that it takes to move the lower leg portion which was found to be 60Nm of torque at each joint. This allowed us to purchase motors that can supply a nominal torque of 0.964Nm which we geared down by 100:1 to increase our output torque. This gear reduction was achieved by using a three-stage reduction: 19-96, 19-76, and 19-96.

This gearbox was manufactured out of steel, aluminum, and titanium, and plastic. The gears were made of 10mm thick #45 steel with square holes machined out for the shafts to pass through. The shafts were machined out of square bar titanium with ⅜ diameter ends to be press-fit into ball bearings on each side. Aluminum rectangle panels kept this gearbox together with ¼-

20 bolts securing the gearbox together. There are plastic spacers separating the gears from each other with a plastic cover over the gearbox ensuring nothing can get stuck
inside the gearbox.

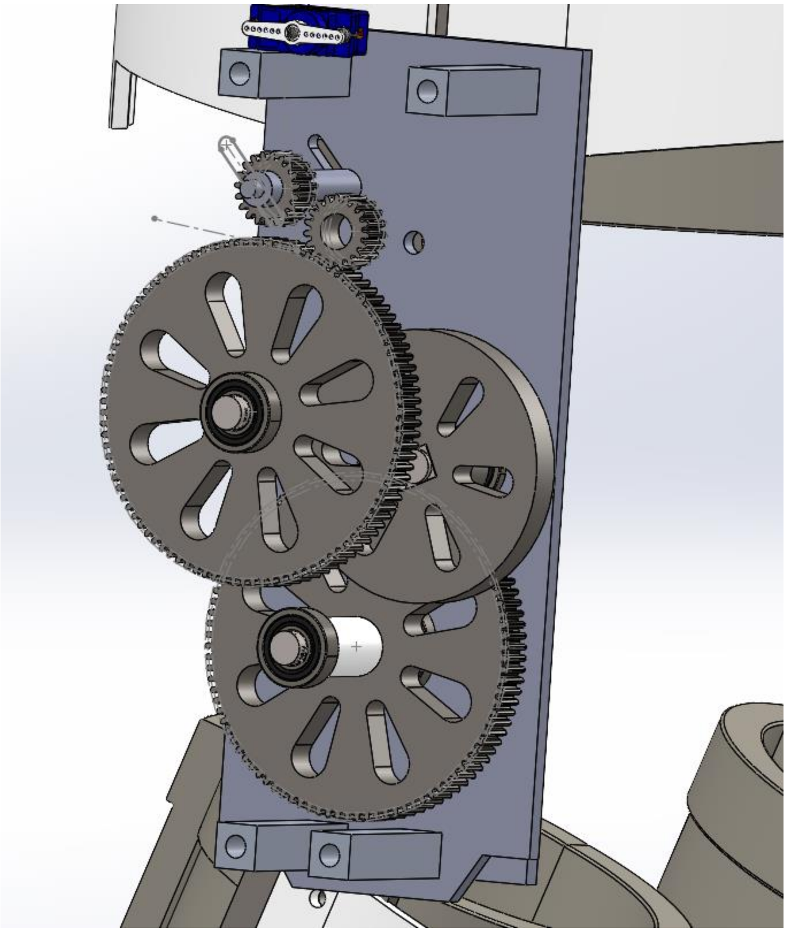

*Figure 24: Final Stopping Mechanism*

The stopping mechanism, shown in Figure 25, was not implemented due to time constraints. The gear lock worked by inserting a third gear between two other gears at the beginning of the drivetrain in order to freeze them in place. The mechanism worked by having a gear slide along a track cut into the aluminum panels, while still rotating freely on its 3D printed mounting in order to more easily be able to insert itself between the two spinning gears. The actual mechanism worked by having two gears mounted inside the tracks constantly applying a downward force that was just enough to overcome that which the servo provided while off, this means that whenever power was cut to the servo, the gears would automatically freeze.

The next final design we reached was the joint stops, shown in Figure 25.

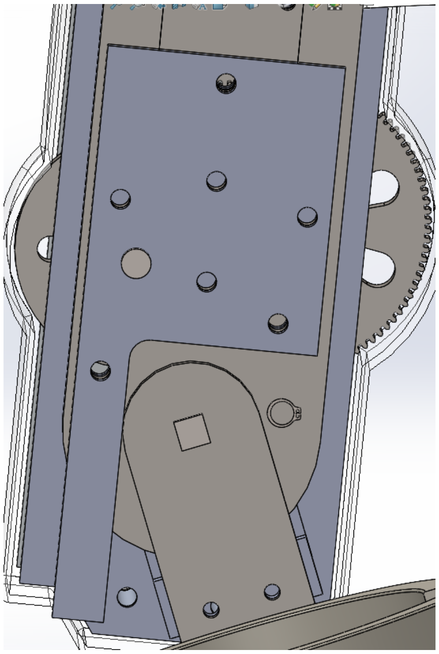

*Figure 25: Final Joint Stops for Knees*

For the joint stops, our final design was reached by angling the Solidworks model into the positions of maximum and minimum angle of movement, then creating an additional piece that would block any motion past those thresholds. For the knees the thresholds were 180 degrees for a full leg extension and 80 degrees for sitting, Shown in Figure 25 above. For the hips, the thresholds were, Shown in Figure 18 below.

We had to use slightly different considerations for the ankles, shown in figure 25 above, since we were not going to be able to use motors in this section. It was decided that the weight from sitting would be handled by the constraint, thus the constraint was placed at the angle for sitting (15 degrees), allowing a shorter stride. The back limit was also placed at 15 degrees as well instead of the full 90 degrees. Even though the ankle is capable of this, there was no need for it.

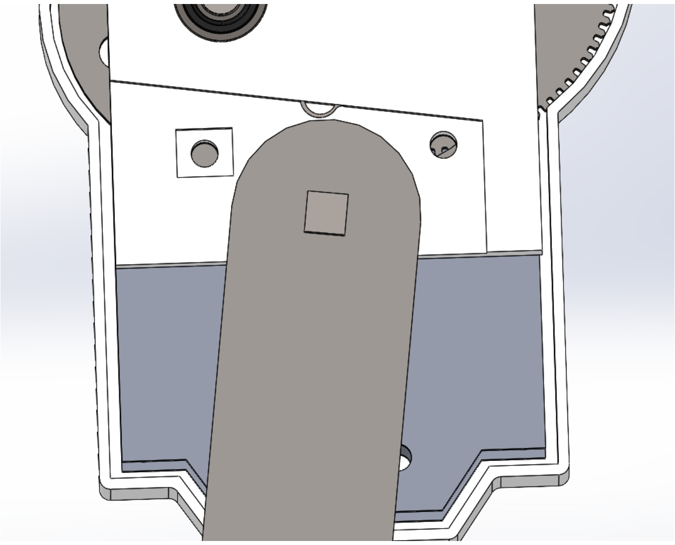

*Figure 26: Final Joint Stops for Hips*

The design is separated into two main compartments, The top compartment is for the battery pack. The battery pack is designed to be removable and holds the batteries facing out so as not to allow interference between them. Ideally, the pack has space for up to six battery holders. Inside the Pack, there are three stretches of empty space, with the top and bottom ones being there to promote wire access, and the middle slot being there to reduce weight and improve air circulation. This is similar to the eight blocks which fit between the battery holders in order to prevent them from moving around but are also designed with slots to promote air flow through to the back. The back portion of the compartment is designed to allow air to flow in from the sides, in addition to the air coming through the spacing blocks. Several holes are also placed at the top in order to allow hot air to rise out, the action of hot air rising out will then drag new cold air into the system and create unaided circulation.

The bottom slot is reserved for the electronics and is designed to have enough space for all crucial electronics to fit within. These electronics are then secured inside by hand by the assembly team.

The Access panel, shown in Figure 27, is designed to be pressed into place over the edges of the box by hand. This panel has a very dense series of holes cut into it in order to impede airflow as little as possible, while still protecting the electronics inside from jostling and outside objects. All of the final CAD models can be found in Supplemental Materials C.

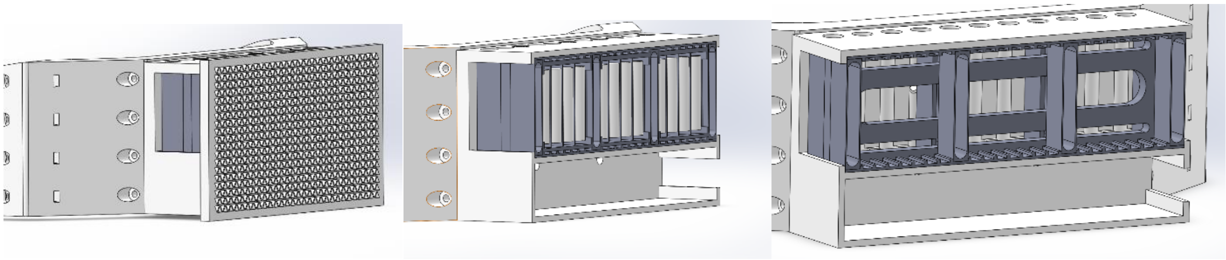

*Figure 27: Battery Casing and Access Panel*

The final circuit design is shown in Figure 28 and can be found in Supplemental Materials D. The changes from the third design circuit design were adding a manual emergency stop button that shuts off all power, adding potentiometers to read the positions of the joints and assist in motor control, adding a 4 relay module to control the forward and reverse of the motor, and adding lowpass filters at each of the analog outputs of the Arduino. This is because the Arduino outputs 490 Hz PWM signals so the lowpass filter smoothed the signal to provide a consistent voltage instead of one that is constantly oscillating.

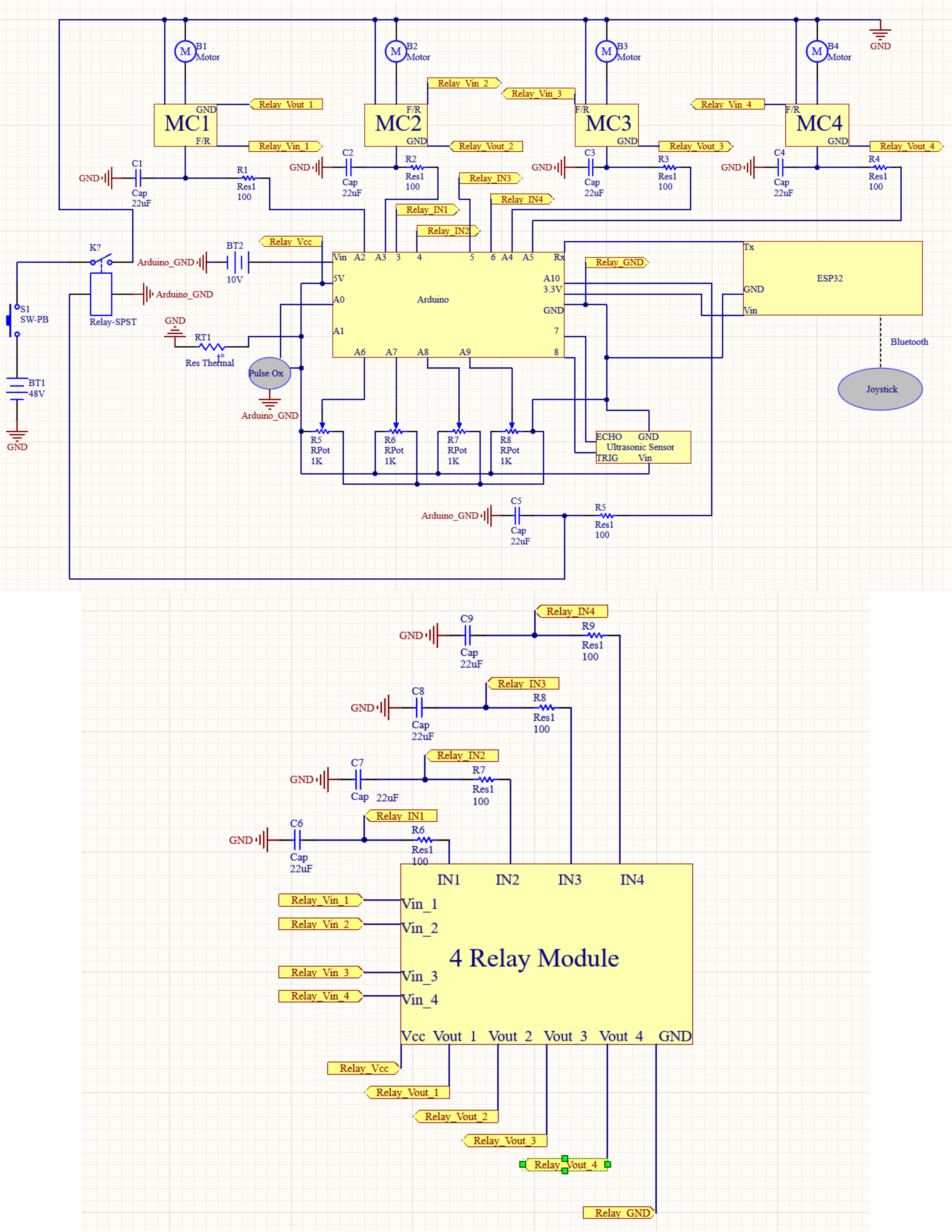

*Figure 28: Final Circuit Diagram*

Specific parts were chosen based on the current and voltage running from the battery to the motors. Any parts that would be along that line had to be able handle 50V and 10A to ensure there would be no issues. The pulse oximeter had to be proven accurate over a period of at least 30 minutes since the device will not be able to run longer than that due to battery capacity. The thermistor had to be proven accurate for temperatures between 50°F (a little lower than standard room temperature) and 140°F (the unsafe temperature for lithium ion batteries). The ultrasonic distance sensor needed to be accurate for distances between 9 and 46 inches to cover the full distance from standing to sitting. The resistors and capacitors for the lowpass filters had to also be able to handle the voltage and current requirements stated earlier. The voltage regulators had to be proven accurate and not overheat over a period of 30 minutes. When choosing parts we chose standard components so that any alternatives would be of similar quality. These features were all tested during the bench testing phase which can be found in the next chapter.

The final design for the battery ended up being 16 3000 mAh, 3.7V, 9.6A Li-Po cells in 2 arrays: 14 in series to produce an overall capacity of 3000 mAh that output 48 volts at 9.6 amps. The last two cells are in series to power the Arduino control boards. They are arrayed in spring loaded holders so they can be removed and charged.

The final concept for the code was very similar to the original concept. The motor movement was coded the same way and the ESP32 read the data from the joystick via Bluetooth and communicated it to the Arduino serially. The main change was that a timer interrupt was added using the Arduino TimerInterrupt library that constantly read data from the pulse oximeter, the joystick, the ultrasonic sensor, and the thermistor. The final code for both the Arduino and the ESP32 can be found in Supplemental Materials E. Once our design was finalized, we moved on to testing and verification.

# Design Verification

## Electronic Components

Each individual electrical component was tested to ensure its efficacy before it was placed in the device. Comprehensive results of these experiments can be found in Supplemental Materials F. The full Bill of Materials can be found in Supplemental Materials H.

To test the pulse oximeter, PulseSensor, it was placed on a healthy participant for a period of 30 minutes and the participant's heart rate and oxygen levels were monitored with the device. The 30 minute time period was chosen since the exoskeleton will only be able to run for 15 minutes with the current battery life so this ensures that the pulse oximeter is accurate for the full time period. During this the heart rate stayed around 70 bpm and the oxygen level stayed around 99%. The device was determined to be reliable and we moved forward with it.

To test the ultrasonic sensor, part number HC-SR04, it was placed 46 inches from a flat surface and the distance was measured with a ruler and the sensor and was recorded. This was repeated at intervals of 5 inches until the sensor was 16 inches from the flat surface. After that, this was repeated at intervals of 1 inch until the sensor was 9 inches from the flat surface. 9 inches was chosen because that is the distance between the sensor and a chair during sitting. At the completion of testing the average percent error of the sensor was determined to be 0.876%. This device was determined to be acceptable and we moved forward with it.

To test the thermistor it was placed in 50°F water and the temperature was measured with both the thermistor and a thermometer to ensure that the reading was within 5°F. This was repeated at intervals of 10°F until 140°F was reached. 140°F was chosen because the unsafe temperature for lithium ion batteries is 122°F so the thermistor would be ensured to work within the full possible range. The average percent error after testing was determined to be 1.5%. This device was determined to be acceptable and we moved forward with it.

To test the joystick, Spektrum VR Control Bluetooth Remote Controller, it was connected to the ESP32 and the results of each test were observed with the serial monitor. We followed these steps when conducting our test:

1. Move joystick to forward position and monitor serial port to ensure that forward motion is detected
2. Let go of joystick and monitor serial port to ensure that no motion is detected
3. Move joystick to left position and monitor serial port to ensure that left turning motion is detected
4. Let go of joystick and monitor serial port to ensure that no motion is detected
5. Move joystick to right position and monitor serial port to ensure that left turning motion is detected
6. Let go of joystick and monitor serial port to ensure that no motion is detected
7. Hold down sit button and monitor serial port to ensure that sitting motion is detected
8. Let go of sit button and monitor serial port to ensure that no motion is detected
9. Hold down stand button and monitor serial port to ensure that standing motion is detected
10. Let go of stand button and monitor serial port to ensure that no motion is detected
11. Press power button and monitor serial port to ensure that power off is detected
12. Press power button again and monitor serial port to ensure that power on is detected

The serial monitor showed the expected results during each test so the device was determined to be acceptable and we moved forward with it.

To test the relay, part number MB3D, we began by attaching a 48V power supply to the relay input and attaching an analog channel from the Arduino to the relay control pin. A 5V signal was then sent from the Arduino to the relay switch. The relay output was read to ensure the 48V signal was able to pass through the relay. The 5V signal was then turned off and the relay output was read to ensure the 48V signal was not allowed to pass through the relay. The results were as expected and the device was determined to be acceptable and we moved forward with it.

To test the motor controllers, part number Yanmisgd7v9o420n, they were attached to a motor and an analog channel of the Arduino. A 3.562V signal was sent from the Arduino to the potentiometer of the motor controller and the rpm of the motor was measured to ensure that it reached 711 rpm ± 10 rpm. This was repeated for all of the necessary speeds we found from our motion capture data. This was repeated for each motor controller using only the speeds necessary for that joint. For example, the left hip does not require the same speed as the right knee so we did not test the same speeds for each of them. We were able to reach all of the necessary speeds and collect voltages for each so we proceeded with the testing.

To test the potentiometers, part number B10k, the device was moved to a 3 degree angle and the position was measured with a protractor and the voltage was measured with the Arduino and it was found to be 4.23V. This was repeated for all of the necessary angles we found from our motion capture data. This was repeated for each potentiometer using only the angles necessary for that joint. For example, the left hip does not require the same angles as the right knee so we did not test the same angles for each of them. All of the necessary angles were found so we moved forward with the device. ‘

To test the emergency stop button a 5V signal was sent through the button and read with a multimeter. The button was pressed and the voltage was read again to ensure that the 5V signal was no longer able to pass through. The results were as expected so we moved forward with the device.

### Battery

The battery design was very simple compared to many of the other electronic components because we created a simple array using smaller cells. The tests that we used to validate the batteries were a continuity test to verify the solder joints, a capacity test using the display on our battery charger, and a practical load test using a simulated load.

The continuity of the battery was tested using a multimeter. With all the cells installed in the battery array, the battery should be one complete circuit. There was proper continuity each time that it was tested, but just to be thorough we fully removed each of the cells and put them back in 5 times to ensure that the system would be robust long term.

The capacity test operated on a cell by cell basis. The 8 bay battery charger we purchased displays the capacity of each cell, and we used this to verify the specifications given by the manufacturer. Each cell had a capacity within 5% of the listed 3000 mAh, and some even read out as having a higher capacity.

To verify our estimated battery life, we used a simulated load of 250W to simulate the load of one motor running at its nominal power requirements. We ensured that the batteries were fully charged before the test by checking the voltage on the battery charger as well as by using a multimeter. We set the simulated load so when the batteries discharged to 3.2 volts the test would end, as that is the safest low range of the battery. We ran this test twice because our batteries took about 12 hours to charge and the access to the simulated load was limited. The first test the batteries lasted 22 minutes and 16 seconds, and the second test they lasted 21 minutes and 46 seconds. We extrapolated from this data to estimate that the load of all 4 motors would last around 5-6 minutes. Due to the variable load of the motors as they move, we may get slightly more battery life in practical use. This was far less than our initial goal for battery life, but unfortunately we didn’t have adequate funding to properly address this issue while reaching our other goals. The battery was decided to be the weakest point because it was easier to plug our exoskeleton into the wall than to compromise other components.

### Full Exoskeleton Bench Testing

In order to determine the efficacy and safety of our final design before human testing we tested each feature of the fully constructed exoskeleton. Each aspect was testing under the following conditions:

1. Exoskeleton was fully powered with no participant in it
2. Exoskeleton was restarted after every test
3. Each test was repeated 5 times by the same operator to reduce variability

Before any testing began, the battery connection to each component was confirmed using a multimeter.

First, we tested the mechanical safety features of the exoskeleton. We began by running the motors against the restraining pieces at full power to ensure that the restraining pieces did not break. This test was successful. Then, we had the motors move the legs to the most extreme angles possible and compared this angle to the future participant’s leg extension angles using a protractor. During the test, the knee reached a maximum angle of 180 degrees and a minimum angle of 81 degrees while the hip had a much smaller range of motion. The hip reached a maximum of 85 degrees in the forwards direction and 140 degrees in the backwards direction. This was determined to be acceptable and we moved on.

To test the emergency shutoff associated with the pulse oximeter we began with the pulse oximeter on a healthy participant. We then removed the pulse oximeter in order to trigger the safety shutdown. Ideally, this shutdown would happen in under half a second and the motors would lose power while the microcontrollers stayed powered. The voltages at the motors and the microcontrollers were measured with a multimeter after shutdown. This test was successful.

To test the motor shutoff associated with the ultrasonic sensor we began with a flat object less than 9 inches away from the sensor. We then moved the flat object so it was greater than 9 inches away from the sensor in order to trigger a motor shutoff. Ideally, this shutdown would happen in under half a second and the motors would lose power while the microcontrollers stayed powered. The voltages at the motors and the microcontrollers were measured with a multimeter after shutdown. This test was successful.

To test the emergency shutoff associated with the thermistor we began with the thermistor at room temperature. We then plunged the thermistor into water that was higher than 122°F in order to trigger the emergency shutoff. Ideally, this shutdown would happen in under half a second and the motors would lose power while the microcontrollers stayed powered. The voltages at the motors and the microcontrollers were measured with a multimeter after shutdown. This test was successful.

To test the joystick stop/start button we began with power going to the entire exoskeleton. We then pressed the joystick stop/start button to trigger a shutdown. Ideally, this shutdown would happen in under half a second and the motors would lose power while the microcontrollers stayed powered. The voltages at the motors and the microcontrollers were measured with a multimeter after shutdown. The button was then pressed again to repower the motors. Ideally, power would return in under half a second. The voltages at the motors were measured with a multimeter after repowering. This test was successful.

To test the manual emergency stop button we began with power going to the entire exoskeleton. The emergency stop button was then pressed. Ideally, this would make every component of the exoskeleton lose power within half a second. The voltages of the motors and the microcontrollers were measured with a multimeter. The button was then pressed again to restart the device. Ideally, this would fully power the exoskeleton within half a second. The voltages of the motors and the microcontrollers were measured with a multimeter. This test was successful.

We then had to test the overall movement of the exoskeleton. Unfortunately, due to battery capacity we could only move one motor at a time. Each motor was tested to determine that it could move in each direction to the maximum angles found above. This test was successful and the device was determined to be ready for human testing.

**Human Participants Testing**

Once the design and safety of the exoskeleton was confirmed we tested the device on a human participant as shown in Figure 29.

*Figure 29: Human Testing in Standing Position*

We set the following safety guidelines in order to ensure that no damage occurred to the participant:

1. The participant will be accompanied by at least 3 (out of 4) remaining group members during testing to help maintain a safe environment.
2. Exoskeleton has an emergency kill switch to cut power to the exoskeleton in case things go wrong.
3. The exoskeleton has insulating materials for electrical shock prevention from the battery, it also has a safety wall around the battery pack. The design elements are to prevent electric shock, battery leakage, and/or battery corrosion/explosion.
4. The participant will wear clothing that covers all skin (long pants, socks, and shoes) to prevent any skin from being irritated, pinching, rashes, etc.
5. In the case that there is an emergency, we are prepared to call Campus Police at 508-831-5555.

We tested the exoskeleton in the WPI Practice Point simulated test apartment using the harness to hold up the participant. We planned to test all five motions of the exoskeleton within one experiment. The exoskeleton would be put on while sitting as shown in Figure 30.

*Figure 30: Human Participant Putting Device On*

The participant would then turn on the exoskeleton and press the stand button to go from standing to sitting. The participant would then use the joystick to walk 10 feet in a straight line. The participant would then use the joystick to turn left 180 degrees and walk 10 feet back to the chair in a straight line. Then the participant would use the joystick to turn right 180 degrees and press the sit button to return to sitting. This would be repeated 5 times to ensure the results.

Due to constraints, we were unable to complete the above test method. However, we were able to test the mechanical motions of sitting and standing by having two of our group members spin the motors to force the user into a standing position and then back to a sitting position. We were also able to test the mechanical motions of walking by having our participant, a group member, force the motions of walking and turning while wearing the exoskeleton. Figure 31 shows our participant using the exoskeleton to perform home tasks.

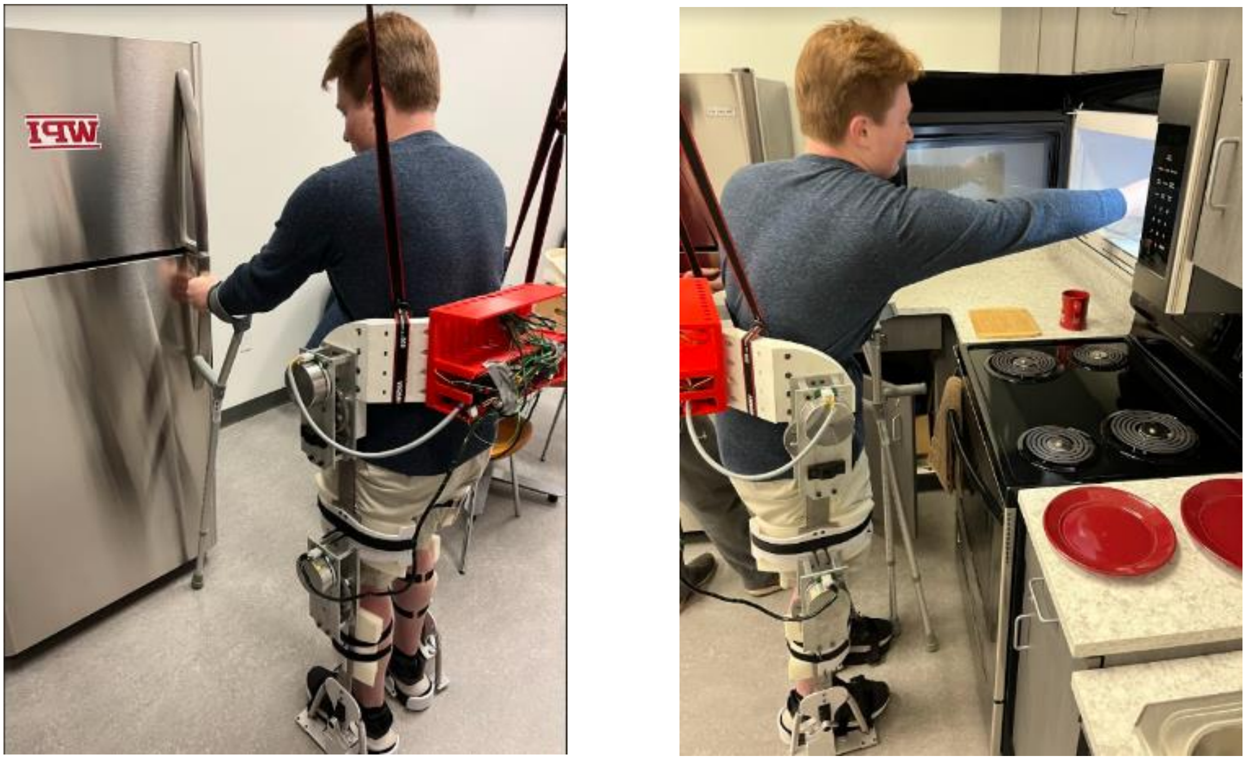

*Figure 32: Human Testing While Doing Home Tasks*

A video of this process can be found in Supplemental Materials G. The member of our group that was the participant, Alek Hersum, had the following feedback: “It goes through the motions pretty smoothly, turning is going to be hard on carpets though.”

# Design Validation

## Review of Objectives

Once we tested our final design, we were able to ensure that we met our objectives. Our first objective was that the exoskeleton must be able to support the motion and forces of standing from a sitting position. This was confirmed during our participant testing. Our group member/participant described the motion from standing to sitting as “This was the easy part, I just sink in and let gravity work”.

Our second objective was that the exoskeleton must be able to support the motion and forces of sitting on a chair or similar height surface from a standing position. This was also confirmed during our participant testing. Our participant described the motion from sitting to standing as “upstanding up was pretty hard since I had to overcome resistance from all the gears. I'm not sure if it was the smoothest it could be, but it worked.”.

Our third objective was that the exoskeleton must support the motion and forces of walking. This was confirmed during our participant testing. Our participant described the motion of walking as “Pretty different from walking normally but definitely possible with some practice”.

Our fourth objective was that the exoskeleton must have a reasonable cost. We did a cost analysis and the cost of all of our materials and our time assuming that we billed $25/hour. The full cost analysis can be found in Supplemental Materials H. We determined that the total cost of our exoskeleton would be $10,000. This number, however, excludes the price of research and development. This also doesn’t account for the larger cost of a properly functioning battery, which will need to be addressed in future analysis. Calculating our time as being valued at $25/hour, we each averaged 15 hours of work per week across our team of 5 people. This average does not include the machining cost, which we included in the exoskeleton price. This means that over the seven terms we totaled approximately 2,100 working hours, which would be a $52,500 cost. If we assumed we would sell 100 exoskeletons, we could split that into a $525 increase per exoskeleton, making the cost around $10,500 total. The average price of an exoskeleton currently on the market is about $80,000. Our cost is well below the average, so we met this objective. These costs could be decreased by using methods of manufacturing such as casting for many of the parts, or by utilizing more advanced CNC machining techniques that require less tool changes and can utilize stock more efficiently. It might also be possible to decrease the cost of materials and electronics slightly by arranging bulk orders with the manufacturers rather than ordering everything off of retail sites.

Our fifth objective was that the exoskeleton must be safe to use. During testing, we constantly measured the participant’s pulse and oxygen levels throughout use which remained at safe levels. We implemented safety systems that shut the system down when pulse and blood oxygen drop below safe levels, allowing the person to be removed safely.

Our sixth and final objective was that the exoskeleton must be user friendly. This was partially confirmed during participant testing. We were limited to one subject, but hopefully in the future it can be tested by more people for a more confident sample. Our subject described the process of putting on and taking off the device as “Easy to put on from a sitting position, and from any position it’s fairly easy to remove. The supports are pretty comfortable as far as that goes” and the process of walking with the device as “It’s kinda weird. You have this huge thing attached to your body, but since it supports itself, you don't feel any weight. Like it's not even there”.

## Review of Standards

The FDA defines a lower limb exoskeleton (product code PHL) as “a prescription device that is composed of an external, powered, motorized orthosis that is placed over a person's paralyzed or weakened limbs for medical purposes” (25). There are several special controls for lower limb exoskeletons. Any elements that come into contact with the patient must be biocompatible, testing must validate electromagnetic compatibility/interference (EMC/EMI), battery performance and safety, wireless performance, mechanical safety, electrical safety, and thermal safety. Non-clinical performance testing must demonstrate device performs as intended through mechanical bench durability testing, simulated use testing, validation of manual override controls, accuracy of device features and safeguards, flame retardant material validation, liquid/particle ingress prevention, sensor and actuator performance, and motor performance. Clinical testing must demonstrate safety and effectiveness and include considerations for the level of supervision necessary for intended use of the exoskeleton and the environment of use. Lastly, the labeling must be detailed and contain all warnings and instructions (25).

There are also some international standards that need to be considered when designing an exoskeleton in order to keep it under legal measures. ISO 13482:2014 has guidelines for the safe design, protective measures, and information for use of personal care robots including exoskeletons. These standards are meant to provide human care related hazards as well as domestic animal or property damage. ISO TC299 WG2 contains general standards for many aspects of devices including, consumer warranties and guarantees, healthcare services, the ergonomics of human-system interaction, preparations for instruction for use, robotics, and 3D printing. All of these will have to be considered when designing and building an exoskeleton. ISO 12100:2010 specifies procedures for general design of machinery including identifying hazards and estimating and evaluating risks during relevant phases of the machine life cycle. Lastly, ISO 14971 specifies principles for risk management of medical devices and is applicable to all phases of the life cycle of a medical device. Since the exoskeleton is intended to treat paraplegia it falls under the purview of medical devices as defined by the FDA and therefore must follow ISO 14971.

## Broader Impacts

The mechanical engineering code of ethics encourages us to use our knowledge and skill for the enhancement of human welfare. Our exoskeleton not only assists paraplegics with everyday living but can have an enormous impact on their mental well-being and feelings of self-worth. The many impacts of this type of device are outlined below.

The use of an exoskeleton would not necessarily affect the economy of everyday living. While the original purchase of the exoskeleton would be a significant cost without the help of insurance, there could also be economic benefits with the increased mobility an exoskeleton brings. For example, this might open up more job opportunities for people with mobility limitations. However, this would not be true for all users so the economic impact would vary from person to person.

The environmental impact of running our exoskeleton would be mostly negligible as it is not meant to be used outdoors and would only use electricity to charge the batteries. As for the battery itself, it would be the main source of environmental impact since it is made out of lithium. Mining lithium requires a lot of water and can also lead to contamination of the water supply, soil, and air (1). Also, it is important to note that lithium batteries are not frequently recycled as manufacturers are often secretive about what they put in them, which makes it harder to do properly. Consequently, once lithium batteries reach the end of their life span they are disposed of in landfills, exposing the environment to the chemicals (46).

On the societal level, the production of exoskeletons can bring a strong positive influence. The interactions and connections between people with paraplegia and those around them can sometimes be affected by their condition/injury, and exoskeletons can be a great way to stop this. They [exoskeletons] allow injured/disabled people to get more mobility when going about their daily lives (47).

This exoskeleton is much cheaper than anything else on the market making it a very competitive product. Assuming our exoskeleton is FDA approved and the shortcomings with the battery and other features are addressed, we would expect to sell much more than our competitors. Our price point would be significantly more accessible for both individuals and hospitals. Also, insurance companies would most likely be more open to covering this cost, as it would be closer to other assistive devices which they already cover.

# Discussion

Overall, we made a large amount of progress with this project. We successfully assembled all of the mechanical components and completed the full structure of the exoskeleton. We ran out of time to fully execute the electronics, but we were able to reach some important milestones, which are discussed below.

As stated previously, even though not all of the motors were able to move at once we still met all six of our original objectives. Our team was primarily focused on creating a mechanically sound frame design, which was a success. The frame was capable of supporting the weight of the test participant in the sitting, sit-to-stand, walking, and stand-to-sit positions and motions, and our gearboxes worked smoothly and effectively. Some of the parts that could be improved were the 3D printed parts, which could benefit from additional reinforcement, as well as more time to ensure high quality prints. Some of the areas where the 3D prints were bolted had imperfections from the printing process which led to some cracking during testing. Additionally, more design considerations could be made for the straps to properly suspend the test participant. Ours were mostly effective but could be improved for long term comfort and better pelvic support to prevent slouching or slipping.

The electrical design of the sensors and controllers in our system was very solid, but we had some issues with our power delivery systems and execution of that design. When we did our bench testing of each component, each was individually successful and worked as intended. The safety features functioned as we designed and were able to successfully send a signal to trigger a system shutdown. However, our electrical team did not have much experience with designing power delivery systems and properly assessing the power requirements of an entire system, and this led to some problems executing on our design. Our power supply and battery were adequate for powering one controller and motor in the system but were not able to power multiple at the same time. Budget and market availability of parts also played a large part in this issue. Sourcing power supplies and battery systems that are capable of outputting 48 volts at 40 amps while having a large capacity to sustain such a high-power system are expensive and heavy, and our limited budget made many of those options unobtainable. Getting the Maxon motors to work with the combination of the less expensive motor controllers and Arduino control rather than the Maxon controllers enabled us to fit a lot more into our very limited budget. Compared to competitors, it is not yet up to their standards, but the project was a successful first step.

We have several recommendations for those who may try to take the next steps of this project going forward. First and foremost, more focus on the electronics will be necessary for a successful exoskeleton. The budget for the battery was too small and would need to be much more thoroughly researched and a more robust design would need to be created. This should be done by an ECE major with a solid background in power systems, ideally. There should also be a larger focus on the controls and programming aspect. We had limited time to execute and test our code that was based on the motion capture data, but with more time spent in the motion capture lab analyzing the movements of different people walking could create a smoother gait profile, and more refined code could allow the exoskeleton to walk more smoothly and execute the movements better. Additionally, motors could be added to power the ankles which would also aid in better performance. Modifying the leg sections to make the exoskeleton adjustable would also be much better for flexibility in testing and application, because our current design needs to be altered before machining to fit the user. This would make it easier to market and also allow for more rigorous testing with different participants. Furthermore, many existing exoskeletons lack a feature that allows the person to use the bathroom, which is something that many patients require. Taking off and re-equipping the exoskeleton can add complexity and extra time to this task and making this more accessible for the user would be a very important feature. Finally, adding more turning assistance would be a great feature. Our plan currently relies heavily on the user to turn themselves with crutches but developing a system where the exoskeleton does more work through this process would be a huge help for the user.

# Conclusion

Our exoskeleton is a first step in our goal to create an affordable lower limb exoskeleton for home use. Since this was the first year of the development, we have several suggestions for future work. The first recommendation for future teams is to increase the battery capacity so that all four motors could run at the same time. This means that we would need 40A of current that would be split between each of the four motors. The next suggestion is to add motors at the ankles for more precise control over ankle movements. While the solution that we found was effective, the ideal option would still be to add motors at the ankles. This would provide a smoother walking experience for the person. We would also suggest providing turning assistance. Currently, the right leg is raised so that the user can turn left and the left leg is raised so that the user can turn right. We would like to add some type of assistance to swivel the hips so that the exoskeleton can actually turn for the user. Furthermore, we would like to add a flexible sizing option so that the exoskeleton would not have to be custom made for each individual. Instead, the long pieces on the thighs and calves would be adjustable with different slots for people of different heights. After our interviews with physical therapists, we decided we would also like to add a bathroom feature so that the user can conveniently use the restroom. Lastly, we would want to add extra ventilation for the electronics. There were no issues with the current ventilation, but as we add more battery capacity we also would be adding more possible issues with overheating so it would be good practice to add more ventilation in the electronics box.

In conclusion, this project was a successful first step towards an affordable exoskeleton. There are still many areas which can be improved by future teams, but we are happy with the progress that we made.

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