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REDESIGN OF ROBOTIC WALKING TRAINING DEVICE TO INVOLVE ZERO GRAVITY CAPABILITIES AND DAILY ACTIVITIES

Chad Ballard

University of Texas at Tyler

REDESIGN OF ROBOTIC WALKING TRAINING DEVICE TO INVOLVE ZERO GRAVITY CAPABILITIES AND DAILY ACTIVITIES

CHAD BALLARD

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CHUNG HYUN GOH, Ph.D., Committee Chair

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This is to certify that the

Master's Thesis of CHAD

BALLARD

has been approved for the thesis
requirement on 04-15-2024
for the Master of Science in Mechanical Engineering degree

Approvals:

DocuSigned by:
3545965553AB4C6...

Thesis Chair: CHUNG HYUN GOH, Ph.D.

DocuSigned by:
1241B86CF855466...

Member: MUATH SALIM, Ph.D.

DocuSigned by:
3A3F3DF38EA844C...

Member: ALWATHIQBELLAH IBRAHIM, Ph.D.

DocuSigned by:
6DE4EEB6CD094A6...

Member: WOOHYOUNG JEON, Ph.D.

DocuSigned by:
30D27AF79E60404...

Chair, Department of Mechanical Engineering

DocuSigned by:
FD302E384F154FA...

Associate Dean, College of Engineering

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Abstract

REDESIGN OF ROBOTIC WALKING TRAINING DEVICE TO INVOLVE ZERO GRAVITY CAPABILITIES AND DAILY ACTIVITIES

Chad Ballard

Thesis Chair: Chung Hyun Goh, Ph.D.

The University of Texas at Tyler

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Many patients struggle with disabilities that hinder their ability to walk. This project aimed to create a leg assembly capable of variable gravity so that it could be combined with a Robotic Walking Training Device, and lead to better rehabilitation options for patients. This was accomplished by deriving equations of joint torque, creating circuit diagrams for Arduino systems, modeling leg assemblies in CAD, and finally combining it to create a working small-scale prototype. The result of the prototype testing showed accurate movement on each joint, especially the ankle and knee segments, to create virtual zero gravity. In addition to this, a walkway module with varying pathway disturbances such as slipping and tripping modules was created, so that gait motion could be tested, and the data used to further the research for the leg assembly models.

Keywords: Leg Assembly, Zero Gravity, Variable Gravity, Daily Activities, Walkway Platform[2]

Chapter 1

Introduction

1.1 Introduction

Ever since we learned how to walk, most of us take it for granted. Yet, movement of the legs is one of the most important movements we do, not only because it is how we get from one place to another, but also because it is how we perform many different tasks, such as standing up, leaning down, and our entire balance is rooted in our leg and hip position. While modern medicine has improved greatly over time and cured a great many diseases, therefore improving patient lifespan, this has also opened the door for more patients with disabilities. With these disabilities, comes limitations to patients range of motion, and their ability to walk as a whole, and while methods for treatment do exist, a better approach is needed; not just in the rehabilitation method itself, but also in a way to test patients' gait, so that their rehabilitation can be tailored specifically to them. This project is aimed at creating a better method of rehabilitation for these patients, by implementing a robotic solution to achieve variable gravity, as well as creating a method to test patients' responses to gait disturbances.

Now, a new design would mean little if rehabilitation had not been shown to work, but existing rehabilitation methods have already been created and used for decades. Studies have shown that rehabilitation can be effective by reducing the force exerted on the legs, which allows the patient to recover in two ways. First, it allows them to slowly apply more pressure to the legs themselves, therefore training them as they would a muscle during an exercise, allowing them to grow stronger with the eventually goal of not needed the assistance. Secondly, it allows them to train the path of their legs once again, relearning one of the most fundamental movements we learn as children; the ability to stand up and walk. Both of these combine to make an effective rehabilitation program, and there are many current programs that utilize this tactic, from simple water assisted movement to Zero Gravity Treadmills designed by NASA [2]. Yet, water assistance requires the patient to have ready access to a pool in addition to a care worker to assist them, and the Zero Gravity Treadmills of NASA are expensive, difficult to operate, and designed more for astronauts than recovering patients. All this leads to a need to improve the techniques used for rehabilitation, to create a device that allows for variable gravity without the assistance of water, with a simple interface that a patient can utilize themselves, as well as the freedom to actually be able to move around in the space of their own home, which is something that neither the water rehabilitation or Zero Gravity Treadmill can achieve.

This solution is a variable gravity leg assembly, called the Robotic Walking Training Device (RWTD). A previous model was created at the University of Texas at Tyler to assist with gait rehabilitation, but now that project is being redesigned with a focus on creating variable gravity for both normal walking motion, and sit to stand motion. In this research, a literature review will be conducted into the history of rehabilitation and the viability for zero gravity leg assemblies. Then, the broader impacts and objectives of the project will be covered, followed by a full exploration of the methodology and design process. Finally, preliminary results will be showcased, and future work will be discussed.

Regarding the method of gathering data on patients' gait, it could simply be done by implementing motion cameras in a room and having patients walk normally. Yet, as all of us know, the roads in life are not always paved without obstacles, and so it is necessary to create a system that allows data to be gathered based on the patient's responses to said obstacles, so that a robotic system could then be tested more effectively. This will be done by creating walkway modules to test patients' reactions to several disturbances, namely surface drop, slipping, and tripping. Computer Aided Design (CAD), models are being created for these modules, and then full-scale modules will be built and placed in a motion capture environment.

All this leads to a working zero gravity system that could later be applied to a full-scale model, that would help patients suffering from disabilities be able to receive better rehabilitation, in addition to a working full scale walkway platform that can be used to test patients' responses to gait perturbations. This would also help close the gap in research, providing a path for more rehabilitation options utilizing zero gravity concepts to be created beyond just this design, but will hopefully one day lead to giving everyone the ability to walk easily, disabilities or not.

In this report, first the significance of the project will be looked at, along with its broader impacts, both of which can be found in Chapter 2. Then, a literature review will be conducted in Chapter 3, both for the Leg Assembly and the Walkway Platform, which can be found in sections 3.1 and 3.2 respectively. Then, Chapter 4 will cover the methodology and design for the Variable Gravity Concept, the Sit to Stand Concept, the adjustable size concept, as well as the walkway creation, which will be covered in sections 4.2, 4.3, 4.4, and 4.5 respectively. From there, Chapter 5 will cover the results, detailing both virtual results and experimental results gathered from small scale prototypes. Finally, Chapter 6 will summarize the findings and provide and insight into possible future works.

1.2. Significance

1.2.1 Problem Statement

This project is aimed at looking into a robotic solution that allows for rehabilitation within a patient's own home, without the cost of an expensive setup. This would allow limb rehabilitation to become more widely used with little inconvenience to the patient. Furthermore, this project aims to incorporate variable gravity, something water therapy cannot do, to allow patients to increase the gravity alongside their healing process, to further aid in rehab. Finally, a walkway platform will also be created in order to further the gathering of information related to gait training and walking impediments. If this was not achieved, then just as the patient's ability to walk is impaired, the research into their rehabilitation would also remain static.

1.2.2 Broader Impacts

The goal of this project is not to create a new method of rehabilitation entirely, but rather reshape the existing methods with a new design that is more accessible to patients. This is where the significance of this project can truly be seen.

Firstly, this project is novel due to it filling the gap in research regarding robotic rehabilitation. While many robotic systems have already been made with the purpose of lifting things, or even rehabilitation, such as those mentioned in the literature review conducted in Chapter 2, for the most part zero gravity concepts have been limited to the upper body, or to robotic arms meant for factory implementation. This leaves an opportunity to create a zero-gravity system for the lower body, that simplifies some of the methods presented in the Anhui Polytechnic University's study [17]. Specifically, this zero-gravity concept will be attached to a movable module, that will increase its degrees of freedom when it comes to motion. In addition, it will be fully robotic based – meaning no springs – and will simplify the design down to only a single motor at each joint, which will reduce cost. This, combined with Arduino programming, will create a simple yet novel design that provides a solution to gravity rehabilitation in the lower limbs, which is a field of research that is currently lacking.

Furthermore, it is the devices application to daily activities that makes in novel from an innovation standpoint. While other devices are intended to be used in specific conditions, such as Aqua-therapy being limited to pools, this device will allow for the training and rehabilitation of everyday movements, such as the sit to stand motion. This will be done in two ways: firstly, by creating the free moving zero gravity in order for patients to stand up with their own gait path, and secondly to create a designated movement set for the sit to stand motion which would help train disabled patients who are unable to achieve the correct gait path.

Beyond that, it could have an impact on the area of rehabilitation exoskeletons. Currently many services are already being streamlined to be accessible to one's home, such as entertainment, shopping, etc. How much more will a patient who is unable to walk prefer to receive rehabilitation at home, if it becomes an option? That is the point of this analogy; if this project is successful and it allows patients to receive treatment in their own home, for an inexpensive price, it could potentially dominate the rehabilitation market, therefore increasing the number of patients able and willing to receive treatment.

In addition, this project has ramifications for the robotic industry as a whole. While the focus is regarding implementing zero gravity in order to aid in rehabilitation, it could also be easily modified to create a strength training program for able bodied individuals, by simply increasing the gravity factor above the standard gravity value of earth. This would allow opportunities for astronauts to potentially utilize this device in space to replicate earth's gravity, or allow for exercise program to use this to artificially increase gravity to improve strength, similar to how bands or parachutes are used to increase the resistance of sprinters training for marathons or competitions. Similarly, it could be utilized as a safety precaution for certain activities, such as a locking mechanism for lifters.

Yet, for all its other applications, the most important application could prove to be the research that it leads to. By creating a portable, working robotic rehabilitation device, it could pave the way for more research to be done regarding ways to improve patient's recovery without needing access to pools or complex treadmills, which in turn will create more and better recovery options for the patients, which is the end goal of this project; improving the recovery of as many patients as possible.

This is furthered by the potential impacts of incorporating the walkway modules as well. While studies have been being done that utilized walkway platforms for gait analysis for decades now, only in more recent history has motion capture technology advanced to the level that specific gait analysis can be more accurately conducted. Even more so is the rarity of these walkway platforms being tested alongside a robotic leg assembly, and so this project will open the door for more studies of its kind to be done, bringing the engineering side and the kinesiology side together to provide a path for better, more comprehensive rehabilitation in the years to come.

1.3 Objectives

Now that the project has been introduced, its time to look at the specific objectives this project achieved. This project has three base objectives: create and test a leg assembly system capable of achieving zero gravity, create and test a leg assembly system capable of performing daily activities, and create a walkway platform that can be used to gather data on gait training and patient's movements.

These objectives are detailed below.

1. The first objective is to create a variable gravity concept design, in relation to the motion of walking. This objective's tasks include creating a new CAD Model of the leg assembly

so that it can be used as the basis for the Arduino System and the Simulink Integration. This will involve creating a leg assembly that allows for rotation at the hip, knee, and ankle joint, while also having a piece that will connect it to the larger machine used for stability and sit to stand motion. This assembly needed to be designed in such a way that the pieces could be 3D printed, should a prototype need to be created. Once the CAD Modeling was achieved, the variable gravity concept itself needed to be created. This will involve creating zero gravity equations based on kinematics and biomechanics. Once the equations were created, the next stage can be accomplished, which is using those equations in a programmed Arduino code, in order to control the torque of motors to achieve Zero Gravity. This was be done with the intention of basing the motors torque on the patient's own movement, so that they have free range of motion in order to recover. Once this was done, the Arduino system was then be modified so that it allows for the gravity to be adjusted based on an input, so that it can go from 0% gravity to 200% gravity, allowing patients the opportunity to scale the gravity alongside their recovery process. This will result in working variable gravity concept. Finally, the system needed to be modified to incorporate differing heights and weights of patients into the same system. This design process can be seen in Chapter 3, subsection 3.1.

2. The second objective is to create a concept that allows for variable gravity in daily activities, such as the sit-to-stand motion, which was be the primary focus at this time. This objective necessitates the modification of the CAD Model for the base machine, such that it allows for the leg assembly attachment pieces to move up and down, that way the patients can actually stand up by planting their feet on the ground, which will create a better, more realistic movement than artificially altering gravity to mimic the sit to stand motion while

in the air. Once this CAD model was modified, an Arduino System was again created, this time programmed to allow motors to spin with variable torque to assist in the sit to stand movement. This resulted in a working Sit to Stand assembly concept, and the design process can be seen in the Sit to Stand Concept section within Chapter 3, subsection 3.2

3. The third objective of this project is to create the walkway platform in order to test patients balancing capabilities, to gather mocap data. This involved the CAD Modeling of the platform, as well as the creation of each module. This includes 3 normal modules, 1 tripping module, 1 sliding module, and 1 surface drop module, in addition to decoys if needed. They were be built using wood and coated with aluminum. This resulted in a created platform that can then be placed inside the mocap space already created, so it can be used for testing. This design process can be seen in Chapter 3, subsection 3.4[3]

Chapter 2

Literature Review

2.1 Review of Existing Robotic Leg Assemblies

As mentioned previously, many patients struggle with achieving the leg motion which is paramount in walking. Part of this comes from motor defects, meaning it is not so much that their legs do not work, or got injured, but instead the rest of their body struggles to send signals to the legs, which in turn makes movement very difficult, and in some cases impossible. An example of this can be seen with something like a spinal injury; the legs themselves were not harmed in any way, and yet the injury to the spine severs the connection between the brain and the legs, meaning they cannot be moved unless externally, rendering the patient paralyzed. Now, while a severe spinal injury cannot be solved by simple rehabilitation, there are many other motor defects in which rehabilitation has shown to help, such as Cerebral Palsy, Multiple Sclerosis, etc. [7-11].

Yet, there is also another aspect to this area of disabilities, and that is when the issue is not from a motor defect, but an injury to the legs themselves. For instance, and ACL tear can render an athlete unable to play for almost a year, and required many weeks if not months of putting no weight on the injured leg. This injury is so severe and has such a rough recovery process that the NFL is actually considering changing the turf fields to real grass, a move that will likely upwards of ten million dollars. Of course, even if the athletes do recover, studies like the one conducted by Roos et al. have shown patients who suffer an ACL tear are more likely to develop Osteoarthritis later down the road [15]. However, this type of injury is not exclusive to athletes, far from it. Anything from as simple as a sprained ankle or as tragic as a car crash can cause someone to suffer an injury that impairs their ability to use their legs in a meaningful way when it comes to walking or even standing up. However, this is where rehabilitation has proven to be more effective. So, now that the potential medical causes for disabilities have been looked into, it is time to look into potential solutions.

As with most research topics, this is not the first attempt made to find a solution to the problem at hand. Many other solutions have been researched and tested with the goal of improving rehabilitation of patients struggling with disabilities with regard to their leg movement. However, this does not affect the significance of this project, rather it actually enhances it, because since these other methods have already been implemented and tested, there is already concrete proof that these concepts of reduced loading on the legs do improve the rehabilitation of patients.

For instance, Hydrotherapy is a very widely used method to treat patients who need rehabilitation. It is estimated that 88 percent of all Physical Therapy Clinics in the US offer Hydrotherapy as part of their programs, showcasing its importance. Furthermore, it is estimated that 32 million American's have sued some form of Hydrotherapy [1]. This does not mean that all 32 million use it specifically for leg disabilities, but this showcases just how widely used this therapy method has become. According to Texas Health & Resources, the more common ailments it is used to treat are as follows: spine surgery, total joint replacement, knee and hip surgeries, back pain, neurological disorders like Parkinson's, fibromyalgia (arthritis), and even pregnancy related pain [3]. Regarding the process itself, it involves partially submerging a patient into water and having them move their limbs. The buoyancy then creates a lower gravity state, which helps with rehabilitation.

Another more recent method being researched is the Zero Gravity Treadmill that NASA has created [2]. While the purpose for its design was related to astronaut training, studies have been conducted to see if the concept would work for rehabilitation as well. It works in a similar way to that of the Hydrotherapy, by placing the user in a state of zero gravity via a harness, which allows for the limbs to move freely with reduced pressure. However, this setup is expensive, and not widely available. Yet, both of these methods showcase that reduced gravity therapy is possible and helpful for rehabilitation.

Regarding the robotics aspect of this project, motorized limbs are something that has been worked on many times. One such example is the Berkeley Lower Extremity Exoskeleton (BLEEX), which was the first lower body exoskeleton designed to carry external loads [17]. Other designs have been made since, such as the ATLAS 2020, which was designed specifically for gait training and sit to stand movement [42]. Other designs have more closely resembled the Zero Gravity Treadmill from NASA, such as the LOPES II [23]. Some have even utilized electromyography to predict how the patient is intending to move, such as the HAL 5 Type C [28-29].

For this project, many of the designs utilized in those machines will be considered, but the primary machine this project will be based upon is the Robotic Walking Training Device (RWTD), which was designed at the University of Texas at Tyler. This can be seen in the figure below.

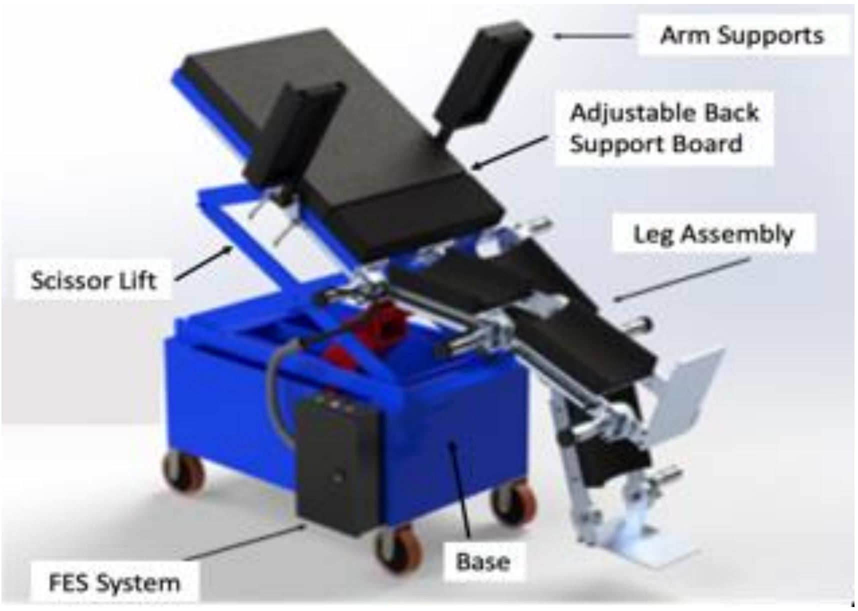

Figure 1. Robotic Walking Training Device.

This machine is a self-supporting robot that patients can be strapped into, designed to treat spinal injuries, MS, and other neurological complications. This controller for this system is a control pad combined with a joystick, and it allows for a wide range of motion. This early design was intended to help replicate gait motions based on mocap data. A redesign is currently being worked on to improve the leg assembly so that it can closely replicate actual gait path trajectory. Whereas this project will focus on creating zero gravity and sit to stand concept for free range of motion.

The CAD Modeling for the RWTD can be seen below.

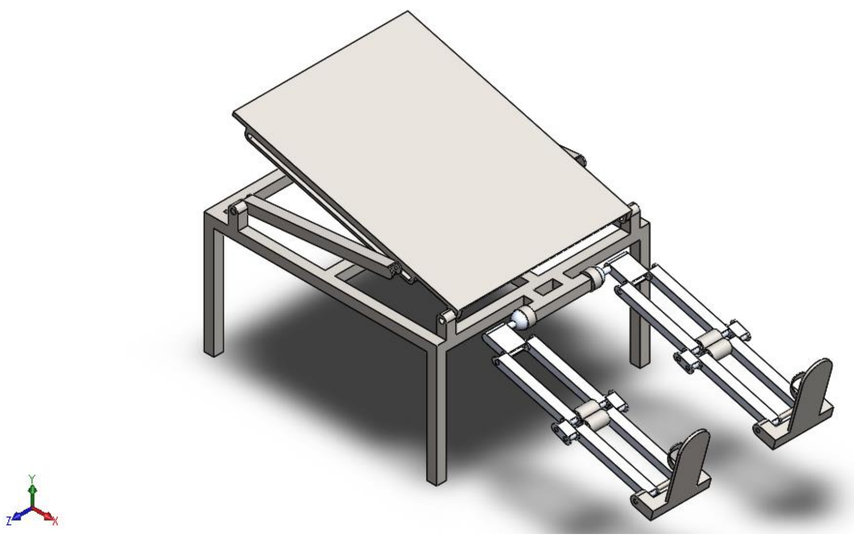

Figure 2. RWTD CAD Model.

In addition, another study is being conducted at UT Tyler with regard to patient balancing. This project is aimed at creating a walkway platform that has several different path disturbances, such as a surface drop, a slipping block, and a tripping block. This platform will be surrounded by a harness for patient safety, as well as mocap camera's that will measure the path trajectory of the subject as they step on the different disturbance modules. That project will be related to this project via the walkway module creation, along with the mocap data gathered.

Finally, one last topic of research was considered, and that was the topic of machines specifically related to zero gravity leg assemblies. For this topic, a smaller portion of research could be found, such as machine designed by the Anhui Polytechnic University's Mechanical Engineering Department [56]. This study delves into the design and equations of a gravity balance machine for a leg assembly, with a robotic design in the seated position. In their design, springs are also utilized to help achieve zero gravity. However, this design is fairly restrictive with regards to the movement of the patient, and would significantly hinder the ability to perform daily activities. In addition, while many studies exist with regard to variable gravity in the upper body, no other significant studies could be found for the lower body. This proves there is a gap in research related to creating a variable gravity system for the lower limbs, especially one that is fully robotic based with a wide range of motion, which is where this project will come it. This project will aim to fill that gap in research, by creating a novel variable gravity machine, which will be detailed further in the Broader Impacts section.

2.2 Review of Existing Walkway Platforms

Similarly to the robotics side, many studies have previously been done to measure patients gait using walkway platforms, or other devices. In general, these tests include incorporating some form of unique walking situation – such as a walkway platform – and then incorporating differing methods of measuring the patients' responses while walking.

The most common method used to measure the patients' responses is that of a force plate, which can be seen in the study performed by Hynd, Hughes, and Ewins, published in the Journal of Engineering in Medicine [56]. This method places the force plate within or along the walkway itself, allowing the force of the patient's steps to be recorded so that they can be compared to one another. This particular study was tamer than others, simply seeking to record data, not hinder the patients attempts to walk in any significant way. This approach was also used in other studies, such as one published in The Foot, which performed a study on a small group of patients to determine how a simple walkway platform itself with no disturbances changes one's gait motion [57]. Their study found that while no significant differences occurred in the planar pressure parameters of patients using the walkway versus not using the walkway, there were differences found with regarding to the choice of the foot placement itself.

Other studies focused more heavily on disturbing the patient's ability to walk, such as the one published by IEEE which tested older patients at increased risk for falling down, and subjected them to a walkway platform with varying movements in order to perform gait analysis [58]. This study consisted of a broader range of testing equipment, not limited to just the force plate but instead including body worn kinematic sensors, cameras, and a pressure sensitive platform as well. The patients were divided into categories of "fallers" vs "non-fallers" and data was gathered, finding that spatial parameters were largely the same between the two categories, but temporal parameters did differ slightly.

Finally, a more comprehensive approach to implementing walking projects for gait analysis was published by the University of Surrey in 1993, which went into the detail in the manufacturing and eventual testing of several different walkway sections, in order to gather information on gait relating to patients that suffered from specific ailments, such as Cerebral Palsy, Sclerosis, Muscular Dystrophy, Amputees, Arthrosis, and many others [59].

Yet none of these implemented the walkway module in combination with a robotic assembly to both test for gait initiation problems with and without a leg assembly attached for support, and this project aims to create the groundwork for one such study, which will be further detailed in the next section.[4]

Chapter 3

Materials and Methods

Walking is not as simple a task as most assume, and therefore if the goal is to improve the recovery of patients, then multiple objectives must be completed. Some of these objectives are subsections of the same primary objective, whereas others are regarding different systems controls, such as walking versus sit to stand motion. However, the primary goal of this project is this: create a working zero gravity concept and sit to stand concept for a Leg Assembly to be attached to the RWTD, to improve the rehabilitation of patients, as well as creating an actual full scale walkway platform so that gait analysis can be performed.

3.1 Variable Gravity Methodology & Design

As stated above, this project can be viewed as having two primary objectives when it comes to the machine's movement itself: to allow for zero gravity when walking, and to allow for assistance with sit to stand motion. First, we will look into the creation of the variable gravity concept, starting with the deriving of the joint equations, and then moving onto CAD Model creation and Circuit Diagrams. Next, prototype creations will be discussed.

3.1.1 Joint Equation Derivation

In order to achieve zero gravity from a robotic standpoint, motors must be utilized to counteract the torque presented by gravity. This cannot be done without first defining the equations that the leg assembly will be controlled by. These equations need to account for the moments on all three joints of the leg assembly, regardless of their angular positions, and be able to be solved for the torque necessary to keep it in equilibrium.

So, for this project, the leg will be treated as a rigid body composed of three sections, the thigh, the lower leg, and the foot. These three rigid bodies will be attached via the hip joint, the knee joint, and the ankle joint. They will be treated as an evenly distributed mass, and equations will be found for the torque at every joint.

For the Hip Joint, the equation is as follows.

$$T_1 = \int_0^{L_1} \left(\frac{m_1}{L_1}\right) * g * r_{1c} * \cos(\theta_1) * dr - \int_0^{L_2} \left(\frac{m_2}{L_2}\right) * g * r_{2c} * \cos(\theta_2) * dr - \int_0^{L_3} \left(\frac{m_3}{L_3}\right) * g * r_{3c} * \cos(\theta_3) * dr \quad (1)$$

For the knee joint, the equation is as follows.

$$T_2 = \int_0^{L_2} \left(\frac{m_2}{L_2}\right) * g * r_{2c} * \cos(\theta_2) * dr - \int_0^{L_3} \left(\frac{m_3}{L_3}\right) * g * r_{3c} * \cos(\theta_3) * dr \quad (2)$$

For the ankle joint, the equation is as follows.

$$T_3 = \int_0^{L_3} \left(\frac{m_3}{L_3}\right) * g * r_{3c} * \cos(\theta_3) * dr \quad (3)$$

Where T denotes Torque, m denotes the mass of each section, L denotes the length of each section, g denotes gravity, r denotes the distance to the center of mass for each section, and theta denotes the angle at each joint.

Now, for these equations, the variable that will be inputted from the system will be the angle. All other variables will remain constant. This is because the leg assembly is designed such that the lengths of the legs do not change, and the weight of the user can either be generally assumed or input by hand prior to the patient’s use of the machine. Whereas the angle of the joints will change throughout the process itself, therefore changing the torque. It is for this reason accelerometers will be used to measure the angle, but that will be delved into later.

After deriving the equations, the next step is to calculate the values for the constants. Based on the previous designs for the leg assembly, Length 1 – the section from the hip to the knee – can be estimated at 18 inches, Length 2 – the section from the knee to the ankle – at 18 inches and Length 3 – the section from the ankle to the ground – at 6 inches. However, it is when it comes to weight that things get more complex.

For the mass of body parts, an equation must be used.

$$m_s = P * m_r \tag{4}$$

Now, P represents a parameter, and it can be calculated from either the Dempster or Clauser tables, an example of which can be seen below.

	D-Parameters	SEGMENTAL MASS/TOTAL MASS
Segment	Endpoints[a] (proximal to distal)	(P)[b]
Hand	Wrist center to knuckle II of third finger	0.0060
Forearm	Elbow to wrist center	0.0160
Upper arm	Glenohumeral joint to elbow center	0.0280
Forearm and hand	Elbow to wrist center	0.0220
Upper extremity	Glenohumeral joint to wrist center	0.0500
Foot	Ankle to ball of foot	0.0145
Leg	Knee to ankle center	0.0465
Thigh	Hip to knee center	0.1000
Lower extremity	Hip to ankle center	0.1610
Head	C7-T1 to ear canal	0.0810
Shoulder	Sternoclavicular joint to glenohumeral joint center	0.0158
Thorax	C7-T1 to T12-L1	0.2160
Abdomen	T12-L1 to L4-L5	0.1390
Pelvis	L4-L5 to trochanter	0.1420
Thorax and abdomen	C7-T1 to L4-L5	0.3550
Abdomen and pelvis	T12-L1 to greater trochanter	0.2810
Trunk	Greater trochanter to glenohumeral joint	0.4970
Head, arms, and trunk	Greater trochanter to glenohumeral joint	0.6780
Head, arms, and trunk	Greater trochanter to mid-rib	0.6780

Figure 3. D – Parameters.

Now, for this project, Dempster was be used [61]. In addition, according to the US Census, research has shown that the average weight of Americans over the past few years has remained around 180 pounds. So, using this, the equations to find the mass of each section can be seen below.

Thigh: $m_s = 0.1000 * 180 = 18\ lb$

Lower Leg: $m_s = 0.0465 * 180 = 8.37\ lb$

Foot: $m_s = 0.0145 * 180 = 2.61\ lb$

Now that the constants have been calculated, and the angle decided to be input, the equations can be applied to the Arduino system. However, before a system can be designed, first a CAD Model must be created so that the Arduino system will have something to control, and also so that eventually a prototype would be created based upon it.

3.1.2 CAD Model Creation

Now, for the CAD Modeling, Inventor software was used. As stated previously, the goal for this Leg Assembly was to make a design that would allow for motorized control of all three joints, while also allowing it to attach to the assembly to be connected to the larger base design that will assist in the balancing and sit to stand motion. This requires a design of multiple connected components, attached to a separate attachment plate. At this stage the design was not intended to be used practically, hence why no opening were made to the leg braces to allow a patients leg to be placed inside, but a practical design will be showcased later.

Below the created CAD Model can be seen.

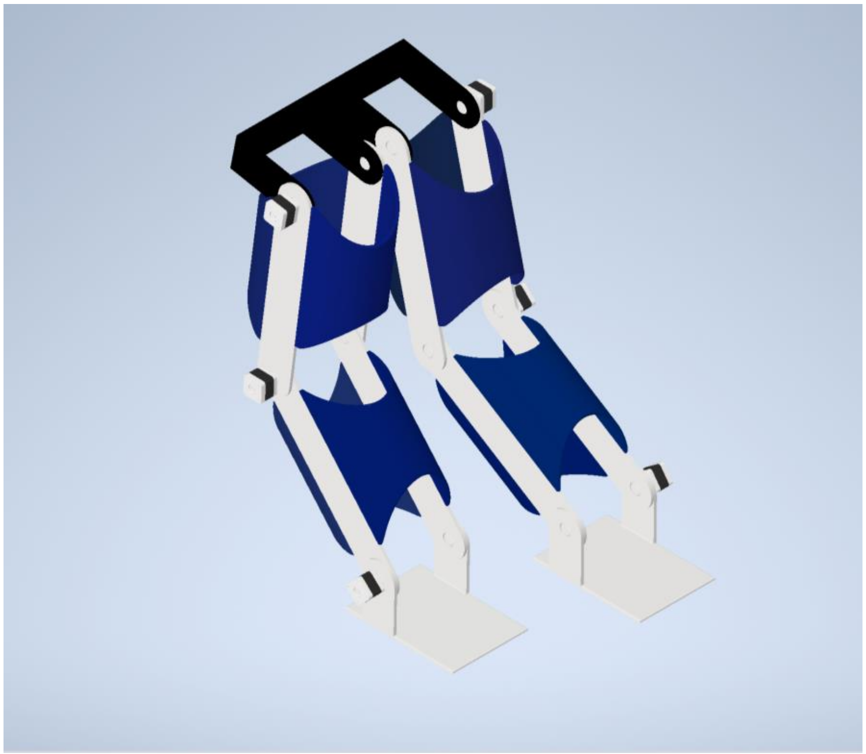

Figure 4. Leg Assembly.

This assembly is constructed of multiple parts joined together to be able to carry an average sized leg within. Starting from the top, the plate shaded black is the plate that will attach the leg assembly to the base machine. Once that the connecting piece was designed, the Leg Assembly itself needed to be created. The first step was creating the rods that would make up the assembly's skeleton, to attach to either side of the leg, and act as the connecting tissue for the motors. This was done using the lengths and widths mentioned earlier, and is shaded grey in the figure above. Next, the thigh and lower leg plates were created to hold the patient's leg in place within the assembly. These were designed with the idea that when eventually 3D printed, they would be able to open up on a hinge joint, and then lock in place once the patient moved their leg inside. They are shaded blue in the above image.

Now, the plate for the lower leg was made with slightly smaller dimensions, as the lower leg itself is smaller than the thigh. However, the dimension change is relatively minor, and the design of the plate remains the exact same.

Once these plates were created, all that was left to design was the foot brace, which would be attached to the assembly at the ankle joint. This brace needed to allow for rotation around the ankle joint so that the motor could artificially adjust the torque. It also required a base plate for the foot to be held by. Given that this device is likely to be used both with and without shoes, this plate will be attached to the foot via a strap, rather than a predesigned latching system.

Next, the DC Motors were modeled so that they could be attached to the model, simulating how the Arduino System would actually control the assembly. The model of a DC Motor can be seen attached to the joints in the above figure.

Finally, pins were designed to attach the various components together. They were simple cylindrical rods of varying length and diameter.

The resulting assembly can be seen in Figure 5 below, at a different position that showcases its mobility, alongside a drawing.

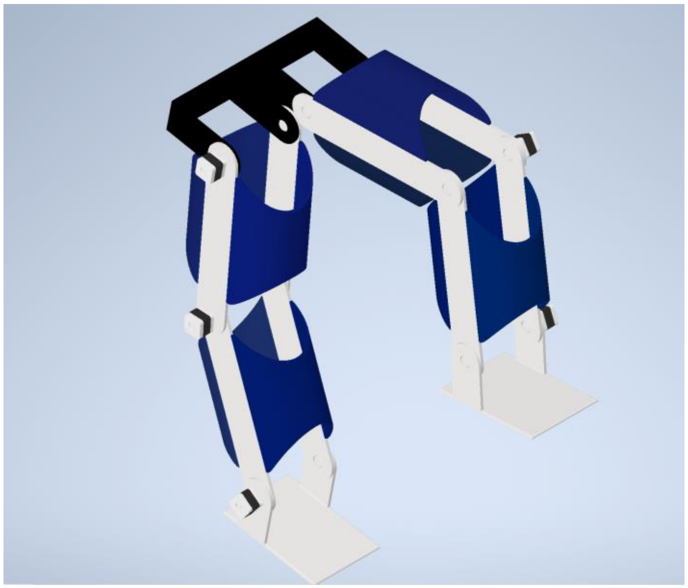

Figure 5. Leg Assembly Variant.

Now that the CAD Model was fully created and assembled, it was time to move onto the Arduino System that would actually control the system, for the robotics are only as good as the software controlling them.

3.1.3 Arduino Circuit Creation – Free Moving

For the Arduino System, the goal was to focus on a single leg, since given symmetry both legs would operate at the same weight, length, etc. Of course, if the patient is only injured in one leg, the gravity compensation of both might be adjusted accordingly, but for the base software they can be assumed to be equal, merely with the motor attached in opposite sides, and therefore spinning in opposite directions.

The first stage in the Arduino System design was to step up a system with three DC Motors, and created the constants and equations to control motors speed based on the weight, length, gravity, and angle of the sections and joints. This was modeled in Tinkercad using DC Motors with encoders and three L2930 Motor Drivers, alongside a 9-volt battery and an Arduino Uno. The first stage of the circuit can be seen below. For this initial design, all the angles were simply inputted as constants, as a test to ensure the motor speed would change depending on the angle position. This test was successful, in that the system ran with no error codes and output the expected data, and so the system operated correctly according to the governing equations mentioned earlier, controlling motor torque to create zero gravity. Once it was verified, the second stage could be started.

The second stage of the Arduino system design was to add three accelerometers. This was done because in the actual system, accelerometers placed at each joint would determine the angle of each joint, and therefore could be used to calculate the moment over the combined distributed loads, and therefore determine the torque. So then, one accelerometer is to be placed at the hip joint, one at the knee joint, and one at the ankle joint. Then the code was adjusted to remove the angles as inputted constants, instead gathering them from the three accelerometers and using the values in the governing equations. Using this setup, first, the accelerometers detect the angle of the joints. Then that angle is fed into the equations, which in turn causes each motor to spin at the necessary speed to create an equilibrium, meaning that if no outside force acted on it rather than the weight of the leg itself, it would remain in place. However, if the patient does move their leg, the new angles will be fed to the motors in real time, and the motors will continue to adjust accordingly, ensuring that no matter how the patient moves, the force of gravity supported by the leg is always zero. This is helpful because it allows the patient to follow their own walking path to retrain their legs, and could actually be used to move freely around their home (depending on the size of the home relative to the larger base machine), given that the motors don't follow a set path, but rather adjust to ensure zero gravity can be achieved at any joint angle or position.

Now that the base objective of creating an Arduino design to achieve zero gravity was complete, a further modification could be added to further refine this design. This modification was done so that the machine would not just be capable of creating zero gravity, but also implementing variable gravity, meaning that the gravity felt by the patient could be adjusted. For example, if originally, they were using it at 100% gravity, they could then adjust the dial to 50% gravity, which would reduce the typical load of gravity by 50%, allowing them to walk with half the effort. This is to ensure that during the rehabilitation process, if the patient were to start to improve, they could increase gravity accordingly, similar to how weightlifters increase the weight they lift as they grow stronger, to further stimulate muscle growth. To achieve this, a potentiometer was added. Then the code was modified such that a gravity scale is created, and depending on the potentiometer's reading, the gravity scale is changed. For instance, when the potentiometers is all the way to the left, the gravity felt by the patient will be zero, when it is in the middle, the gravity felt will be 100% or normal gravity, and when it is all the way to the right, the gravity felt will be 200%. This also includes increments for the middle positions, allowing for a smooth gravity transition with many options.

Once this was achieved, the next step was to incorporate variable length into the system. This needed to be done so that if patients were of different height, the system could adjust to the difference and update the torque values accordingly. At this point the system did allow for this, given the values could be inputted directly into the code itself, but it was necessary to make an easier way for it to be adjusted, so that non-specialist could easily use the system. This was done by adding another potentiometer to the code, and having it control the values for Length 1 and Length 2, which are the values for the length of the hip to knee joint and the knee to ankle joint respectively. Then the values r1c and r2c where set to be half the values of L1 and L2 respectively. This was set on a range from 14 inches to 22 inches for L1, meaning the length of the patient's entire leg could be adjusted from 32 total inches to 46 total inches. This was done assuming the ankle to floor joint was consistent at 4 inches, given it does not vary to the same extent the other values do based on total patient height.

Next, given that is rare that weight does not change at all with varying heights, and so the weight of the patient needed to be adjusted as well. The first step in this was to take the equations derived for calculating the weight of each leg segment and modify them to include the total mass as a variable, which can be seen in the equations below.

$$\text{Thigh: } m_s = 0.1000 * m_{total} = Weight_{hip-knee}$$

$$\text{Lower Leg: } m_s = 0.0465 * m_{total} = Weight_{knee-ankle}$$

$$\text{Foot: } m_s = 0.0145 * m_{total} = Weight_{ankle-floor}$$

These equations were then added to the code in place of the direct inputs that had been used previously. Then a third potentiometer was added, this one coded to control the value of the total mass based on the position of its dial, for a range of 110 pounds to 330 pounds, or 50 to 150 kilograms, which gives a large space on either side of the average weight of 180 pounds.

This final variation of the Arduino Circuit can be seen below in Figure 6.

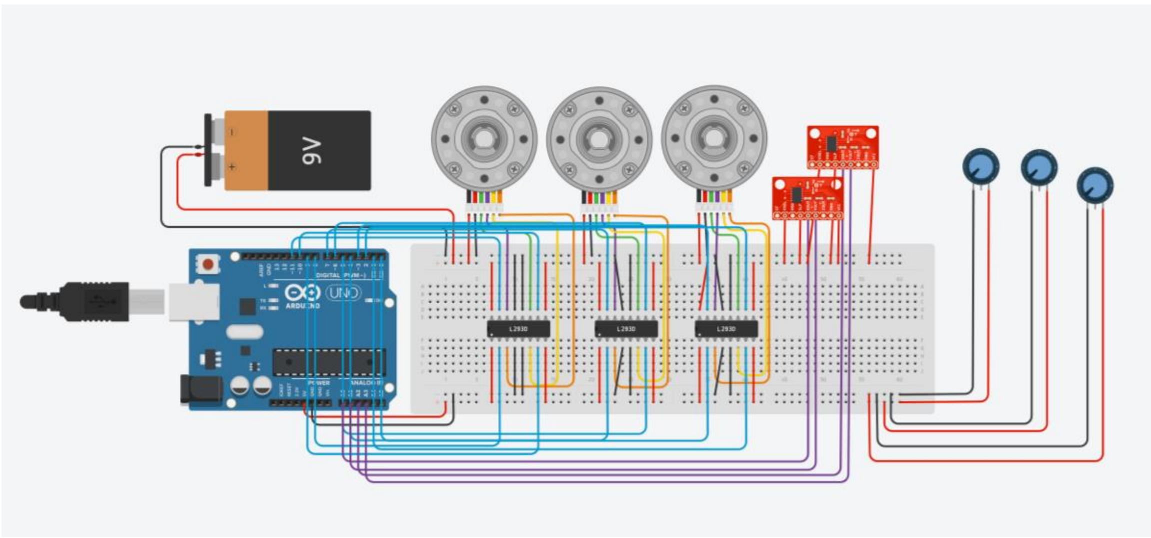

Figure 6. Arduino Circuit Vol 5

Unfortunately, given the limitations of Tinkercad's parts catalog, the only system available is an Uno, which does not have sufficient analog imports to add a potentiometer to the design, given all six are being used by the accelerometers. So, for the above design, the potentiometer's analog wire was left unconnected. However, in practice an Arduino Mega could be used to allow for the additional analog input.

3.1.4 Arduino Circuit Creation – Controlled Movement

For zero gravity to be achieved, this could be done using two methods. The method showcased above was the method of allowing the patient to freely move their joints however they wished, and allowing the system of motors to simply counteract the forces of gravity to allow their joints to stay supported in any position. However, another way to negate the effect of gravity is to have the motors themselves control the motion.

This can be done by utilizing servo motors rather than DC motors, given that servos are designed to remember their relative positions, and coding them to move in a way that mimics the typical movement of a leg.

The first step in achieving this zero-gravity variation was to create an Arduino Circuit consisting of three servo motors, which can be seen below.

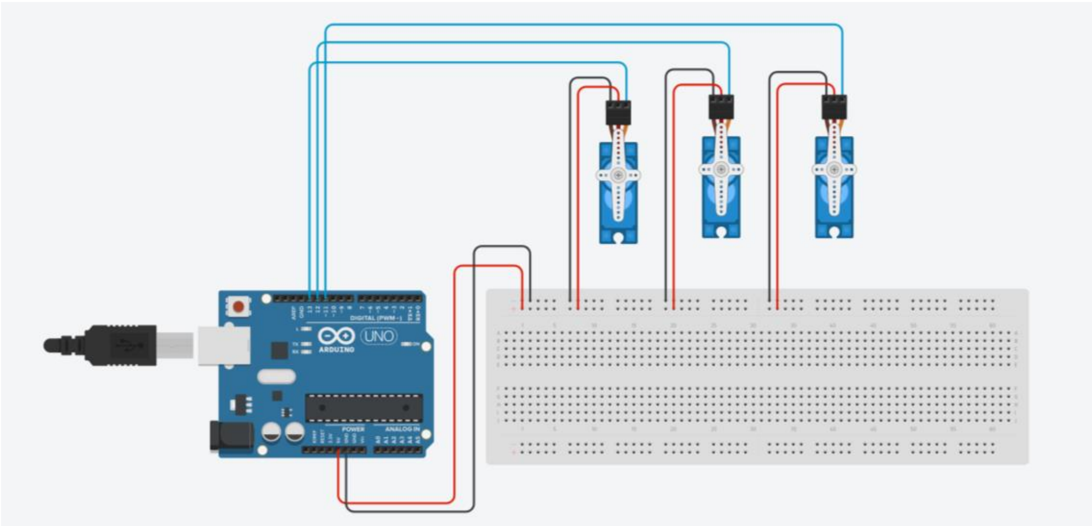

Figure 7. Arduino Circuit – Servo

Once that was achieved, the code could be completed. There are many different ways to code the movement of servo motors, from having it turn in specific angles to recording its own movement and adjusting accordingly. In this project, it was coded such that it would immediately "zero out" as in move all motors to a position that would make the leg straight down, and from there it treated the raising of the knee joint and flexion of the lower leg – knee to ankle segment –

as the first movement, the retracting of the knee and extension of the lower leg as the second motion, and the backwards flexion of the lower leg as the third motion, to create a standard stepping motion. Each motion was broken up into many smaller sub-motions, each with their own delay, so that the movement could be controlled to become either fast or slow.

Similarly to the free moving variable gravity concept, this design can also be adjusted alongside a patient's recovery by simply adjusting the strength of the motors being used. At first a strong servo motor could be utilized to have it compensate for the entire weight of the patient's leg and make the movement on its own, and then as they recover, weaker motors could be used that could only handle a portion of the weight of their leg, and so they would be forced to assist in the motion themselves.

Once the equations were calculated, the CAD Model was completed, and the Arduino system was designed, it was time to import the designs into Simulink.

3.1.5 Importing Model into Simulink

Another aspect of this project was to take the CAD Models created and import them into a Simulink model. This is so that it can be tested in a virtual sense, given that a full-scale prototype cannot be completed at the current time. There are two main tools that can be used for importing CAD Models into Simulink, and the first is the File Solid Block.

The File Solid Block in Simulink allows for stl files to be downloaded and then created within Simulink. Using the File Solid Block, the Leg Assembly created was imported into a Simulink model, and the result can be seen below in Figure 8.

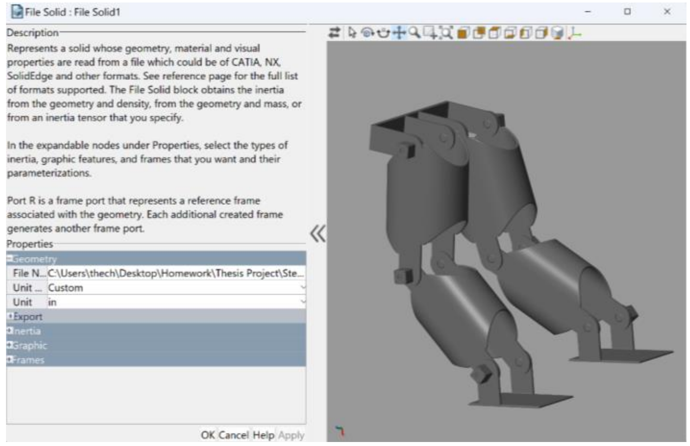

Figure 8. CAD Model in Simulink.

This is a method that works; however, there are several drawbacks. The first drawback is that by using the File Solid Block, the individual joints and sections need to still be modeled and set by hand. Secondly, it cannot connect with an Arduino system in a way that something like a smimport could, given the axis is set based upon the File Solid Block and not the original file, which brings us to the second method.

Rather than using a function such as smimport, instead, a Simulink model of the DC Motors coded to the equation can be seen in Figure 9 below, which when connected to the actual Arduino system rather than constant blocks, would change the Torque of the virtual motors accordingly.

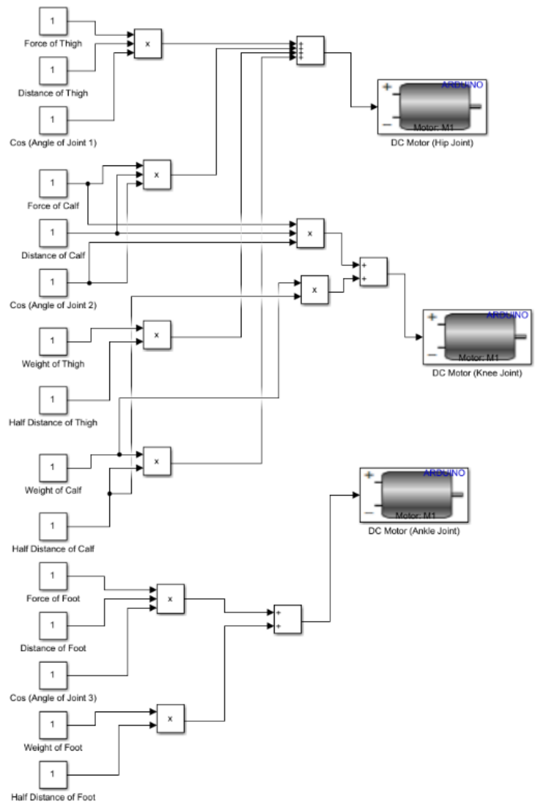

Figure 9. Simulink Model of DC Motors.

Now that the virtual models have been covered, it's time to move onto the methodology for prototype creation, and then create a small-scale prototype that would allow this concept to be tested.

3.1.6 Prototype Creation in CAD for Small Scale Model

In the earlier sections, the CAD Model for the Leg Assembly was showcased. This model was created to become a virtual model for the assembly, and while it was measured and dimensioned for the average person's height, as every engineer knows, a perfectly viable virtual model often does not equal a working physical model. So, changes had to be made in order to have a model that could be used in practice.

The first step of this was to decide on the scale that the prototypes would need to be. Given the limitations of the 3D Printer being used – only allowing for a maximum of a ten-inch-long piece – in addition to the weight requirements that the DC and Servo Motors could handle, it was decided that a small-scale model with leg segments equaling that of 4 total inches would be used. This would ensure that none of the parts would be outside of the range of the 3D Printer, and also would allow the motors to be scaled correctly.

In order to achieve this, a new CAD Model was created from scratch in order to fit with the new dimension requirements. In addition, it needed joints specially fitted to match that of a DC Motor, and also a base for it to be attached to.

The design for the leg braces can be seen below in Figure 10. Notice the joints on the upper end are on the outside edge with a larger round circle, and the joints on the lower end are on the inner edge with a smaller, more rectangular circle. This is to allow joints to be connected to each other, with the large round circle on the outside and the small rectangular circle on the inside. This will allow the DC Motor to fit through the larger circle and attach directly into the smaller one. The result of this will be that when the motor spins, it will not move the upper joint, simply spinning inside it without moving it, but it will move the lower joint that it will be attached more closely to. So therefore, by mimicking this design for a foot assembly, and placing DC Motors at each joint, it will be able to create a walking motion.

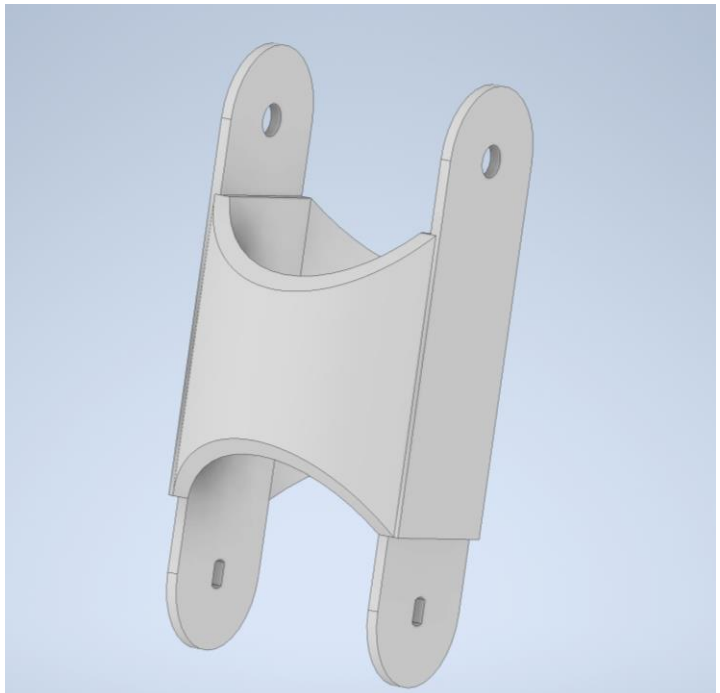

Figure 10. Small Scale Prototype – DC – Leg Brace

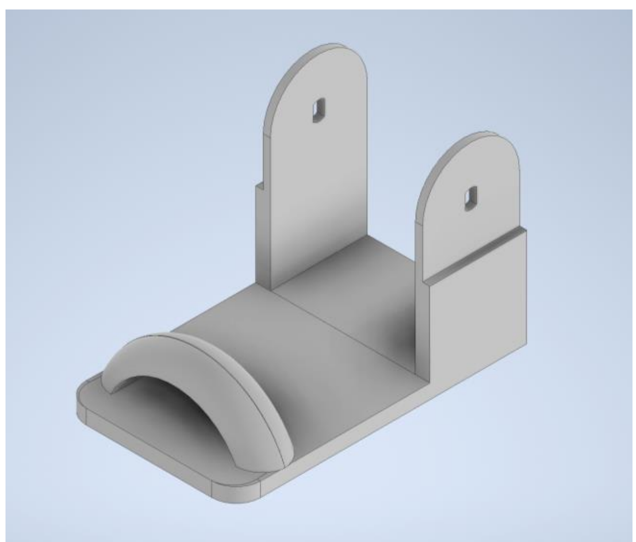

Figure 11. Small Scale Prototype – DC – Foot Brace

From there a collection of pins was also made in order to hook the sections together that would not be joined by a motor. The next step was to make a base for the assembly to attach to. This was done by first creating a hip brace that would allow for two legs to be attached to, acting as the hip, and would also have columns moving down that would fit into the base's slots. For the base itself, a simple design was used; that of a wide base platform with two columns going up that allowed for the hip plate to slide within them snugly. Once these pieces were created, the entire model could be assembled. This assembly can be seen in Figure 12 below.

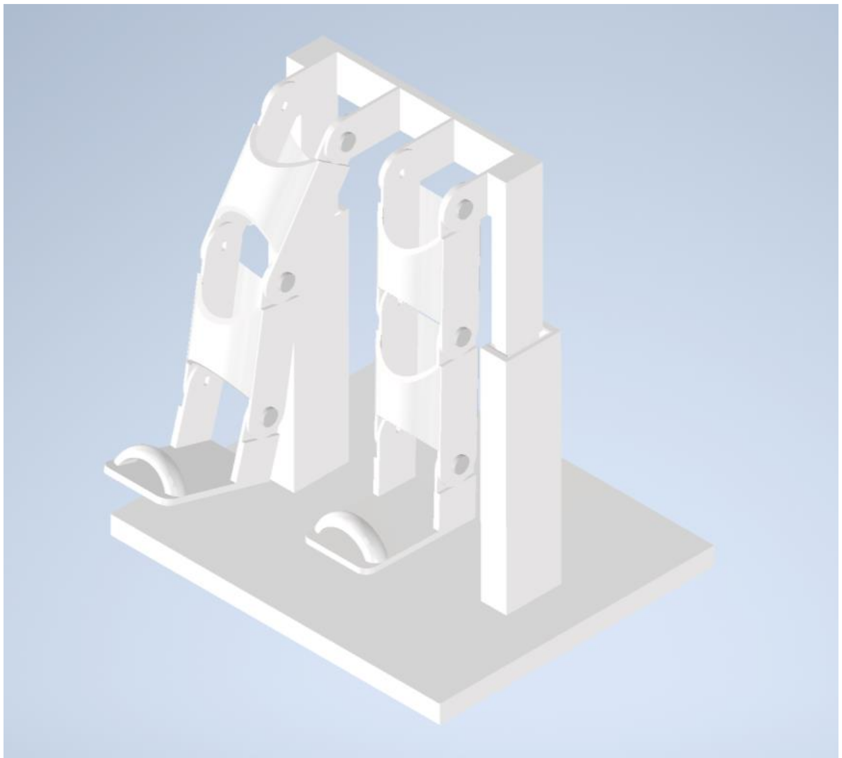

Figure 12. Small Scale Prototype – DC – Assembly

This was modeled with ABS Plastic, so that it would be similar to the plastic it would eventually be printed with. Overall, the small-scale prototype stands 10.5 inches tall, 9 inches wide, with the leg assembly itself being 8 inches tall and 1.8 inches wide. This resulted in a CAD Model that was ready for 3D printing and assembly, to create a small-scale prototype.

3.1.7 Prototype Creation for Variable Gravity Concept

The first step towards creating the small-scale prototypes was to create all the CAD Models which was detailed in the methodology section above. The next step was to 3D print all of the parts that were created, and use them to make the small-scale prototype. This was where the first problems began, as the first batch of pieces printed broke very easily, so easily that they could not be fitted together at all without snapping. Several days of work adjusting CAD Models later – and several boxes filled to the brim with broken 3D printed pieces later – the first usable pieces where created. While multiple factors played a role in increasing their strength, the most notable was that of increasing the inner fill percentage on the 3D printer from 15 percent to either 30 or 50 percent for most parts.

The image below showcases some – but nowhere near all – of the initial parts that were 3D printed, for creating both the Small-Scale DC Motor Prototype and the Small-Scale Servo Motor Prototype.

Figure 13. Various 3D Printed Parts

Once the working pieces had finally been printed, the small-scale prototype itself could be constructed. This was done by sliding the hip brace into the base, and then connecting 8 leg braces to the hip joint and each other via the use of the pins, and then finally attached the feet to the lower leg braces. The resulting small-scale prototype can be seen below in Figure 14, next to a can to give it a size reference.

Figure 14. Small Scale Prototype

Here the small-scale prototype can be seen displayed without any motors attached. This was done to verify a few things. Firstly, it was to ensure that all parts were the correction dimensions. Secondly, it was to ensure the pins were not so tight that they restricted the movement of the joint in any way. Thirdly, it was to verify that the legs were able to move with a full range of motion. All of these were checked and found to be achieved with this small-scale prototype. And so, a prototype had been created that was ready to be tested.

Mechanical material needed for the project can be seen in the Appendix.

The primary focus of this project had been on DC Motors, given that in the small scale testing they worked better for allowing themselves to be moved while spinning without breaking, meaning that if they spun at a low force, they could be turned the other direction easily with no risk in breaking the motor, whereas servo motors were not as successful at allowing themselves to be freely moved while attempting to move themselves. And so, the DC Motor was the one better capable at achieving variable zero gravity, and so therefore it was the one the prototyping plan was initially focused on. This changed later, but that will be touched on below. For now, the prototyping process for the DC Motors was as follows. The prototype was adjusted to only have one leg, and DC Motors were added to one side of the leg in place of the pins. Then, in order to keep the motors themselves in place, they were attached to the prototype via small black screws. This made it so when they activate, they would spin the joint below them i.e. the hip motor spins the thigh section, the knee motor spins the lower leg section, and the ankle motor spins the foot.

This small-scale prototype with the DC Motors attached can be seen in Figure 15 below.

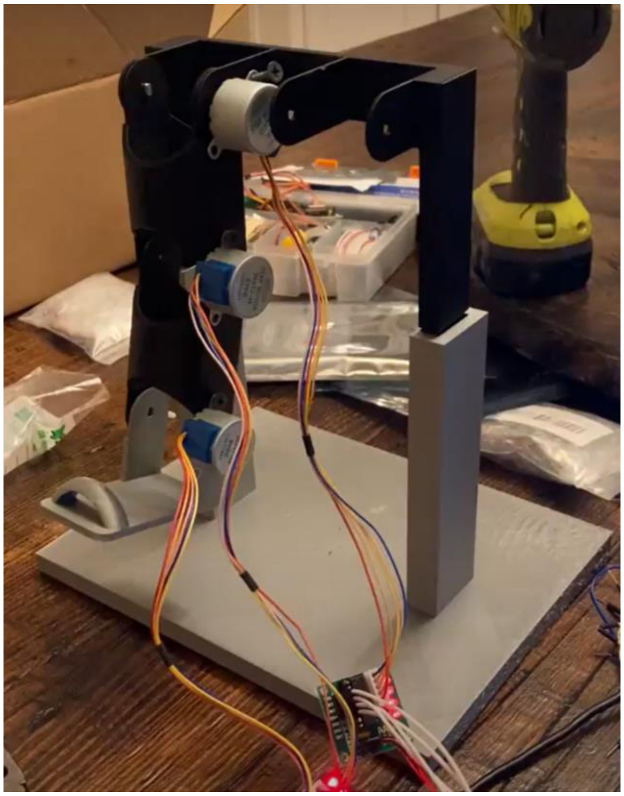

Figure 15. Small Scale Prototype – DC Motors

Once this was connected, each motor was connected to an Arduino board and verified to work, and the additional Arduino Circuit that was showcased in section 3.13 was implemented as well, utilizing an Arduino Mega to allow for room for all three accelerometers and all three potentiometers to be connected. Once this was done, trials were be started to test if the prototype achieved zero gravity. The results of these trials can be found in Chapter 5, subsection 5.2.

3.2 Daily Activities Methodology & Design

As mentioned earlier, another goal of this device beyond variable gravity was to be able to support patients in daily activities, such as sit-to-stand motion, balancing, and more. In this section, it is the sit-to-stand motion, and inversely stand-to-sit motion, that was focused on. This necessitated the creation of a new circuit diagram, new CAD Models, and a new small-scale prototype.

3.2.1 CAD Model Creation – Sit to Stand

For the sit to stand motion, the first objective is to modify the design of either the leg assembly or the base machine so that the assembly is able to slide up and down on the machine. This was done because with a fixed hip attachment plate, there is no opportunity for the patient to actually stand up, meaning the motors would have to be coded to match the force the ground applies on the leg when standing up, which while possible, is not as accurate to the real-world rehabilitation. So, the solution is to have the hip attachment plate be adjustable with regard to height while in sit to stand mode, which allows the freedom of motion for the patient to actually sit down, and then stand up from the ground.

There are a few different ways this could be designed. For the purpose of this, a modification was done to the hip attachment plate itself to add a section that would allow the pins connected it to the base machine to slide up and down up to 24 inches. This design can be seen below in Figure 16, attached to a model of the RWTD.

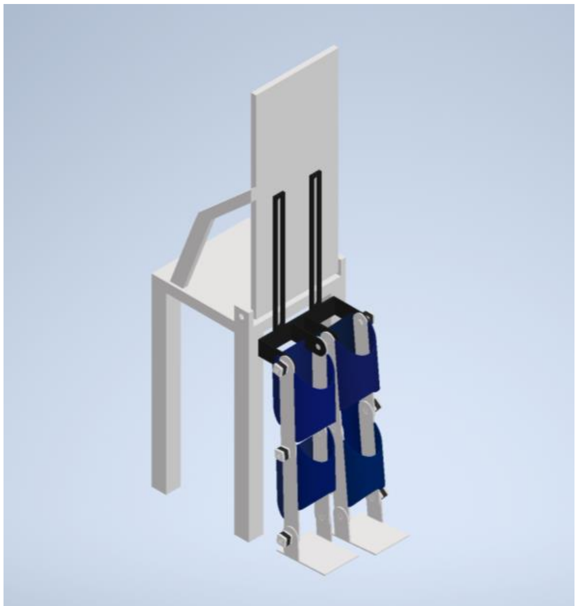

Figure 16. Modified Hip Attachment Plate.

3.2.2 Arduino Circuit Creation – Sit to Stand

Once this was done, the modified Arduino System could be completed. One important aspect of this process was that the base circuit diagram should not be any different than that of the zero-gravity concept. This is because the goal is to eventually combine them both into one system, so having the circuit diagrams set up the same way aids in that process. Here, the circuit is the same as the one from Figures 6 and 7. Yet while the setup remained the same, it was the programming that needed to be adjusted.

For this objective, the motors serve one basic purpose: help the patient stand up from a sitting position. To simplify this objective even further, the goal is to have all joint angles equal 180 degree's, regardless of the original position. Furthermore, when a person stands up, all joints typically reach 180 degrees at roughly the same time, again regardless of original position. So then, the purpose of this code is to control the motor such that they each spin at a speed that will aid in allowing the joint angle to reach 180 degrees, which in turn helps the patient stand up. Once 180 degrees at each joint is reached, the motors will stop spinning.

This was done for both the DC Motor Circuit and the Servo Motor circuit, and it was tested in Tinker CAD, showing the code ran as intended. This system now allowed for motorized assistance in the sit to stand motion, with the ability to alter the assistance given by the motors, again allowing for variable gravity to be changed as the patient increased in strength and capability.

Once the Arduino Circuit was created, a small-scale prototype could be modeled in CAD, this one to be used with Servo motors.

3.2.3 Prototype Creation in CAD for Small Scale Model

Given that servo motors were also intended to be used to test both the sit to stand motion as well as variable gravity concept, a modification to that design needed to be made as well. While the hip and base parts could be carried over from the small-scale prototype discussed previously, the leg and foot braces, along with the pins, needed to be remade in order to work with the attachment of a servo motor.

This process included some trial and error, with several different designs working in the virtual space but breaking or not turning once they were printed. The design that was finally settled on can be seen below. It places blockers on the inside of the innermost edge, that way the flat head of the servo motor can be attached from that side, and when it spins it will hit the blockers, and therefore spin the joint along with it. This modification was also applied to a new set of foot braces, which can be seen below in Figures 17 and 18 as well.

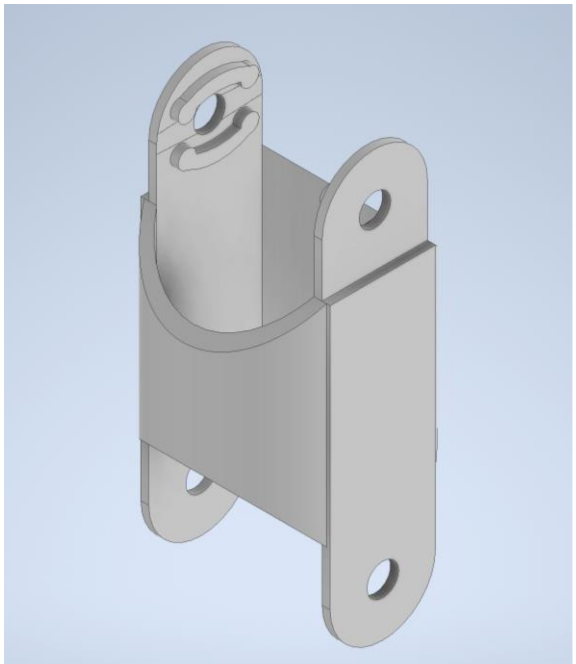

Figure 17. Small Scale Prototype – Servo – Leg Brace

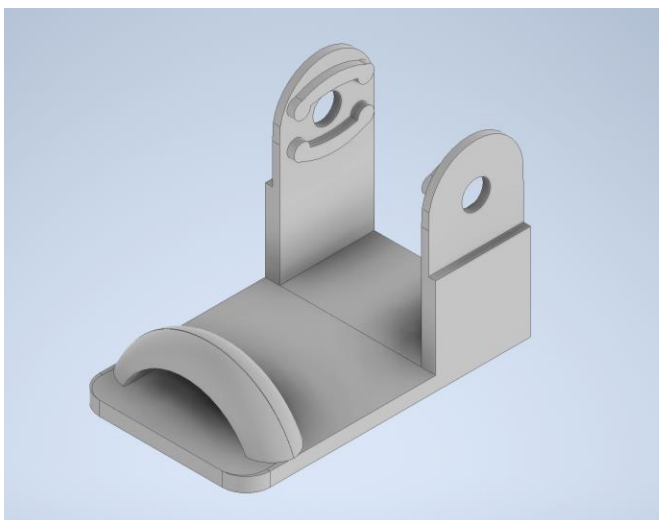

Figure 18. Small Scale Prototype – Servo – Foot Brace

Small pins were also created to fit into these new joint sections, and from there an entire assembly could be made. That assembly can be seen below in Figure 19.

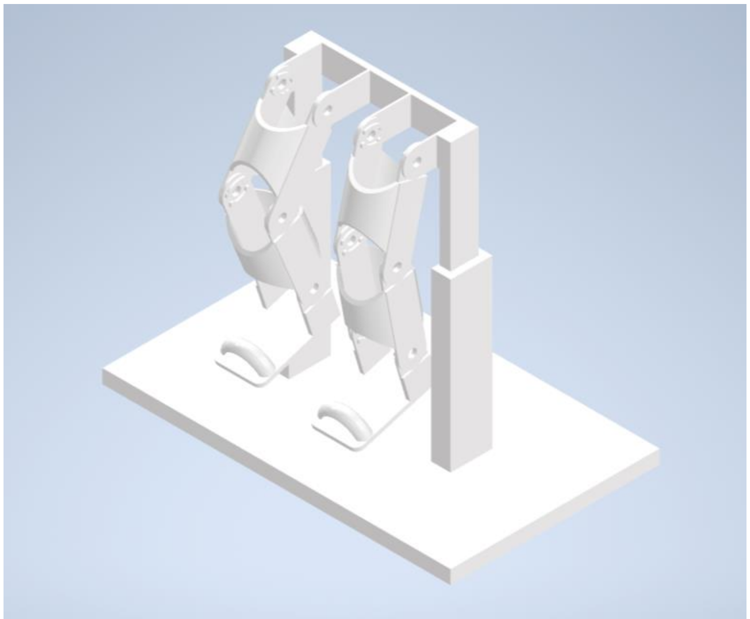

Figure 19. Small Scale Prototype – Servo – Assembly

After the CAD Model was completed for the Servo Motor version of the small-scale prototype, the 3D printing and prototype creation could begin.

3.2.4 Prototype Creation for Sit to Stand

Here, much of the process was already detailed in section 4.2.7, which covered the 3D printing of various parts and subsequent assembly, and so it will not be covered again here. Starting with the new material, once the models were 3D printed, they were assembled together using Servo motors at each joint, which can be seen here in Figure 20.

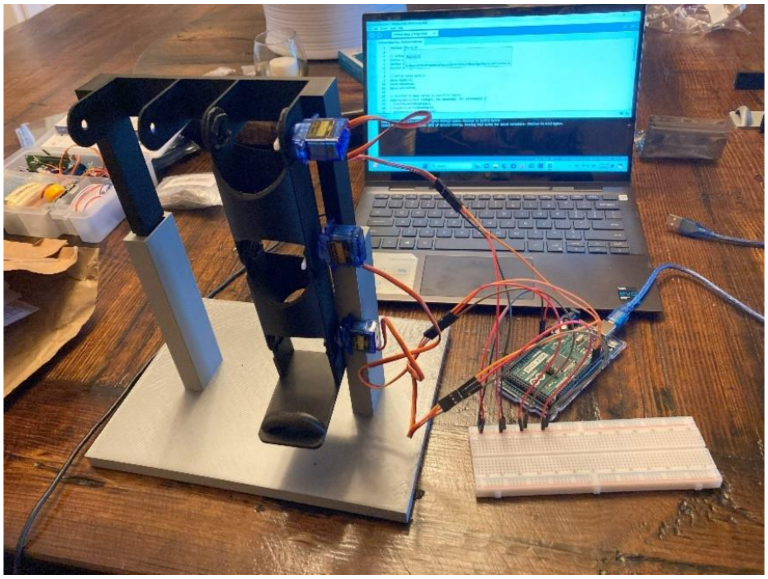

Figure 20. Small Scale Prototype – Servo

Now that the CAD Creation, Arduino Circuit System, and Small-Scale prototype creation has been covered, for both the variable gravity concept and the sit-to-stand concept. This leads us to the next section, which will cover the design of a full-scale model.

3.3 Full Scale Adjustable Size Leg Assembly

So far, virtual models and small-scale prototypes have been covered. Yet, while this is sufficient for testing, eventually a full-scale model will be created, and so this project hoped to cover the design, CAD Modeling, and Prototyping for it as well. Here, the goal is to create a leg assembly that could actually be worn by someone, has adjustable size capabilities, and would be able to be attached to the RWTD as needed.

3.3.1 Design & CAD Modeling for Full Scale Prototype

Up to this point all the CAD Models were made with specific dimensions in mind, but one needed to be made that would allow the dimensions to be adjusted in order to reduce or increase the length of each section, in addition to the width of each section.

To achieve this, the first thing that was done with design a system of rods that would make up the frame. These rods need to have holes for pins along the side, so that they could be joined together at varying places in order to create a leg assembly. This design allows for them to be placed on top of one another and adjusted up or down to achieve varying length. These rods will also be used to form the hip plate, and smaller hinges with slots of the same size and distance apart will be placed on them, which will allow the legs themselves to achieve adjustable width.

Given that the hope was to 3D print a full-scale model of this to showcase how the variable dimensions will work in practice, the leg braces also needed to be significantly redesigned in order to allow them to open up so that someone's leg could actually be placed inside them. This was done by utilizing a pin system that could attach to one side of the leg, allowing the braces to open up to allow the patient to place their leg inside, and then close back once the leg was in place.

A figure showcasing the overall design of the leg braces can be seen below in Figure 21.

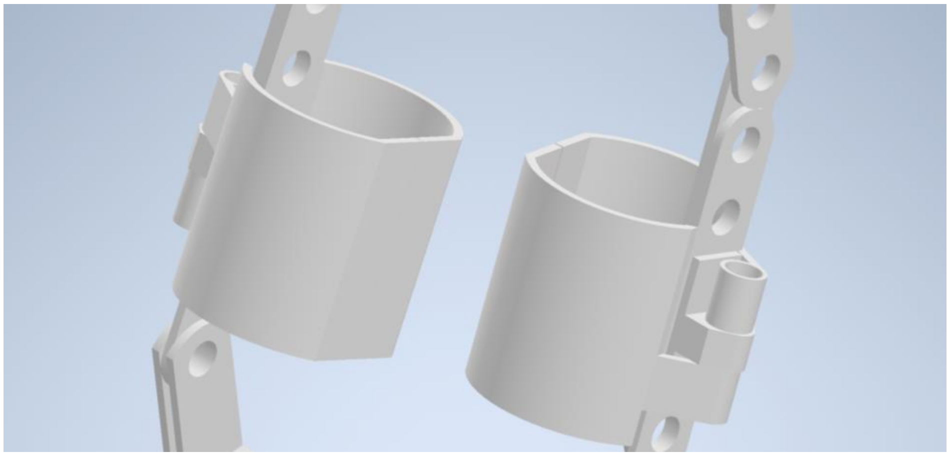

Figure 21. Full Scale Adjustable Size Prototype – Leg Braces

In an effort to allow for variable sizes, leg braces with widths of 5 inches, 6 inches, and 7 inches were modeled. In addition, foot braces were also created with the same three widths for both the right and left side, and the basic design of them can be seen below in Figure 22. They include a plate at the front that the patient's foot will be able to slip into, holding it in place. If desired, the same effect could also be achieved with a strap, which might increase comfortability.

Now the assembly of the parts could be achieved. In this figure, the assembly was done using the leg braces and the foot braces of 5-inch width. The rods were also placed in their shortest positions, along with the hinges, to showcase how the leg assembly would operate at its lowest possible dimensions.

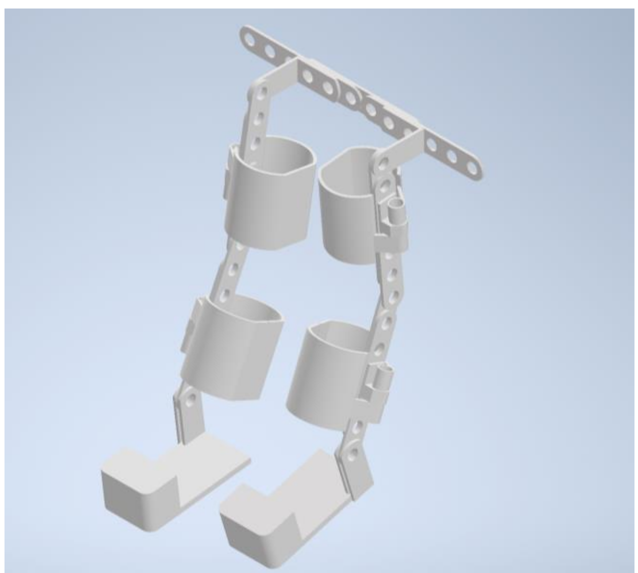

Figure 22. Full Scale Adjustable Size Prototype – Small Assembly

Overall, in this configuration the width of the leg assembly is roughly 12 inches, the height is 26 inches, and the width of each leg is 5 inches, which would be suitable for a patient of small height and weight.

Now, another assembly was made that showcases the leg assembly in another configuration; namely at its largest possible length and width. This assembly can be seen in Figure 23 below.

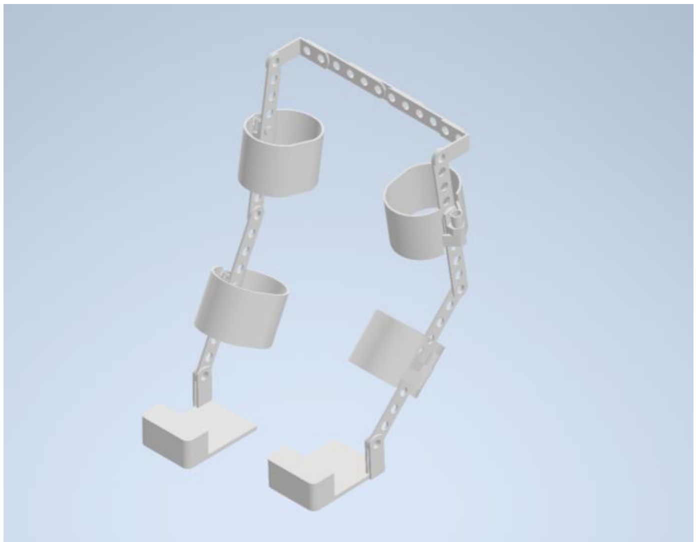

Figure 23. Full Scale Adjustable Size Prototype – Large Assembly

Overall, its width is just over 24 inches, and its height is approximately 38 inches, with the legs having a width of 7 inches. Note that there is room in this design for larger leg braces to be made, given the room between the two legs in this design when the hip hinges are at their widest point.

But while numerical dimensions can showcase the difference in sizes between the two configurations, it is always good to also incorporate a visual representation, and so this assembly seen below in Figure 24 was made that showcases both the smallest and largest configurations side by side.

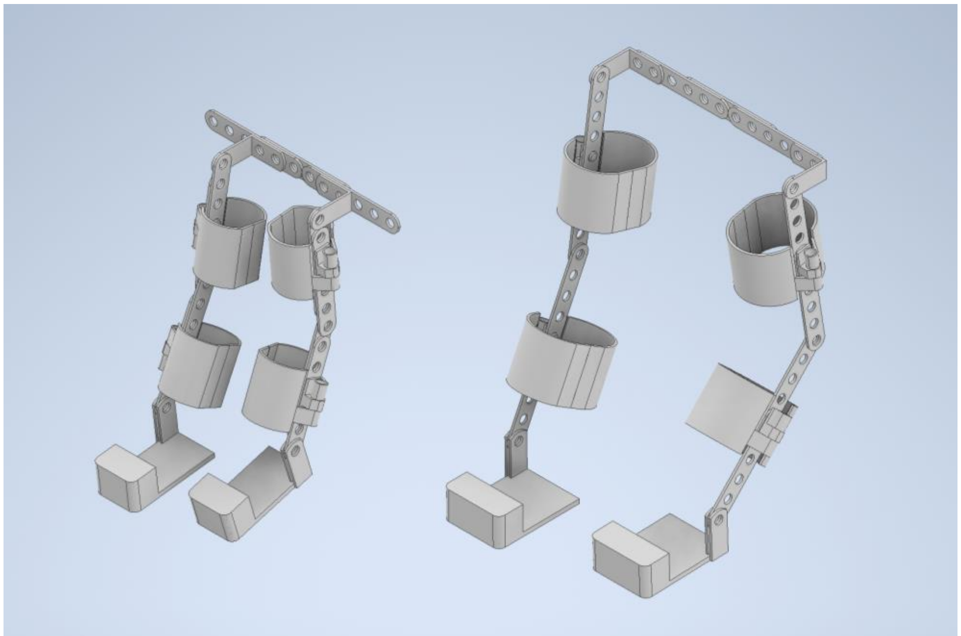

Figure 24. Full Scale Adjustable Size Prototype – Size Comparison

As seen here, there is a significant different in sizes between the two configurations. In addition, switching between these configurations is simple, as it only required the rod placement on the sides to be slid up or down, the hinges on the base to be moved in or out, and the leg and foot braces to be swapped out with the needed size. Removable pins were also made for this assembly, which aid in locking it at the differing sizes.

Finally, all pieces were made so that no single piece was over 10 inches long, so that a full-scale model could be created from this design using the 3D Printers that were accessible.

3.3.2 3D Printing of Full-Scale Prototype

Once the CAD Models were created, it was time to begin 3D Printing the full-scale model. This was done using a similar method to the one described previously with regard to the Small-Scale prototypes.

Here, the various 3D Printed pieces can be seen, laid out in a way to showcase their placement within the assembly.

Figure 25. Full Scale Prototype – Adjustable Size

This full-scale model will be covered more in the results chapter, specifically subsection 5.3, as well as the future work section.

Now that the leg assembly methodology and design was covered for both variable gravity and sit to stand motion, including CAD Modeling, Arduino Circuit Creation, and Prototype creation, its time to focus on the second aspect of this project, which was the walkway platform creation.

3.4 Walkway Platform Design & Methodology

For all the discussion of the leg assembly modeling and creation, the walkway platform itself has still not been forgotten. As mentioned previously, the goal of this project is to create a series of modules, that when placed together, will create a long walkway platform. This platform will have interchangeable modules that can achieve a variety of differing walking disturbances, including a surface drop, a slipping motion, and a tripping block.

The design and modeling for the walkway project can be seen in the following sections, starting with the CAD modeling.

3.4.1 Design and CAD Modeling of Walkway Modules

For the walkway platform creation, first the overall design was modeled in CAD. The base CAD Design for the platform can be seen below in Figure 26.

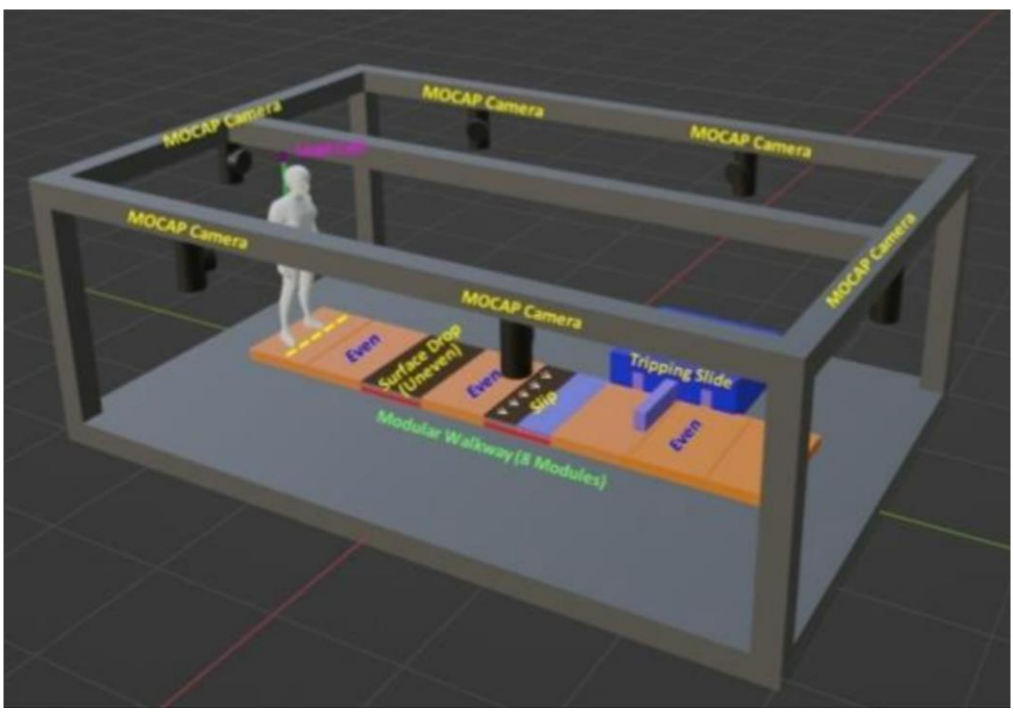

Figure 26. General CAD Modeling of Walkway Platform.

In the above figure, the mocap camera setup can be seen, as well as the harness bar. The goal of this project, in relation to the walkway platform, is to create the modules seen in the middle, as the motion capture setup has already been completed, and so it is merely awaiting the completion of the final full-scale modules. In practice the motion capture cameras were set up on tall tripods and positioned around the empty space meant for the platform, a bard was hung over the middle two tripods that allowed for the center harness to be attached for safety.

For the normal modules, that is the modules that don't cause any balancing disturbances, they were designed as followed. The base was created with plywood, according to the specified dimensions. The base and top is a solid sheet, and the middle with be smaller blocks arranged in the corners and center to maintain stability, while reducing weight. Then, the plywood is coated with a thin layer of aluminum. Aluminum L stock will be used to trim out the blocks. This will be done for 3 normal modules.

The basic design of the platforms before any aluminum is added can be seen down below in Figure 27, modeled in CAD.

Figure 27. Base Design of Walkway Modules - CAD

As seen above, the top and bottom layer of the module is a solid sheet of 1" plywood – 0.75 inch thick in reality – and the middle section is composed of two layers of smaller squares, placed at various spots around the edges and in the center in order to provide a firm base. This was done to reduce the material cost, as well as greatly reduce the weight of each module. Even with this reduction the modules still proved to be very heavy, and so the decision to hollow out the center proved to be a good decision in the end, as it did so without sacrificing the strength of the module itself. The dimensions for these blocks, as well as all other modules, was set to be 39 inches by 47 inches.

Once that base was constructed from plywood, the aluminum is applied, and then the edges are trimmed with aluminum L stock. This can be seen modeled in CAD in Figure 28 below.

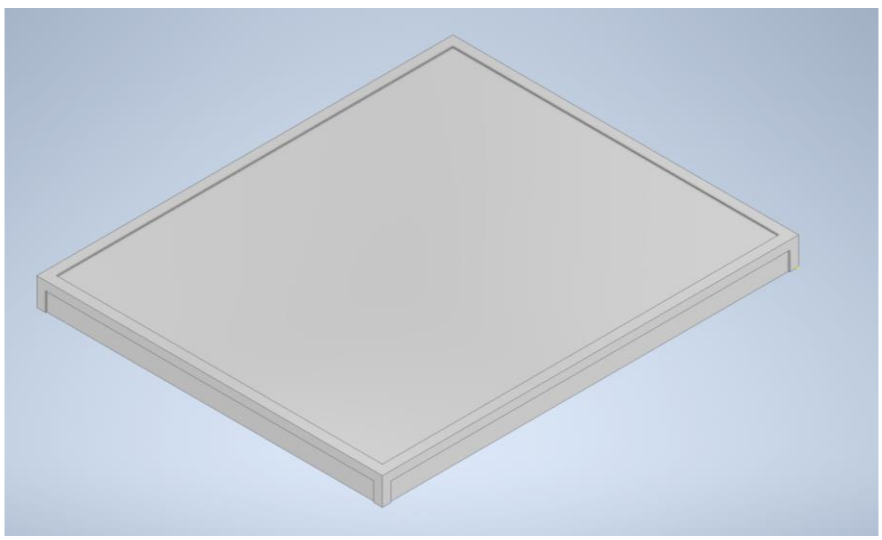

Figure 28. Normal Modules - CAD

Moving on from the normal module, we will now drop into the discussion of the surface drop module. For the surface drop module, the inside was be hollowed out, so that when the subject steps on the top sheet of aluminum, it falls to the bottom. This required a hollow inside, but it needed something in place to hold the sheet of aluminum up that would quickly release if it was stepped on, and it needed to be something that would not break after a single use. The original concept was to use foam for the hollow part that would compress when stepped on and then fill back up once pressure was no longer applied, in order to lift the aluminum back up. However, in practice this turned out to be ineffective, as the foam did not decompress enough to achieve a smooth surface drop, and the aluminum was also being bent in the process. So, instead magnetic strips were applied to the edges of the aluminum L stock that hung over the top, as well as on the edges of the surface aluminum itself, in order to connect the two. Other magnetic strips were used along the outside edges to hold the trim in place. The result was a module that allowed the aluminum to be held up by the force of the magnets, but when any additional force is applied to it, the surface aluminum immediately falls down, and the surface drop is achieved.

The CAD model for this design can be seen in Figure 29 below.

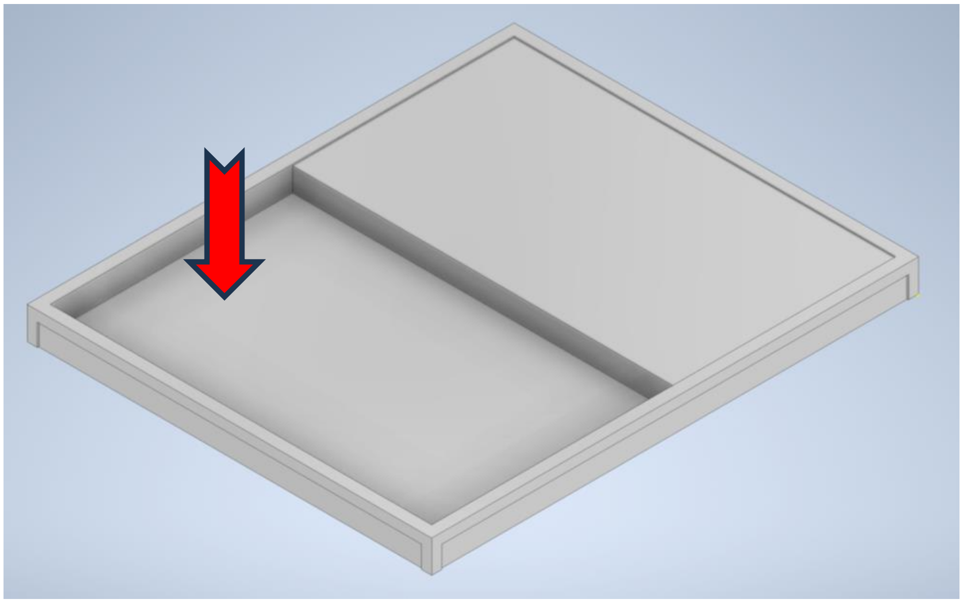

Figure 29. Surface Drop Module – CAD

As seen by the red arrow, the front half of the module drops down the length of the upper three layers once it is stepped on by the subject.

Sliding onto the topic of the sliding module, it was created using a hollowed out interior and a top piece of plywood attached to small wheels. These wheels are designed for rail systems, but for the purposes of this setup no rails were needed, as the siding of aluminum holds the middle wheels in place nicely. The top piece of plywood was then cut 6 inches shorter than the base, in order to allow it to roll freely in either direction, up to 6 inches. The base design for this module can be seen in the CAD model below in Figure 30.

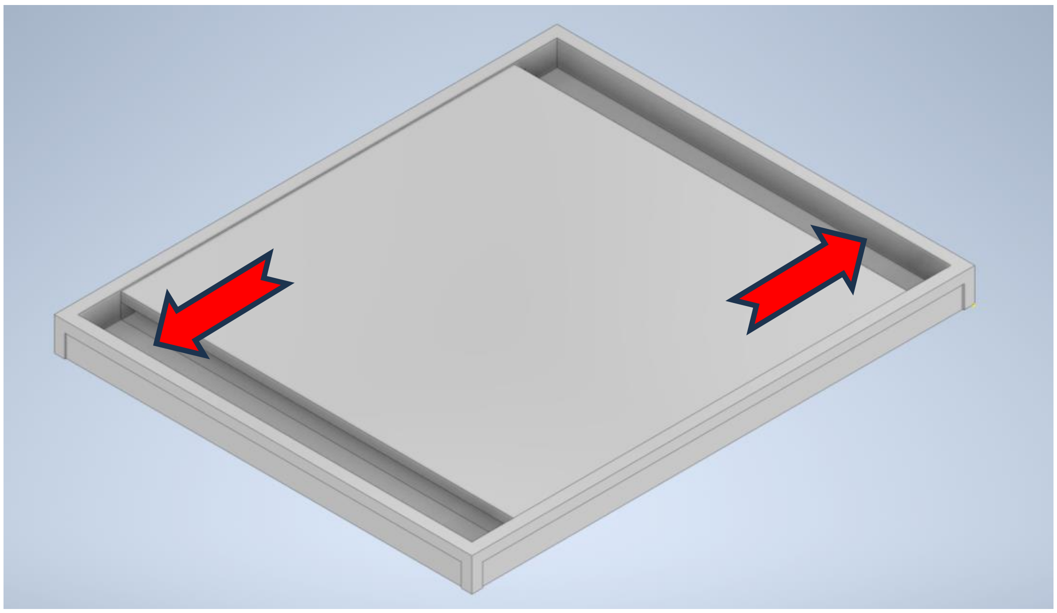

Figure 30. Slip Module - CAD

As seen above in Figure 30. the slipping module can roll in either direction. Now, in order to disguise the slipping motion – as a slipping module that can be expected would be like a plot twist that readers see coming, predictable and ineffective – thin sheets of aluminum will be placed over the gaps on either side in order to hide the gaps, maintaining the illusion that it is just another normal module. This was left off of the CAD Modeling so that the slipping motion could be showcased, but in practice it was added.

Falling over into the tripping module design, this module is intended to have some form of object suddenly spring out and disturb the subjects' walking paths. Now, the original concept for this included blocks that were to be placed to one side of the module that would slide out and trip someone. However, it was deemed that the subject would be able to notice the blocks to the side too easily, and so a new design had to be made.

This new design would incorporate a cut out portion of the walkway module itself, that when activated, would raise up suddenly and trip the subject. The base design for this redesigned tripping module can be seen in Figure 31 below.

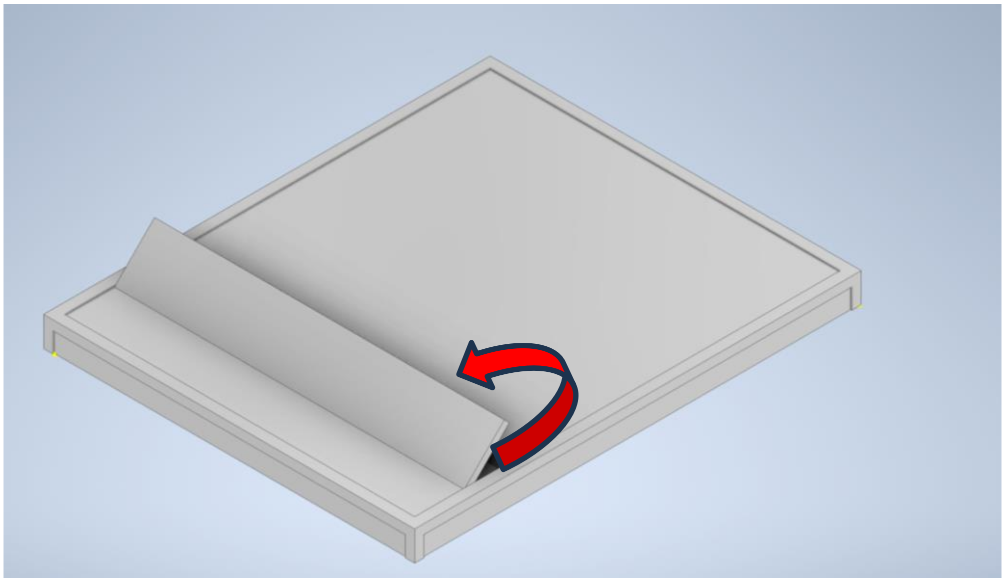

Figure 31. Tripping Module – CAD

There are a few different ways in which the tripping motion can activate. The first is an actuator placed within the hollowed out inner surface of the module. The drawback to this design is the limited amount of space in the center, and so only a mini actuator could be used. The second way to design it would include using a manually activated spring system, which would entail placing springs along the center that would compress down when the tripping block is pushed down, and then the tripping block itself could be locked in place. Then when the pin locked it in pace is removed, the force of the springs would propel it up, creating what is essentially a large-scale rat trap, only this one is designed to trip much larger prey.

Descending further into the realm of this topic, the basement modules can now be discussed. The intention is to create a series of modules that can be placed beneath the existing modules. This is done to allow a force plate to be placed within one of them, so that when the subject steps down onto the modules that causes a disturbance, the force with which they step can be measured, which as the studies from the literature review proved, will only increase the amount of data collected in addition to the motion capture cameras.

Now for these designs, three of them needed to be made such that they were simply blocks the same length and width as the walkway modules, but with a height that was just slightly less than the height of the force plate.

The design for these three normal basement modules can be seen in Figure 32.

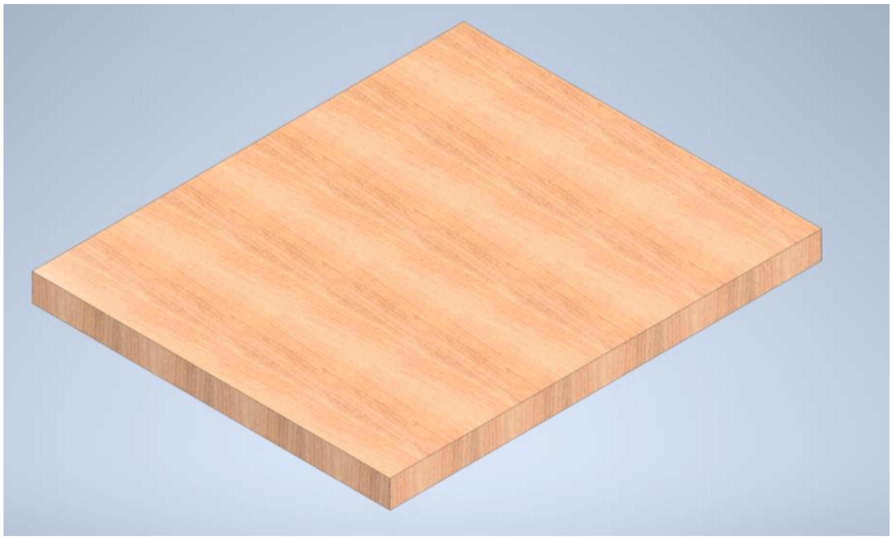

Figure 32. Basement Modules - CAD

As seen above in Figure 32, the design is simple, and rows of smaller wood to brace it were placed in the middle to provide extra strength and stability.

Forcing our way into the discussion of the force plate, one basement module needed to be designed that would allow for the force plate to be placed within it. This was done by measuring the force plate and cutting out a hole in a fourth basement module. The CAD model for its design can be seen in the figure below.

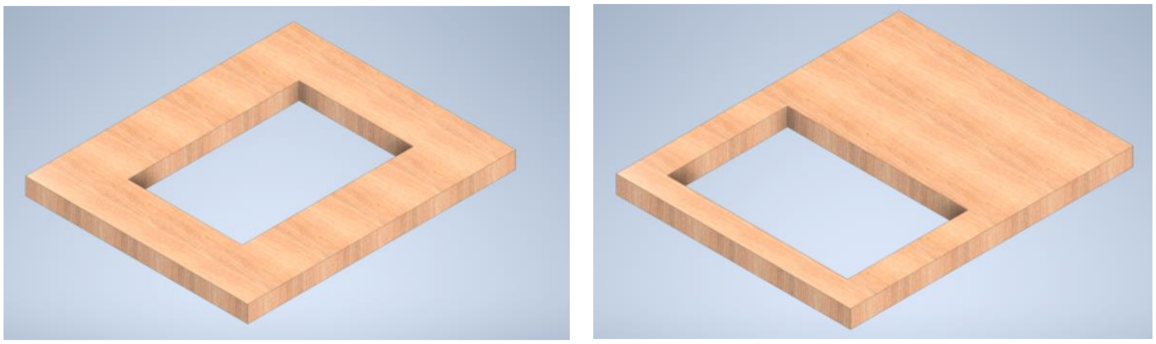

Figure 33. Basement Modules with Force Plate

From here, it was decided to make an additional two basement modules, one being a basement module like the one seen above but with the force plate cutout being in the anterior position, allowing subjects to step on it more directly, which can be seen beside the other model above. The second design added at this stage was a basement module design to look like a normal module, so that the force plate could be placed on the actual walkway, rather than having to drop down. This also necessitated the creation of 3 smaller platforms to be used to raise the height of a normal model to that of the basement models, which are taller due to the force plate's height.

The basement module trimmed in aluminum and the smaller base modules used to adjust height can be seen in Figure 34 below.

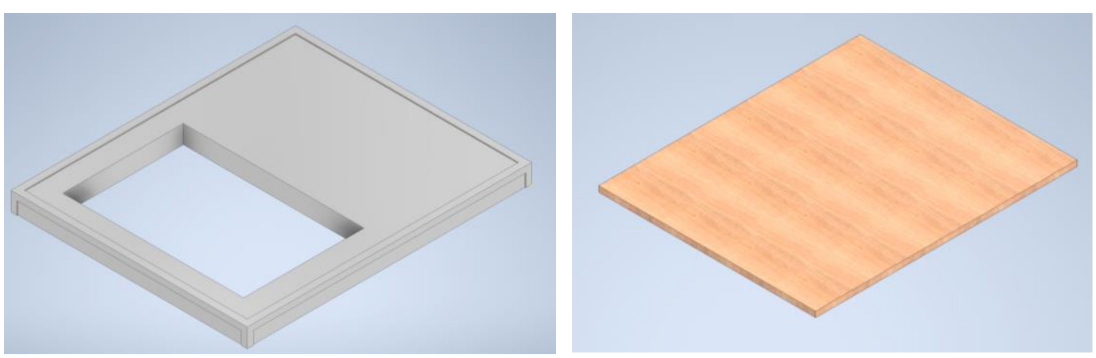

Figure 34. Additional Basement Modules

Finally, now that all the modules were completed individually, the assemblies showcase how they will be implemented can be designed. While many different combinations of the modules could exist, the plan is to have only one disturbance module per trial, and to have four blocks total, supported by the three basement modules designed.

Below the assemblies for the three different disturbance blocks can be seen in Figures 35, 36, and 37.

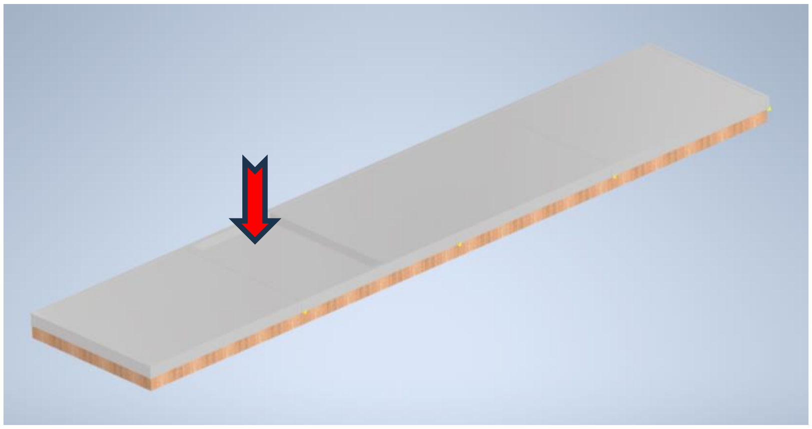

Figure 35. Surface Drop – Full Walkway

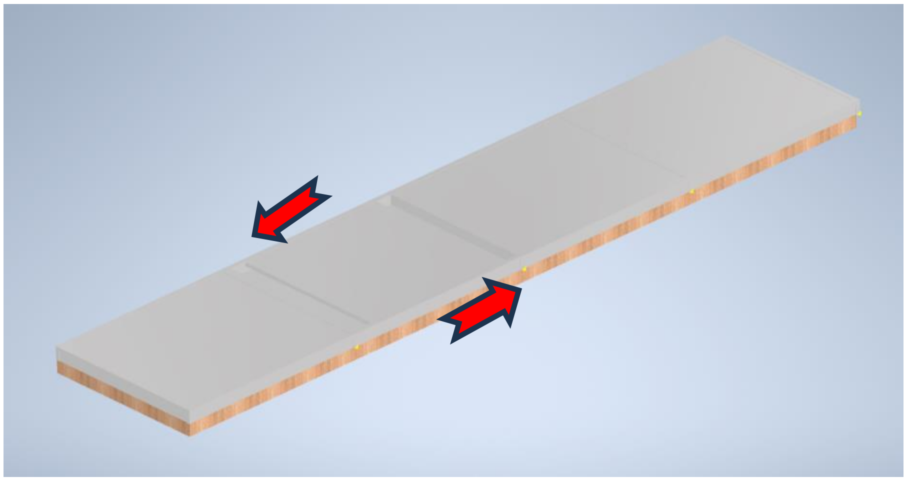

Figure 36. Slipping Module – Full Walkway

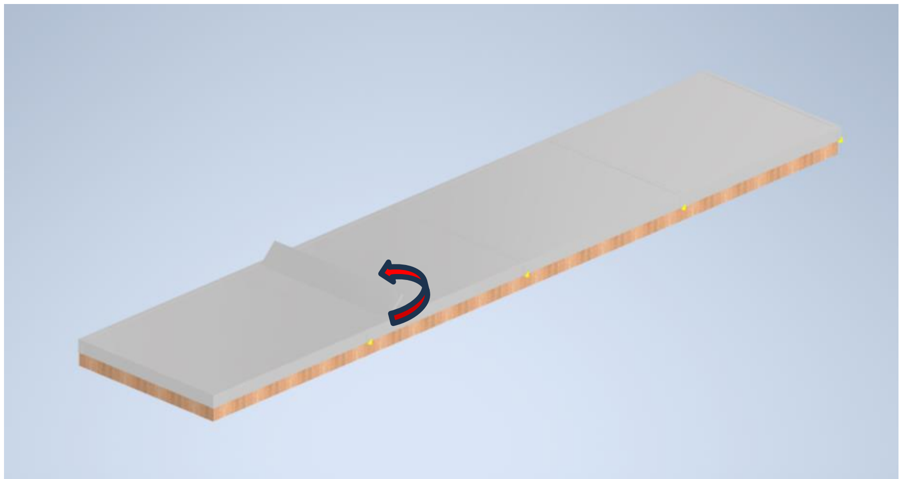

Figure 37. Tripping Module – Full Walkway

As showcased above, all the normal modules and disturbance modules were modeled in plywood and aluminum, and the basement modules were modeled in plywood. The length of each module is 47 inches, and so a complete walkway comprised of four modules would be 188 inches long, or approximately 15 and a half feet. Each module is 3 inches tall, so when placed on the basement modules the walkway will stand approximately 6 inches tall.

Now the time has come to look into the resulting walkway modules that were created, along with the results from the leg assemblies, which can be seen in the results section below.

3.4.2 Safety Concerns and Countermeasures for the Walkway Platform

With any project that involves subjects potentially falling, the topic of safety is a very important one. For this project, the two primary ways that someone could get injured are the following: the subject falls, or the modules themselves break. For the modules themselves, FEA Analysis was conducted to ensure that the material and design used is strong enough to support the weight that will be placed on it. This, coupled with additional support beams placed inside the modules will ensure they do not break under the load of the subject.

Concerning the subject falling, several different countermeasures will be put into place to ensure they are not injured in any way. The primary method of safety will be a harness that they will be strapped into, connected to a sliding joint above them. This harness will lock in place at a certain height, making it so that it is impossible for them to fall down completely. Of course, precautions will also be taken with regard to the subjects clothing, specifically their shoes, to ensure they are properly protected.

Additionally, if it is deemed necessary after the walkway modules creation, the edges of each module could be trimmed with soft edged rubber, which would negate any possible injuries if someone did impact the sides of the walkway modules, although that would require both straps of the harness snapping.[5]

Chapter 4

Results and Discussion

This project produced a wide variety of results, including both qualitative designs for the walkway project and leg assemblies and qualitative data for the variable gravity and sit to stand motion. All of these results are covered here, starting with the created CAD Models, then the virtual results gathered in TinkerCAD, before moving onto the Qualitative Data gathered from the prototype experiments. This will be done for the variable gravity concept first, and then for the daily activity (sit to stand) concept second. After both are covered, the resulting walkway platforms will be showcased and discussed.

4.1 Variable Gravity Concept – Results & Validation

Here, the results from the variable gravity concept will be seen, starting with the CAD Modeling, before moving onto the experimental results that validate the design.

4.1.1 CAD Model Creations for Variable Gravity Concept

For the results, many of them are qualitative. For instance, the results from the CAD model creation process were simply the CAD Model was created, which was detailed in full in the methodology section. Here the completed CAD Model can be seen again, with an exploded view of the right leg.

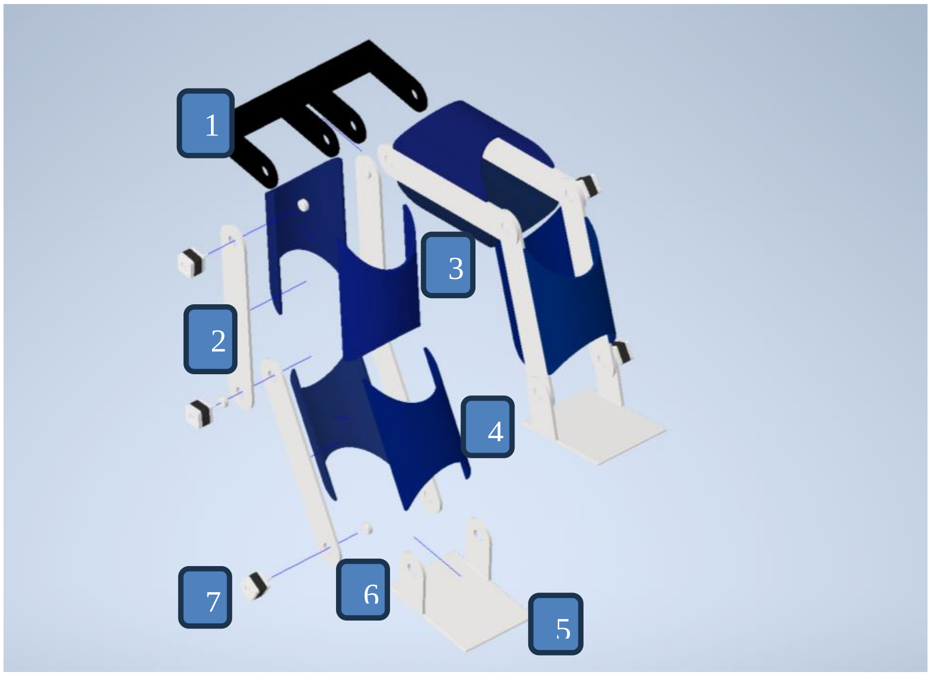

Figure 38. Exploded View of Leg Assembly.

Appendix B contains a list of each component showcased in the exploded view

Furthermore, here is the completed Small Scale Prototype Model in an exploded view.

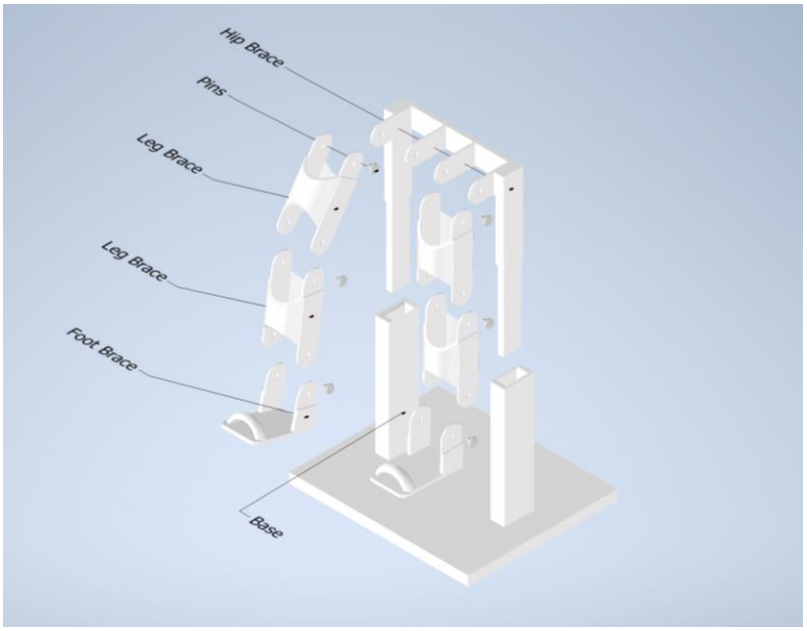

Figure 39. Small Scale Prototype – DC – Expanded View

4.1.2 Validation of Virtual Results via TinkerCAD

Now that the virtual models have been discussed, the results from the virtual prototypes can be discussed. While the results and data differ from the Tinkercad Model to a physical prototype, results were able to be gathered within the virtual system itself, based on certain input variables, that proved the system was working as intended.

For the variable gravity system setup, intended for walking, all the values found for length and weight were input into the code, and it was run. Two important things to note: firstly, given that this is a Tinkercad simulation, the values read for the angles of the joints will all be equal, and will not change. This will affect the data somewhat, in the sense that it will not change based on the position of the leg, as it would in practice. Secondly, as noted above, the potentiometers cannot be attached without an Arduino Mega, so its value is not able to be adjusted. Given that, for this test its valve is fixed at the value of 200%, and the values for length and mass are also set to the max within the range. However, if this code does work correctly, then the expected outcomes from the serial monitor will show that Motor 1 has the highest torque value, Motor 2 has the second highest torque value, and Motor 3 should be substantially lower, given the equations of moments found above. Also, given that the weight of the entire system is around 13 kilograms, the torque generated at the motors should be close to that range, with Motor's 1 and 2 being higher due to the distance over the sections that creates the moment. However, given the relatively short distance, it should not be drastically more than that force.

Once the simulation is run, it outputs these results, found in Figure 40 below.

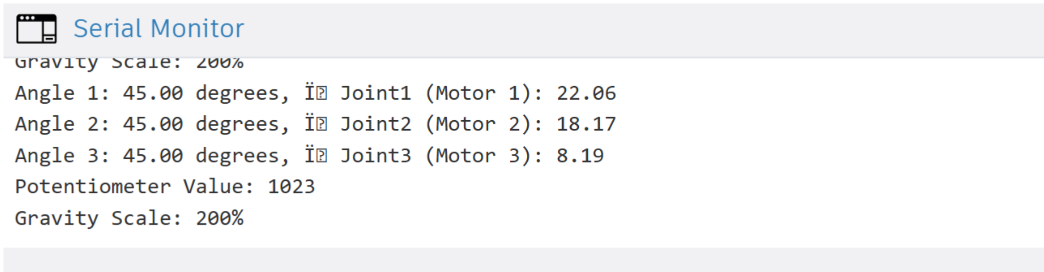

Figure 40. Close Up of Serial Monitor.

As show, at the initial angle of 45 degrees, and the gravity scale of 200%, the torque for the motors is 22.06, 18.17, and 8.19 Newton Meters, respectively. This falls in line with our expected outcomes, and so the Arduino System to create variable zero gravity for the leg assembly was successful.

Now, given that a full scale model would not be created – although results were gathered from the small scale models which will be touched on later – it was also important to validate the results from a virtual standpoint. The biggest obstacle to this was the fact that TinkerCAD does not allow the accelerometer angles to be changed, nor the potentiometers for gravity scale, weight value, and length value. To counter this issue, a new code was written that allowed the values for length, weight, and angle values to be directly inputted into the serial monitor, and calculated from there. This would aid validating that the values were being correctly sent to the motors to achieve zero gravity, and that a full-scale model would work with this code, assuming it was wired correctly.

Many trials were done with this method, and the first of which will be detailed here. The three angles were input to be 30 radians, and values were also chosen for length, weight, radii, etc… Now, the TinkerCAD Simulation outputs can be seen in figure 41 below.

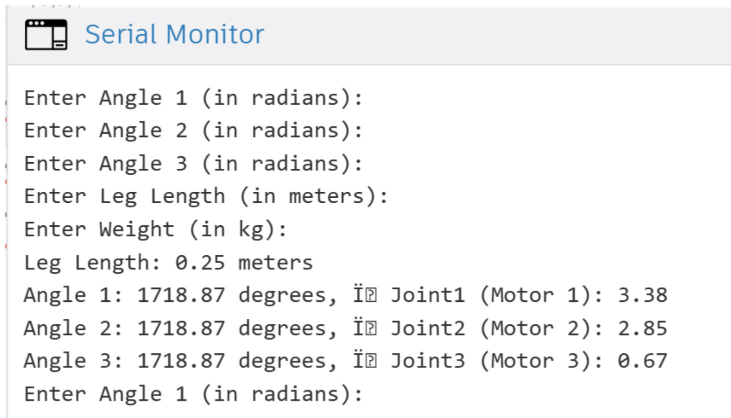

Figure 41. Close Up of Serial Monitor 2

From here, the values of 3.38 Nm, 2.85 Nm, and 0.68 Nm can be found for the torque applied to the motors at the Hip, Knee, and Ankle joints respectively. Once again they fall in line with the pattern expected and mentioned earlier, but here we want to validate them by comparing it to actual hand calculated results.

The hand calculated results using equations (1), (2), and (3), from above – calculated by hand and verified with an online equation solver – were found to be 4.8 Nm, 2.97 Nm, and 0.68 Nm. This gives an error of roughly 40 percent for motor 1, 4 percent for motor 2, and 120 percent for motor 3. While this is not outside of the realm of possibility, the error for motors 1 and 3 is relatively high, and so more tests were done, which found that overall motor 2 was the most accurate, while motor 1 and 3 where more accurate for lower values for theta, and less accurate for higher values of theta. On average the percent error for values of theta less than 45 radians was 28 percent for motor 1, 3 percent for motor 2, and 38 percent for motor 3, whereas for thetas above 45 radians the percent error values increased. Because of this, modifications where made to the code to try and fix how it was applying the equations to the motors, and the results of subsequent tests can be seen below in Figures 42, 43, and 44.

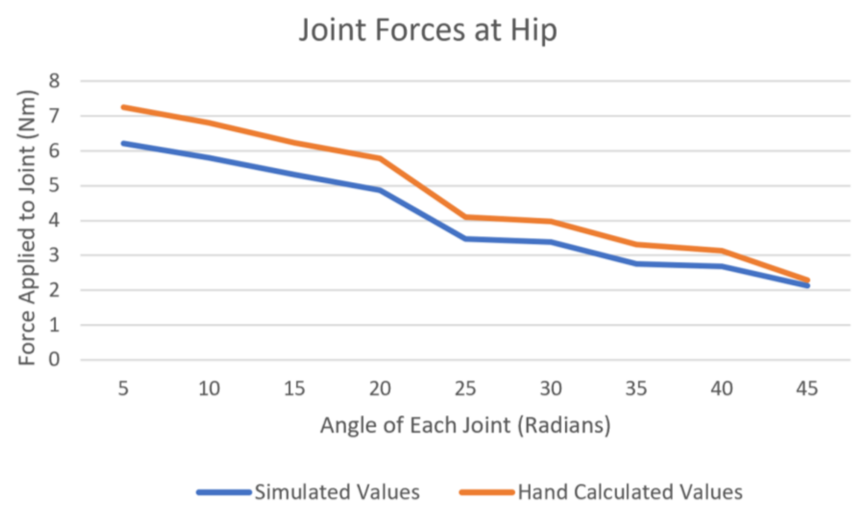

Figure 42. Joint Forces at Hip

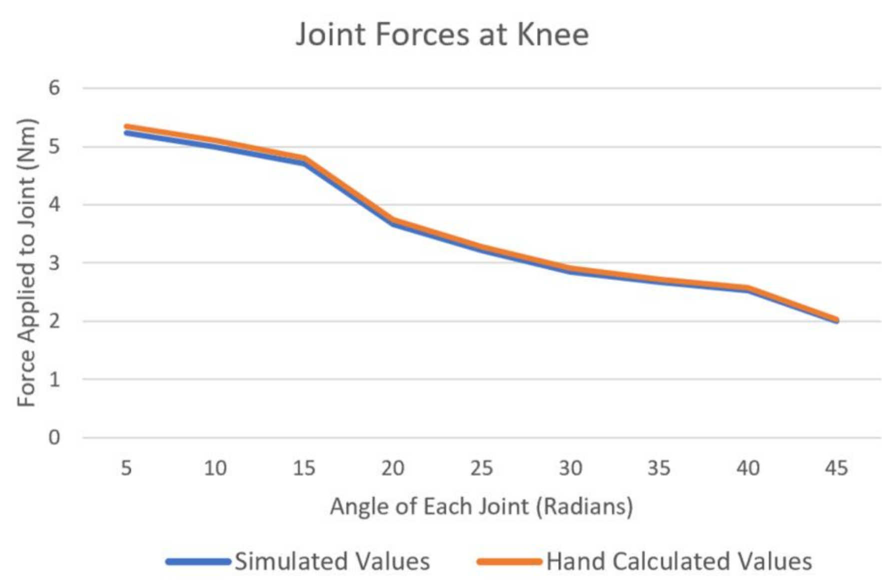

Figure 43. Joint Forces at Knee

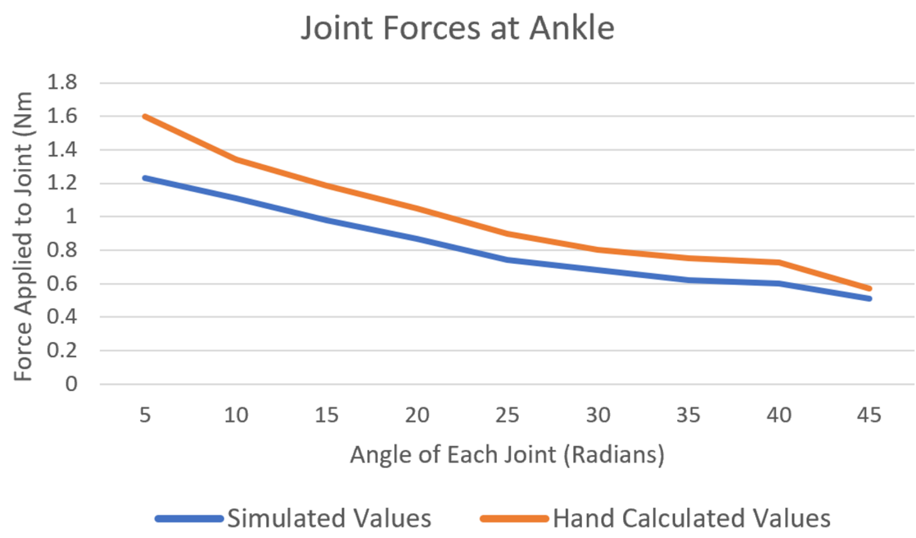

Figure 44. Joint Forces at Ankle

Error was able to be reduced to an average 17 percent for motor 1, 2 percent for motor 2, and 21 percent for motor 3, which can be seen by the deviations in the graphs. One variation of the code gave much closer error values, but only for very low angles, and so it would not be viable to use in practice.

For a virtual simulation, those error values were found to be acceptable, and would be close enough to achieve "virtual" zero gravity in a real-world application. If it was applied to a full-scale model, it would be possible to use the data there to further refine the code so that would reduce the error even further. This series of tests via direct input of variables validated that the virtual model for variable gravity was a success, giving values that would achieve zero gravity conditions with relatively low error, especially at lower angles – which will be expected in a walking motion – and especially with regard to the knee joint.

4.1.3 Results & Validation from Small Scale Prototype

Given that the stipulation for zero gravity in this project was that the leg could be moved freely, and they would stay in place at any point they were left at, that is how the initial tests were conducted, and the early results were promising.

Since these results are based on movement and this is simply a report, images will instead be used and the movements of the prototype will be described. For the presentation itself, the actual videos will be showcased. Also, for these tests a new code was created that simply adjusted the variables such as length and weight down to the model's scale.

For the initial tests, the test was done by moving the knee joint out to its front – in practice this would not be possible without injuring the patients but for a test it works well – and testing if it stayed in place, or fell down. At the moment seen in Figure 45 below, the leg had just been let go, and the motors managed to keep it in place at first.

Figure 45. Initial Prototype Test

However, about one second after it was released, the knee joint began to lower slightly, and eventually rested 21 degrees lower than it was originally. So, modifications were made to the code. After this, it was tested several more times, and the knee was found to be working more accurately, whereas the foot joint needed its position adjusted into the opposite direction, but once that adjustment was made it worked as well.

Yet, throughout the next series of trials, an issue started to become clear. While the model was working as intended, and the knee and ankle joints were allowing their sections to be moved freely, and then holding them in that position, the hip joint was not able to move the leg section with its full range of motion. Initially this was thought to be an error with the code, and so modifications were made to test this, putting the maximum amount of torque on the hip joint, and then seeing what the result was. In this test, the knee and foot joint spun freely upwards, but the hip joint was able to turn roughly 30 degrees before it could not overcome the weight of the assembly, and so the movement stalled as the motor began to burn out. So, while the prototype was created to be lightweight in order to work with these motors, the motors themselves proved to be too heavy when attached to the prototype, and so the hip joints motion was restricted.

A final test was conducted to showcase this issue, and verify that the knee and foot joints worked as intended, achieving zero gravity, while the hip joint was held back by the motor's own capacity. Images from this test that showcase the knee and hip joints staying in place can be seen below in Figure 46.

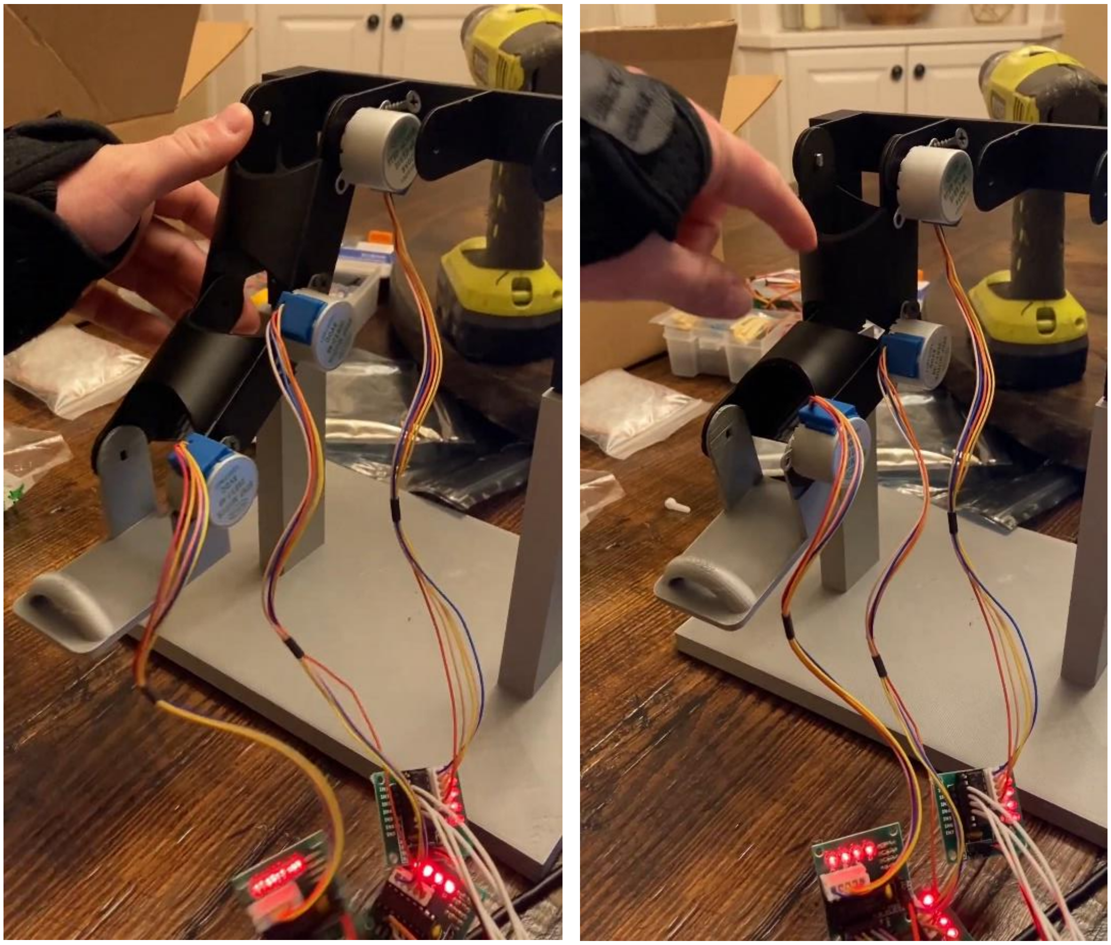

Figure 46. Prototype Knee and Foot Achieving Zero Gravity

In Figure 47 below, the knee and foot joints were moved closer to motor 1 in order to reduce its load, and the result can be seen. The knee and hip joints stayed in place – achieving zero gravity conditions – but the hip joint slowly moved down as the weight overcame the torque capabilities of the motor.

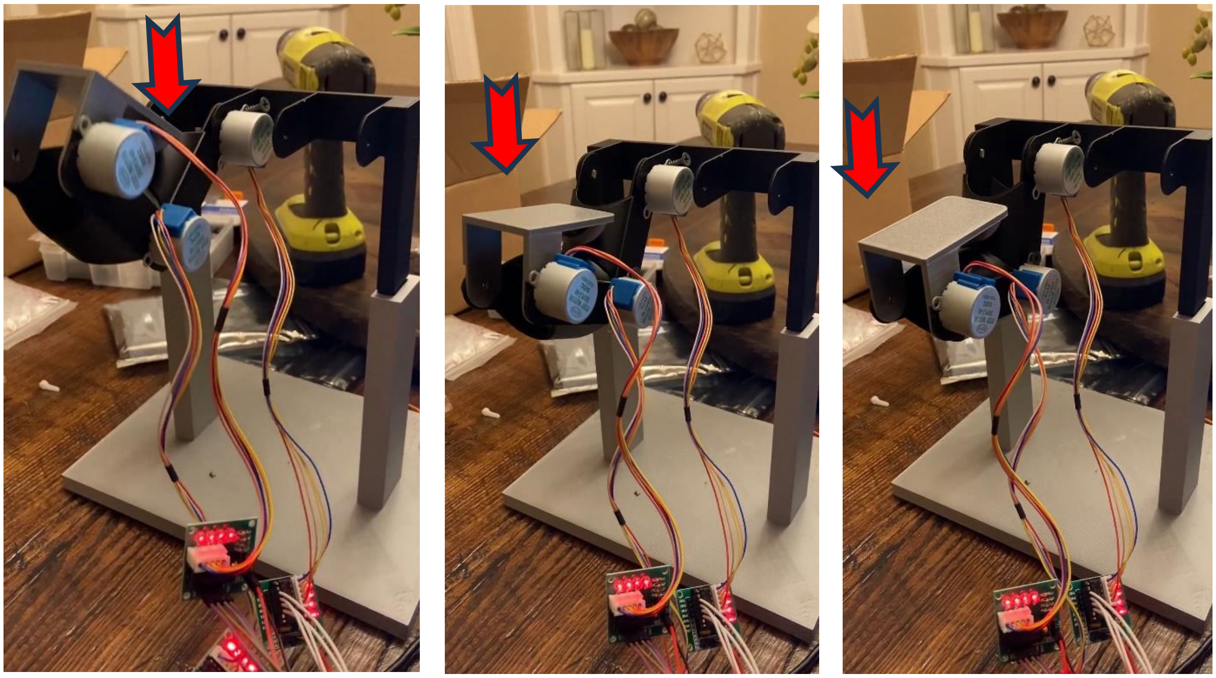

Figure 47. Hip Joint Test Position 1,2,3

Now that the visuals of the experiment has been showcased, lets look at the overall results of the test from a numerical standpoint. As stated earlier, the validation method for this prototype was this: at any combination of joint angles, the motors torque would automatically adjust to compensate for the force of gravity, meaning the assembly would stay in place however it was left, and move without force.

So then, the control variable in the experiment was the angle at which each joint was placed, and the measured variable was how much the joint moved after it was released. To explain, if the hip, knee, and ankle joint are all at 90 degrees, the leg would be straight out, and if it performed correctly, the movement in each joint after it is released should be zero.

Firstly, we will cover the results for the Ankle. Here, the ankle was manually adjusted and released every 5 degrees, and the movement of the joint after release was then measured, and compared to the expected value. Here, a perfect result would be the Set Position and the Position After Release being equal to one another.

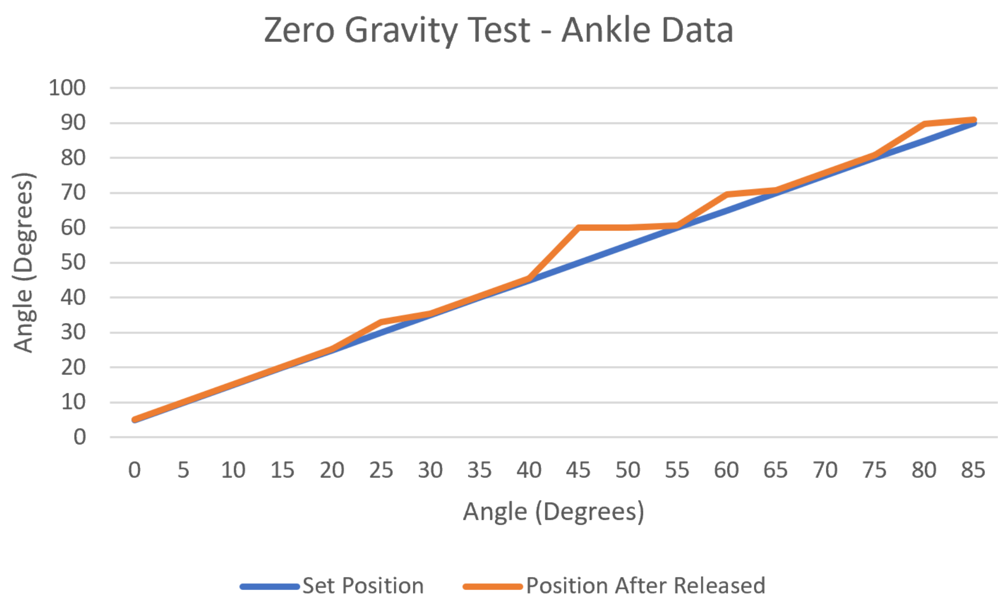

Figure 48. Zero Gravity Test Results – Ankle Joint

Based on the data here, it can be seen that for any set position up to 90 degrees, the small-scale prototype was able to achieve zero gravity in the ankle joint. The one primary fluctuation in this data can be seen at the 45-degree mark, where the small-scale prototype tended to overcorrect its joint torque, causing an – on average – 5 degrees of unwanted movement.

Next, the results for the knee joint can be seen. Many experiments were done with the Ankle joint at varying positions as well during this study, but in the one shown below only the knee joint was moved, as moving the ankle joint did not prove to affect the results. In this study the hip joint angle was set to be 45 degrees as well.

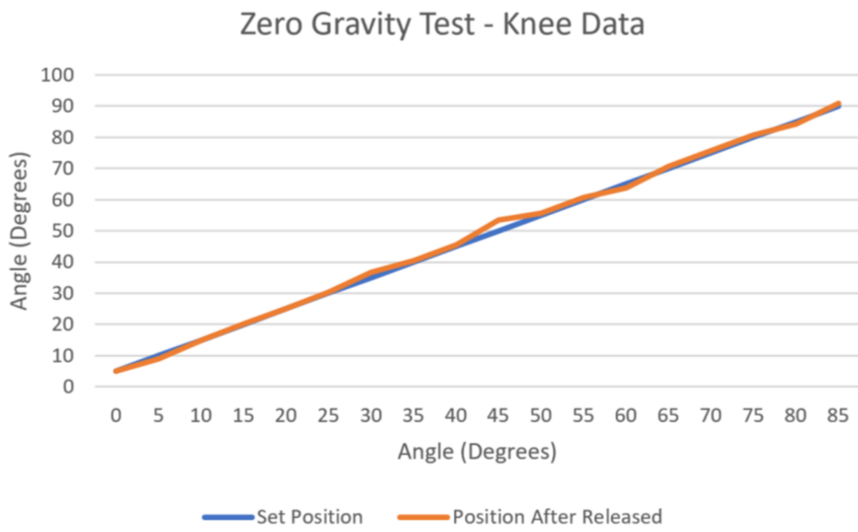

Figure 49. Zero Gravity Test Results – Knee Joint

As seen here, the knee joint movement stayed in its set position even after release, with a very small margin of error. The knee joint actually had an improved performance compared to the ankle joint, which falls in line with the error percentages found in the TinkerCAD results that utilized a base version of this system.

However, the Hip Joint is where problems arose, as already mentioned. The resulting movement data can be seen below.

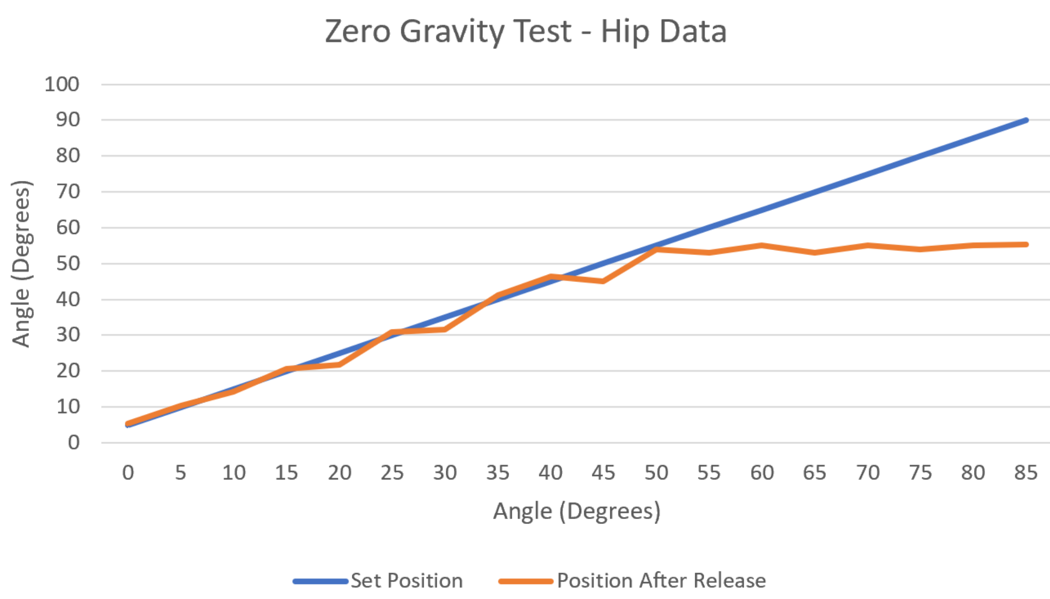

Figure 50. Zero Gravity Test Results – Hip Joint

As seen here, at lower angles, the hip joint performed exactly as expected. However, the angle was increased beyond 45 degrees, the motor was unable to support the weight, and so it would fall back to the 45–55-degree position regardless of set position. This experiment was also conducted again with the knee joint extended out, and a similar result can be seen below.

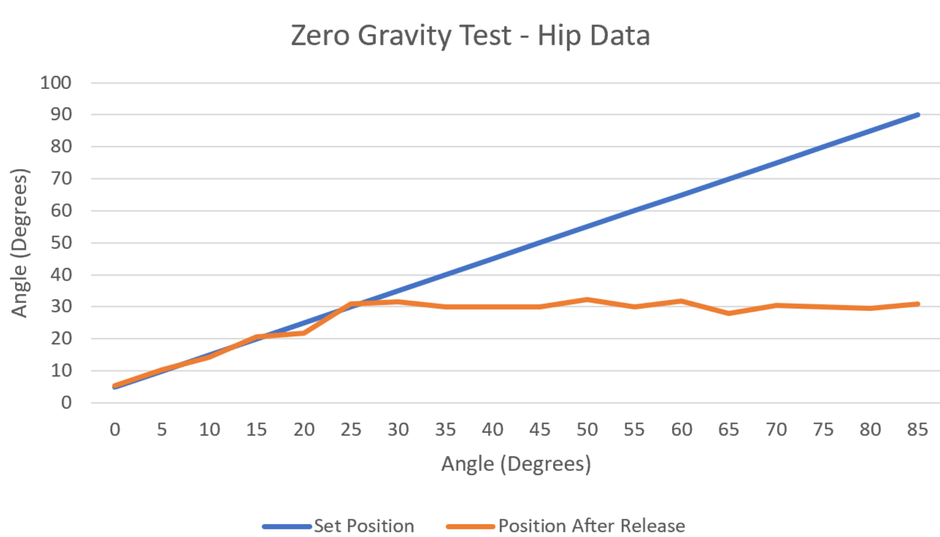

Figure 51. *Zero Gravity Test Results – Hip Joint 2*

Here, given the additional load due to the extended knee joint, the hip could not support any position greater than roughly 30 degrees from its own initial starting point. After multiple tests, it was concluded this was not due to an issue with the code, but rather the motors themselves are too heavy with relation to their output torque, and so the hip joint simply does not have the torque capabilities to support the leg assembly with two other motors attached.

All of this data validates the zero-gravity concept, by way of the experiment with the small-scale prototype, proving it is capable of keeping the leg assembly suspended evenly at any needed position, while also allowing free movement with minimal effort.

4.2 Daily Activities & Sit to Stand Movement – Results & Validation

Now that the zero-gravity concept was tested and validated, it's time to focus on the second objective of the leg assembly, which was to aid in accomplishing daily activities such as sit to stand motion.

4.2.1 CAD Model Creations for Sit to Stand Motion

For the Sit to Stand model, it can be seen attached to the preliminary RWTD below. This first figure represents how it will work when the patient is in the sitting down position, or with their knees bent at a 90-degree angle.

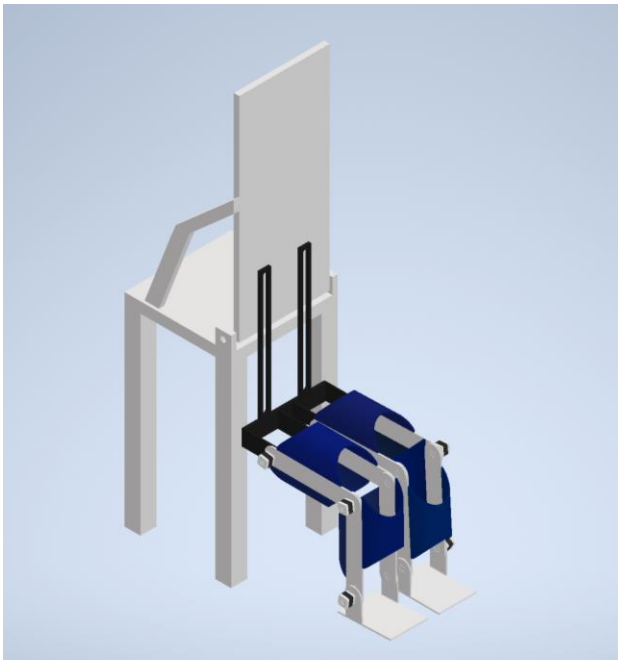

Figure 52. RWTD with Sit to Stand Assembly.

Now, the modified hip base allows the leg assembly to slide up the RWTD, which allows the patient to stand up.

Now, in addition to the virtual model created above, the CAD modules for the small-scale prototype utilizing servo motors can be seen below.

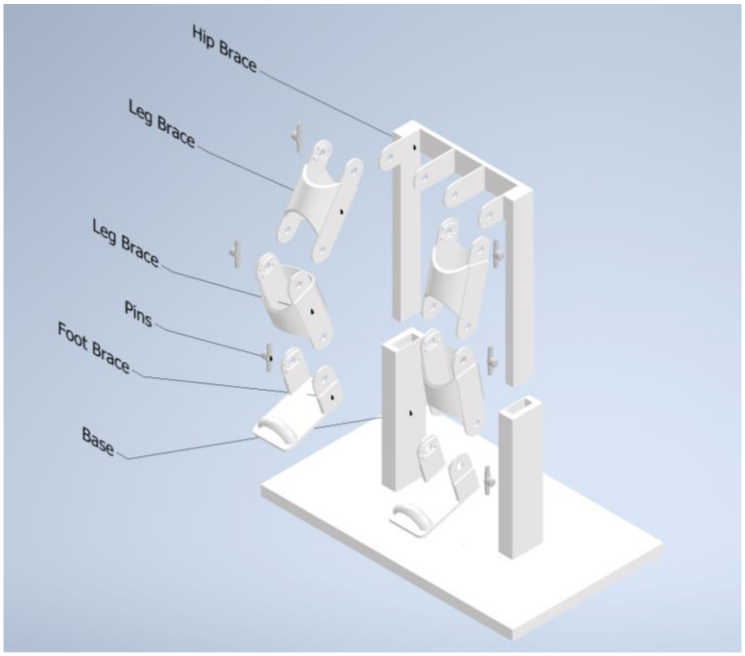

Figure 53. Small Scale Prototype – Servo – Expanded View

4.2.2 Results & Validation from Prototype

For this stage, given that the DC Motors were not capable of supporting the hip joint at full extension, and since free moveable is no longer a concern, it was decided to change to using Servo motors to accomplish the experiments. From here, the first validation attempted was that of the sit to stand process. Here, the hip brace that would allow for a sit to stand motion had not been created, but the motion itself can be verified.

After a few trials, the sit to stand – or in this case stand to sit – movement can be seen below.

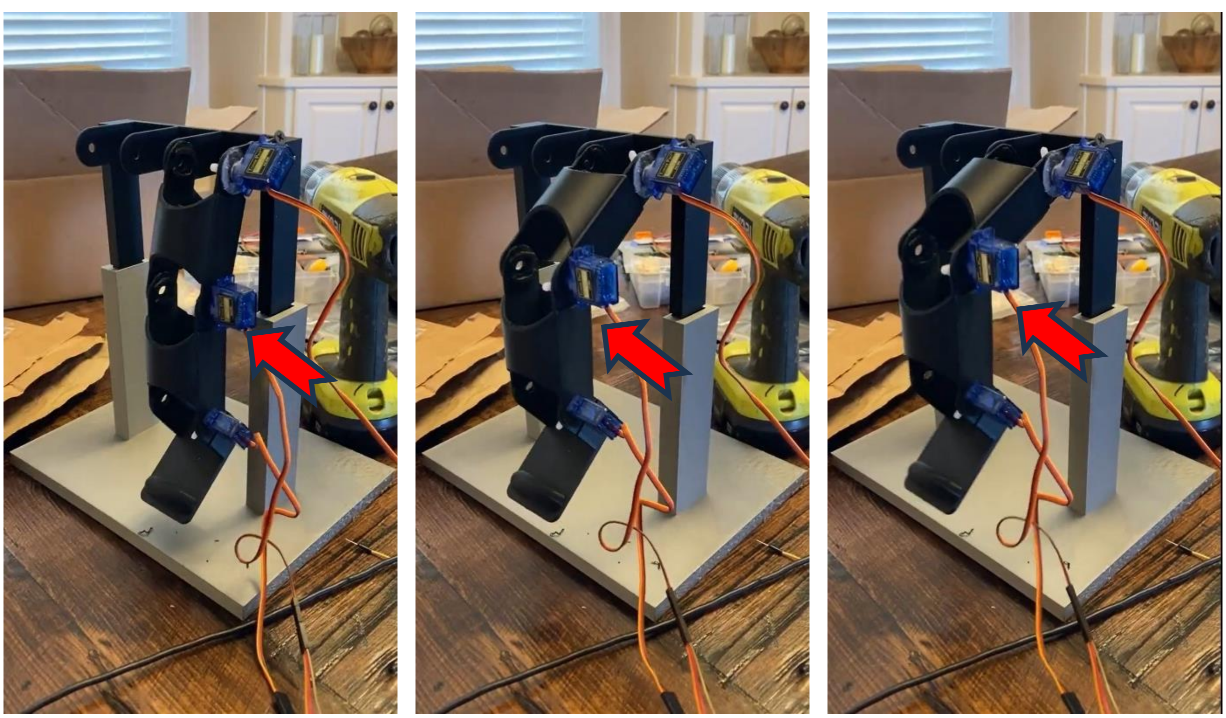

Figure 54. Stand to Sit Movement 1,2,3

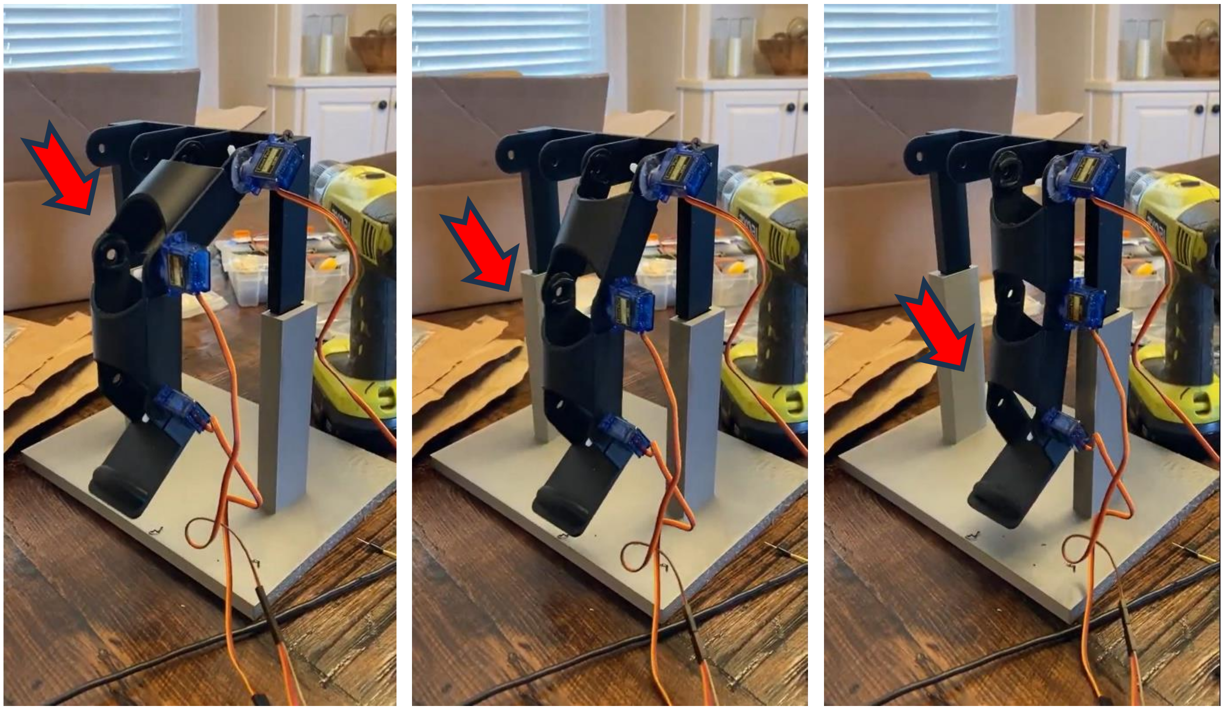

Figure 55. Sit to Stand Movement 1,2,3

In the images seen above, it can be showcased that the prototype was able to move from both a sitting to standing position, and then back from a standing to a sitting position. One caveat to this test is the fact that it can be noticed the hip does not extend straight out in the sitting position, rather it stops at the 45-degree mark. This is because like the DC Motors, the servos struggled to be able to lift the weight of the prototype once they were attached to it. However, with the slightly extra range of motion than the DC Motors, it was able to validate the sit to stand motion, and with a more powerful motor, full range of motion would be achieved.

Now that the prototypes had validated the sit to stand motion, it was time to try and use the servo motors to implement other daily activities as well, and what better to test than that of simply walking.

So, the code was adjusted, and the first test was done.

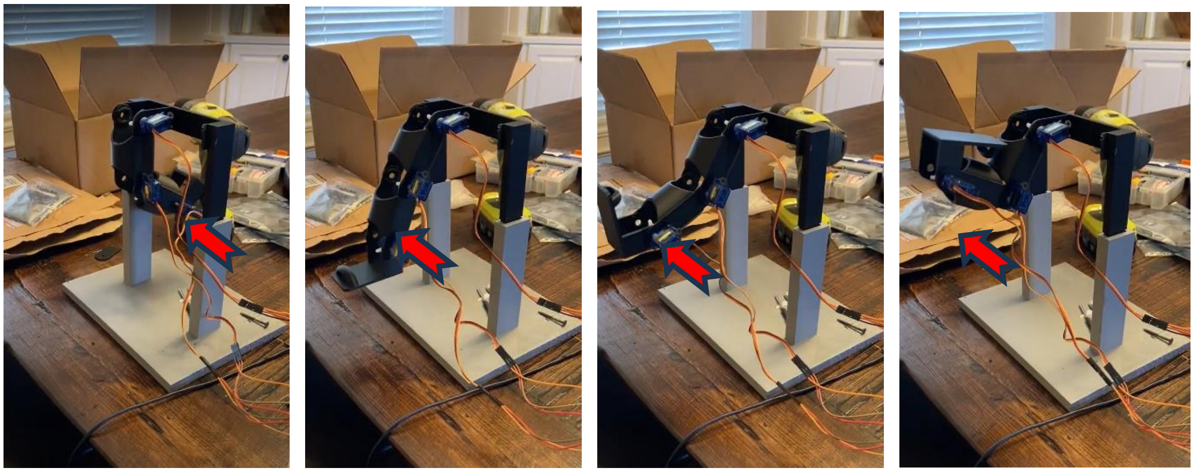

Figure 56. Walking Motion – Servo – Test 1

As showcased by the images above, the initial test was a success for the hip joints motion, as well as the backwards portion of the movement. However, for the front portion of the movement, both the knee and ankle motors spun in the wrong direction, which in practice would not be a desirable outcome by any patient wearing it, unless of course a variation was made for certain species of birds, such as flamingos. So then, the code had to be adjusted to fix this issue, and this was done by adjusted the target positions for the knee and hip joint.

Several tests later, this was the result.

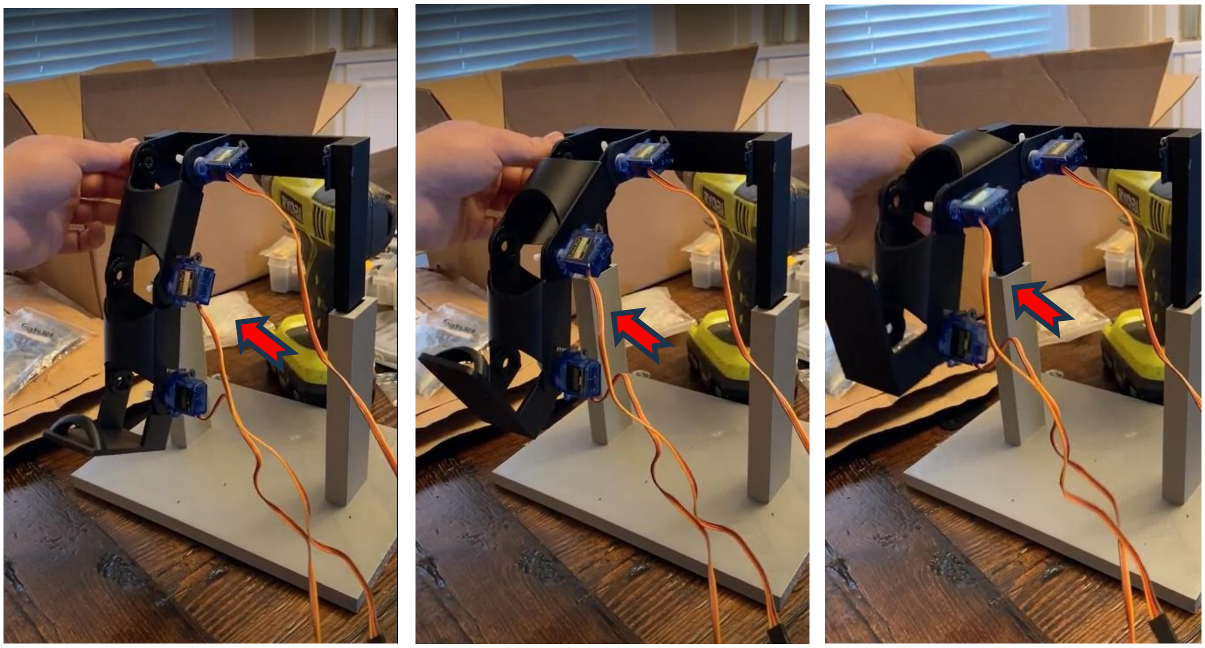

Figure 57. Walking Motion – Test 7

From here it can be seen that the forward motion grew much more accurate, although the ankle joint still overextended the foot at the end of the motion. From here, more tests were conducted to adjust the movement further and add the entire movement back in, and the result was the following.

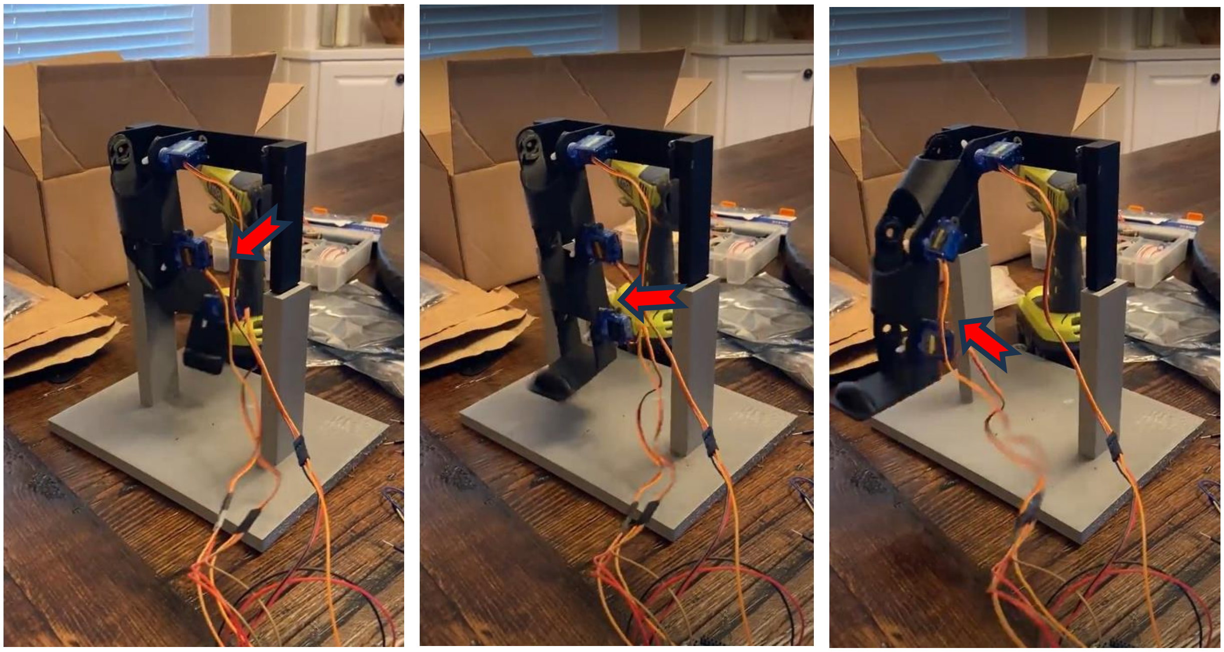

Figure 58. Walking Motion – Test 17

As seen here, this motion more closely resembles that of a human step. From here more iterations were made to adjust the speed at which it moved, which cannot be captured via these still images, but overall, the motion of a human step was achieved. Not only this, the coding was done using the process of actually controlling each step the motors take relative to position, so any daily activity could be programmed in so long as the data existed for it.

This experiment in controlling movement validates the objective to achieve daily activities such as sit-to-stand motion and walking, etc.

4.3 Full Scale Prototype Creation & Results

Now, that the leg assembly has been covered in full, its time to look into the creation for the Full-Scale Adjustable Size Prototype. As stated previously, this prototype was designed such that its size could be adjusted to fit various persons.

Here, the full-scale prototype can be seen, being worn by a person of average size.

Figure 59. Full Scale Prototype in Action

Now this model does not have motors attached, so it’s not at a stage to be used for variable gravity, but this test validates both the dimensions of the full-scale model, as well as its adjustable size capabilities.

4.4 Walkway Platform – Results & Validation

While up until this point the prototype creation and results have been focused on the leg assembly aimed to help people walk, this brings us to the other half of the project was that intended to do the exact opposite; make people fall. Or at least, disturb their walking path.

4.4.1 Stress Analysis of Walkway Modules

With this goal in mind, the first step taken was to perform some analysis on the CAD Models themselves. While the aluminum would provide some additional support, it was thin enough that the base design itself was to be tested, to ensure the hollowing out of the inner sections would not lead to a fracture. Unfortunately, Inventor does not support surface analysis for wooden materials. To bypass this issue, the platform was set to be made of a weaker material, namely ABS Plastic, and a stress analysis of it was done, which can be seen below in Figure 60.

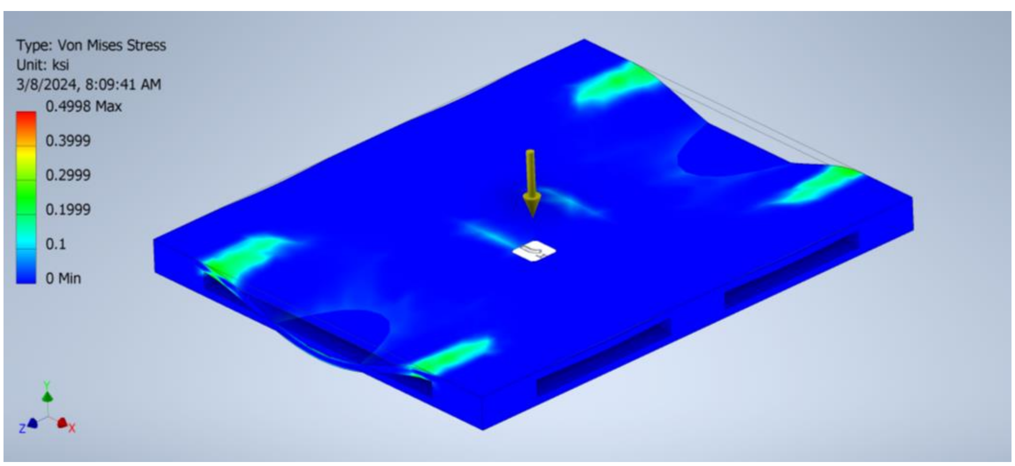

Figure 60. Stress Analysis of Base Design

This was the result of a 100 Nm force applied to the top surface. The actual values found for the deformation will not be accurate to that of the actual model, given the differences between

ABS Plastic and Plywood, but this was useful for finding out where the weak points would be, if any. As shown here, the joints under the most stress are the inner corner joints. So then, when a model is built from plywood, they are the joints that will be tested the most to verify they are strong.

Stress analysis was also done for the slipping module, as it is the only module that will undergo force that is not similar to the top-down force shown above. For the slipping module, the force comes from the impact of the sliding block onto the front piece of trim. Here, this force can be seen both when the module is isolated, as well as when it is placed within the larger walkway assembly, in Figures 61 and 62.

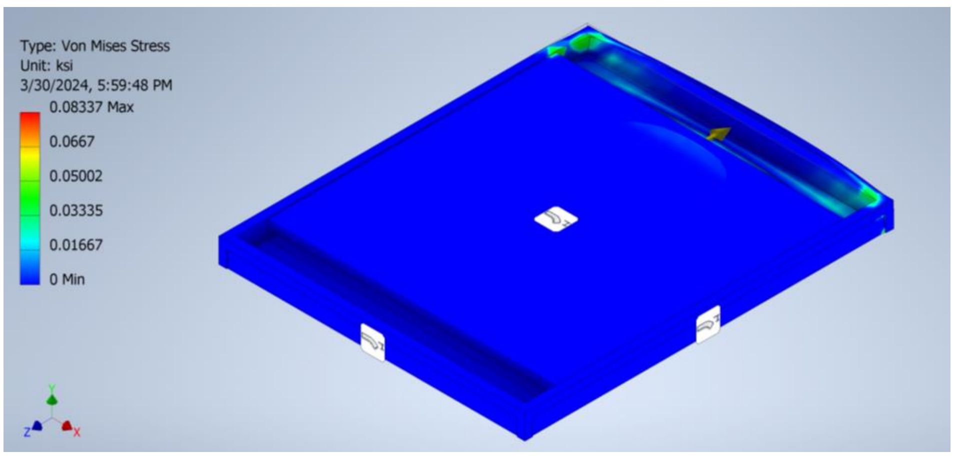

Figure 61. Stress Analysis of Sliding Block

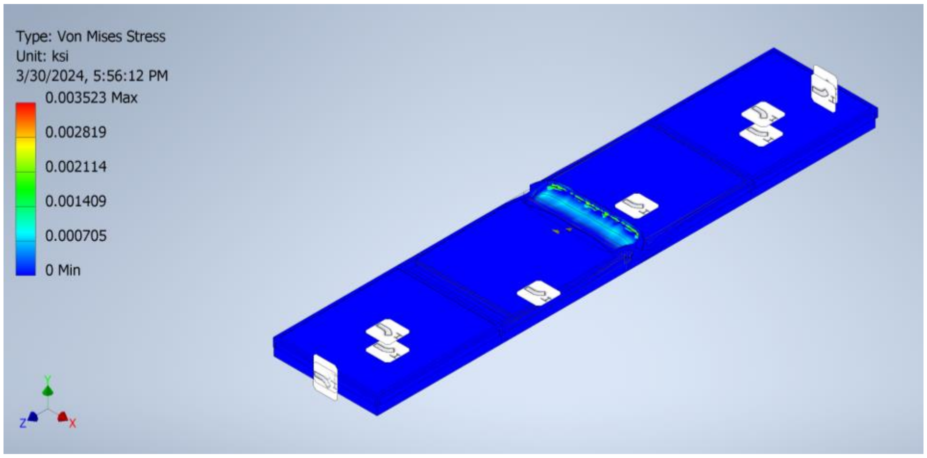

Figure 62. Stress Analysis of Sliding Block in Assembly

4.4.2 Creation of Walkway Modules

From there, creation of the actual modules could be started. For the base design the pieces of wood were cut out to be 47 inches x 39 inches, with the middle two layers being constructed from 6 x 6-inch blocks stacked on top of each other. All of this was connected via wood screws to increase stability. From there, aluminum sheets where cut to the same length and width and placed on top of the plywood's surface. L Stock was then cut off and placed on the edges of the entire modules to provide the trim. Liquid Nails was the original adhesive used to connected the aluminum to the plywood, but after strength testing it was found to be too unreliable and would break when force was applied – such as the force of the slipping block which will be mentioned later – and so screws were instead applied to the surface aluminum as well as the trim, to ensure everything stayed in place.

The resulting normal module can be seen below in Figure 63.

Figure 63. Normal Module

Notice the wheels attached to one side, and the handles attached to the other. This was due to the weight of the modules, to allow for easy movement. The wheels can also lock in place so that the modules can be stored upright. This was applied to every module.

In total, three normal modules were created.

Next up, the surface drop module was created. One side of the platform was hollowed out, and only a thin layer of aluminum was placed at the top, with nothing holding up other than a strip of magnets. This was attempted using foam for the hollow surface, as mentioned earlier, but eventually magnets were settled on, as they allowed for a much more abrupt and steep drop.

The surface drop module can be seen below in Figure 64.

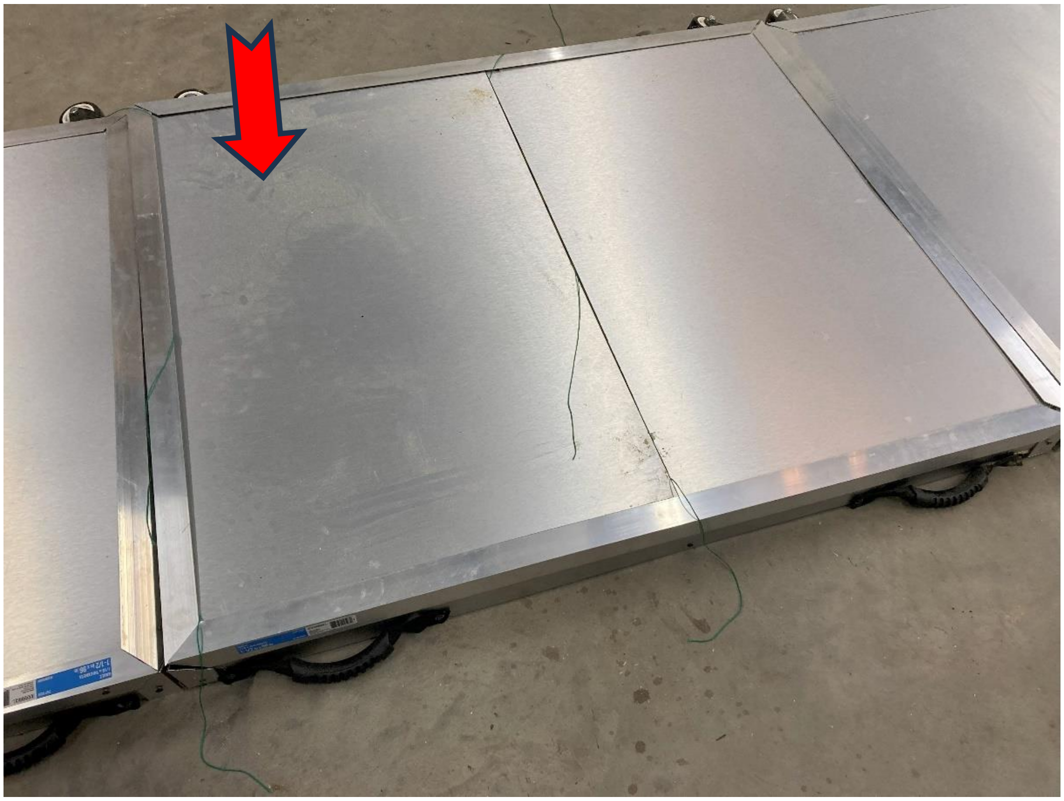

Figure 64. Surface Drop Module – Initial Position

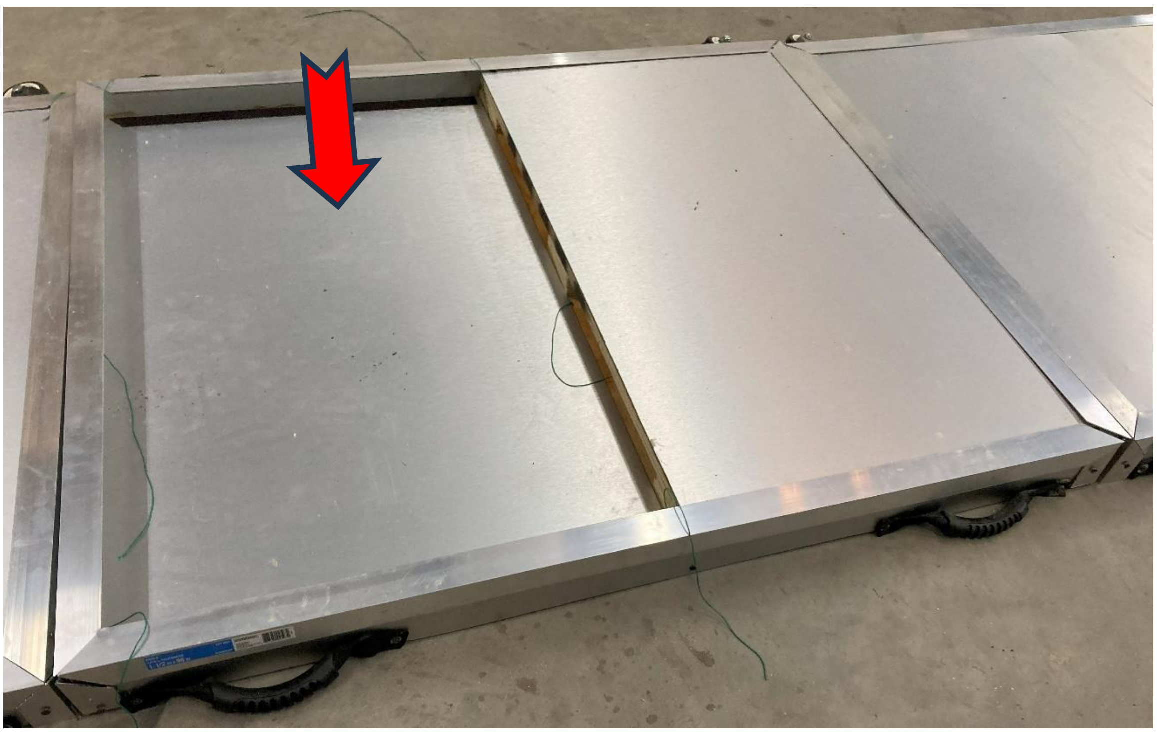

Figure 65. Surface Drop Module – Dropped Position

Showcased above in Figure 65 is the surface drop module at its lowest point, so that the drop can be seen. In the upper edge the strip of magnet attached to the surface aluminum can be seen. The string pictures was placed as a way to lift the surface back up once it had fallen over. For this example, it was left green so it would show up, but in practice grey string can be used to better conceal it.

With that achieved and tested, the slipping module was the next one to create. This was done using rail wheels beneath the top surface, which slides on the bottom layer of plywood. This top sheet was cut to be 41 inches rather than 47 to allow for it to move freely up to 6 inches, and the side, front, and back aluminum trim held it in place, providing a firm barrier once they were attached via screws.

This slipping module can be seen below in Figures 66 and 67.

Figure 66. Slipping Module – Initial Position

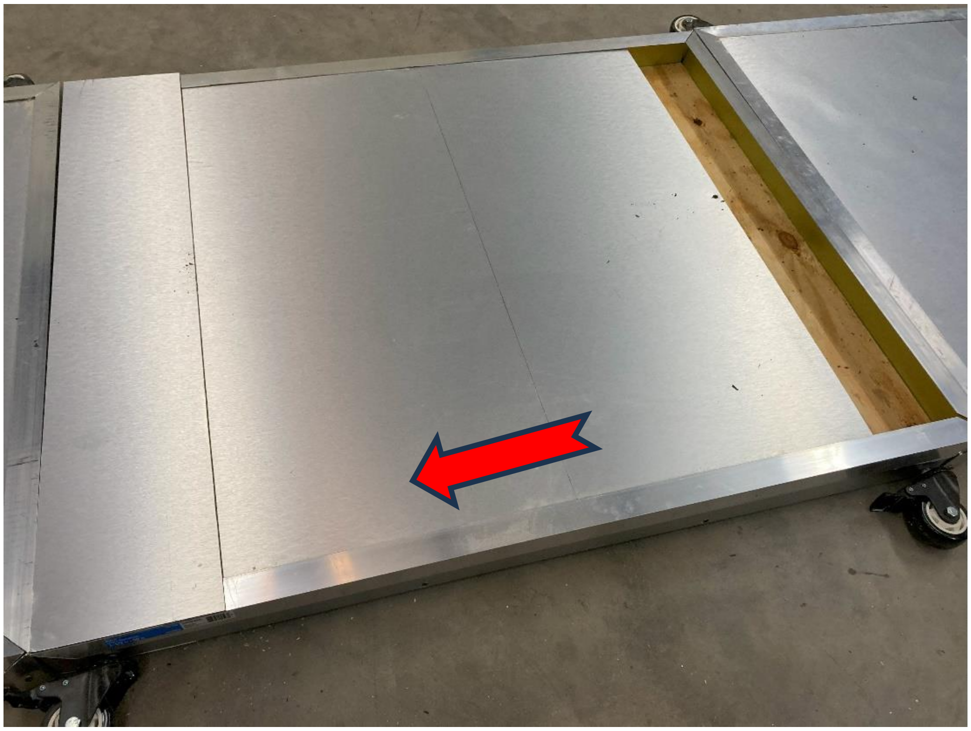

Figure 67. Slipping Module – Slid Position

This direction was set in order to slide backwards, therefore making the patient fall forwards, but it can slide in either direction if the need arises. Testing also proved it to be effective, so much so that when loading it up with the others it almost caused two different people – and a German Shepard – to fall down by mistaking it for a normal module.

The original design for this was intended to be freely moving, but a modification was requested to implement locks on either side via catches, which will hold the sliding platform in place on either side once the slip has occurred, until excess pressure is applied to overcome the catch and return it to its original position.

For the last of the disturbance modules, the tripping module was created. This one was completed with a few different variations, to test the tripping motion. The base design was a normal module with a rectangular slit cut from the top of it, and then hinged on one side to allow it to rotate up.

The first version created utilized a mini actuator in order to raise the tripping block. This actuator had a speed of 1 inch per second, but was placed in such a way as to artificially extend the length of the block it could raise in that time, to achieve something closer to 2 inches per second. This version can be seen in the Figure 68 below.

Figure 68. Tripping Module with Actuator

As seen here, the tripping block raises in such a way that would disturb the walking path of the subject walking across it.

Another variation of this module was then made, this time utilizing a spring rather than an actuator, in order to increase its speed. The first version of this included a manual release, but it has since been modified to include an actuator in place of a manual release pin, which can activate with the pressing of a button, which will increase safety. This can be seen in Figure 69 below.

Figure 69. Tripping Module with Spring

Once those were completed, it was decided that basement modules should be added to the project as well, in order to provide a platform where the force plate could be hidden. These basement modules needed to be the same length and width at the normal modules, but with a modified height to set just a centimeter below the force plate. For the first three, they only needed to provide a base to raise the other modules up, and so they were made as simple wood blocks with strips of support running down the middle of them to increase stability. For the fourth, a rectangle was cur from the middle to allow space for the force plate to be placed into. These basement modules can be seen in the Figures 70 and 71 below.

Figure 70. Basement Modules

Figure 71. Basement Module – Anterior

In practice they will be placed beneath the normal modules.

As mentioned earlier, another variation of the basement modules was also added, this one designed so that it could be placed alongside the normal models, so that patients could step directly onto the force plate, rather than it being hidden beneath another module. This one also required a small cutout of aluminum that could be layered on the force plate in order to hide it, all of which can be seen below in Figure 72.

Figure 72. Alternate Basement Module

This design also required a variety of smaller basement modules to be made that could adjust the height of the normal modules, and some of them can be seen below in Figure 73.

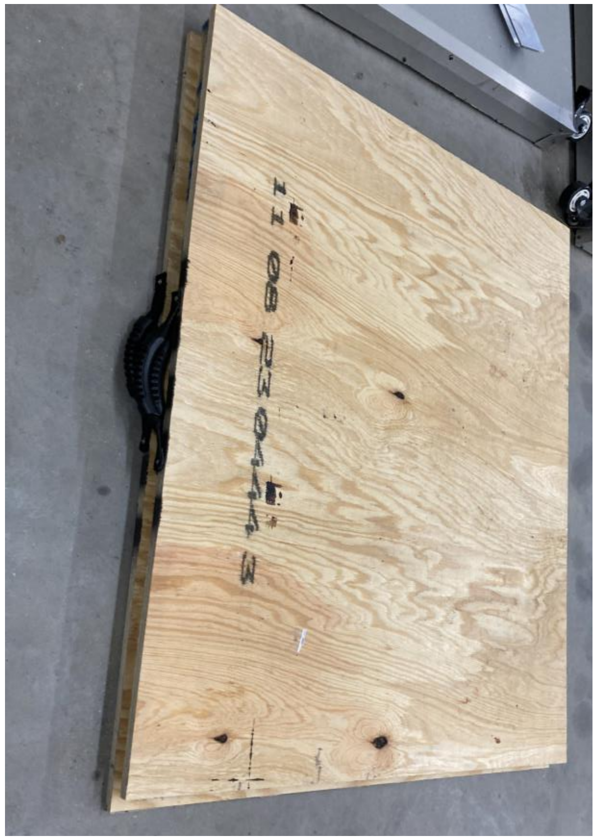

Figure 73. Shortened Basement Modules

In Figure 74 below can be seen that showcase most of the modules created, placed in line with one another. At this stage the aluminum had not been added to the top of the tripping module, but that was resolved later after this photograph was taken.

Figure 74. Complete Walkway Platform

In total, a platform of almost 40 feet could be constructed from the blocks made, with a total of 1,336 square feet of surface area. In practice, different configurations of 4 modules will be made, totaling at 15.6 feet long, which fits within the testing space required, in addition to matching the length of the bars supporting the safety harness.

The actual motion capture tests that will be conducted using this walkway platform was not within the scope of this project, as this project's goal as aimed solely at creating the walkways modules themselves to the standard of testing set by the Kinesiology Department, which has been achieved.

This completes the walkway module section of this project, with all the necessary modules being created, tested, and validated.

4.5 Suggested Future Work

Now that the results have been showcased, and the designs validated, it's time to discus what can be done in the future to further this work.

4.5.1 The Leg Assembly & The RWTD

Now that the small-scale models were validated, the next step would be to expand further and make a full-scale prototype. For this the Full-Scale Adjustable Size CAD Model could be used, as it is to scale and fit all the requirements needed.

For the Full-Scale model, larger motors such as a Robotzone 12 V Planetary Gear Motor could be used – which on average cost between 25 dollars to 50 dollars apiece – or one of a similar kind, while most of the other material such as accelerometers could stay the same. Regarding The leg braces could be 3D printed with ABS Plastic, which would reduce the cost of each brace to less than 10 dollars, with the various pins costing less. The cost for the frame would vary based on what type of metal was used, and whether it was precut to the shapes required or bought as sheets, but currently the price of $1/4^{th}$ inch steel sheets that are 4" by 7 ft 8" is 33 dollars, so it follows that the frame could be constructed for less that 150 dollars, meaning that a complete leg assembly with six 12V motors could be created for approximately 300 dollars to 500 dollars, although that price would vary heavily depending on what brands of motors were purchased, alongside what type of metal, so it is likely possible to design one at a lower cost than this approximation.

An example of this, with the rods modeled in Iron and the Braces modeled in ABS Plastic, can be seen below in Figure 75, fitted with Planetary Gears.

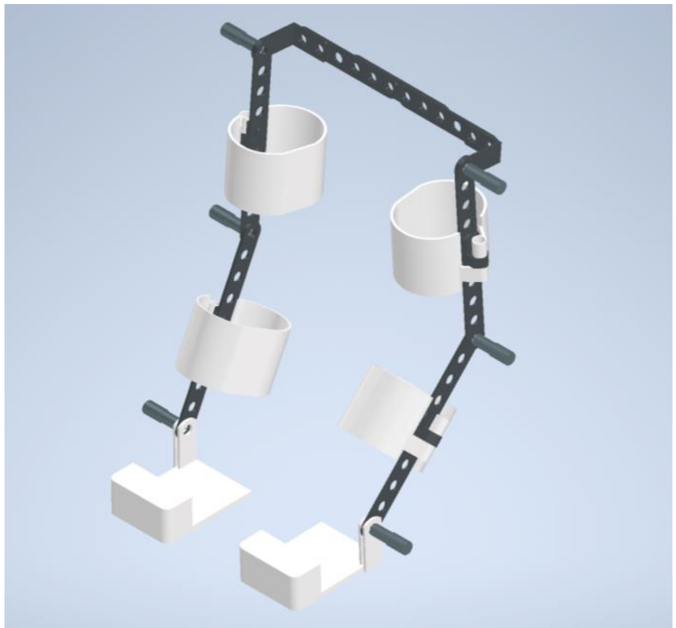

Figure 75. Full Scale Model

Once this CAD Model is built using stronger motors and materials, actual trials could begin, using the same systems already tested, simply on a larger scale, and from there hopefully a fully designed and working leg assembly could be created.

For a finalized prototype in the future, it would be advantageous to make a few further adjustments to the design. Firstly, while the hip plate designed here would allow for complete freedom of motion when combined with the wheels of the RWTD, it could be modified to allow trunk flexion while the RWTD remains stable, which might assist patients in earlier stages of rehabilitation who need more support. In addition, at this stage each joint allows only range of motion in the XY plane, meaning that while the leg can be moved up and down, the leg segments themselves cannot bend left or right. This would be especially noticeable on the ankle joint, given the human foots ability to balance itself by shifting its weight side to side, and so adding additional range of motion to the joints to allow them to rotate in the Z direction – that is, twist side to side – would be very useful. For that, more motors would be required, and additional equations would need to be derived to achieve zero gravity, by compensating for any additional torque that the twisting of a joint would cause.

4.5.2 The Walkway Platform

For the walkway project, the next step for future work will be for the actual motion capture tests to be conducted using it. As stated previously, this project's goal was to create the modules, but in the long term they will be used by the Kinesiology Department to test patient's responses to gait perturbations, and this data will hopefully prove invaluable for a great many research topics in the future, especially for later stages of the RWTD, such as the plan to eventually include gait training to the design. This will hopefully result in a RWTD that can achieve free moving zero gravity, while also using the data gathered from the Walkway Platforms to implement more accurate controlled motion, which will allow it to assist patients in recovery regardless of what type of rehabilitation they require.

The modules have already been delivered to the lab where they will be tested, and the motion capture cameras are already set up, as is the harness, and so testing should be able to commence in the near future.

4.5 Summary of Results

Thus ends the collection of results gathered from this project, which will be summarized in the conclusion down below. All this research, virtual and psychical prototype creation, results, as well as the foundation laid for future work will lead to gait analysis testing to be performed later using the walkway modules, as well as a robotic device that fills the gap in research by creating a simple, cost-effective design that could be implemented for rehabilitation across the country, in both rehabilitation clinics, and hopefully in patients own homes.[6]

Chapter 5

Conclusion

Ever since we learned how to walk, most of us take it for granted. Yet the purpose of this project was to not only shine a light on how many patients struggle with disabilities, but also provide methods for better testing and treatment of those patients, to ensure a better path to rehabilitation. Many disabilities were looked into, such as physical ailments like an ACL tear, to more neurological disorders like Cerebral Palsy or Multiple Sclerosis. Rehabilitation methods were researched, including Hydrotherapy and Zero Gravity Treadmills. Robotic Leg assemblies such as the BLEEX, ATLAS 2020 and LOPES II, to see how previous robotic leg assemblies had been constructed for different purposes, such as lifting heavy equipment. The RWTD developed previously at UT Tyler weas also investigated, as it would be the device that a full-scale model of this zero-gravity system would one day be attached to.

From there well over a dozen different variations of circuit setups and codes where tested and refined until a final version was completed that was able achieve virtual zero gravity. A small-scale prototype was modeled, printed, and tested using DC Motors, and it was found to achieve zero gravity in the knee and ankle joints, and achieved zero gravity in the hip joint to up to a 30-degree angle, at which point the motor itself could not apply enough pressure. A small-scale prototype for DC Motors was then designed and used to test the sit to stand motion, which was achieved. Then, the Servo prototype was coded to create a movement path of that of a human step, which could be used to achieved zero gravity in another direction.

From there, modifications were made to the circuit diagram as well as the code that would allow for the leg assembly to be adjusted for patients of different heights and weights, utilizing potentiometers for easy control. A CAD model of this adjustable size design was created with multiple different size options, and this was also 3D printed as a full-scale model to further validate the variable size capabilities.

While that was being completed, a concept for a walkway platform that could be used to test patients gait and reaction to disturbances was also looked into. Research was done on existing studies of a similar nature, finding that force plates and motion caption cameras were commonly used, but it was not common to be used in conjunction with robotics. Next, all of the walkway modules were created in CAD for advanced testing, and all the materials and dimensions were specified. From here, the full-scale platforms could be created. 3 Normal Modules were built, alongside 1 Surface Drop Module, 1 Slipping Module, 1 Tripping Modules, and a collection of basement modules to go along with them. All of this was then tested and validated to work as intended.

So, in total, this project results in several different Arduino Systems creating for zero gravity, an Arduino System created for a sit to stand motion, validated results via virtual models and small scale prototypes, CAD Models for four different leg assembly variations, over 100 3D printed parts that were constructed to form two small scale prototypes and one full scale prototype for variable size, as well as 10 total walkway modules that total up to almost 50 feet in total length and over 1,336 square feet of area. All this was done to further the testing and rehabilitation methods for patients suffering from walking disabilities. In conclusion, this project provides a better path towards rehabilitations for all patients suffering from these types of disorders. Because the unfortunate truth is, for some, the ability to walk is not something they can take for granted, but something that must work hard to ever achieve, and as engineers it is our duty to constantly push the research further, until the day comes that everyone can walk freely without pain.[7]

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Appendix A. Drawings of Assemblies

This appendix consists of a collection of drawings of the Leg Assembly shown in Figures 2, 31, 39, 43, and 44.

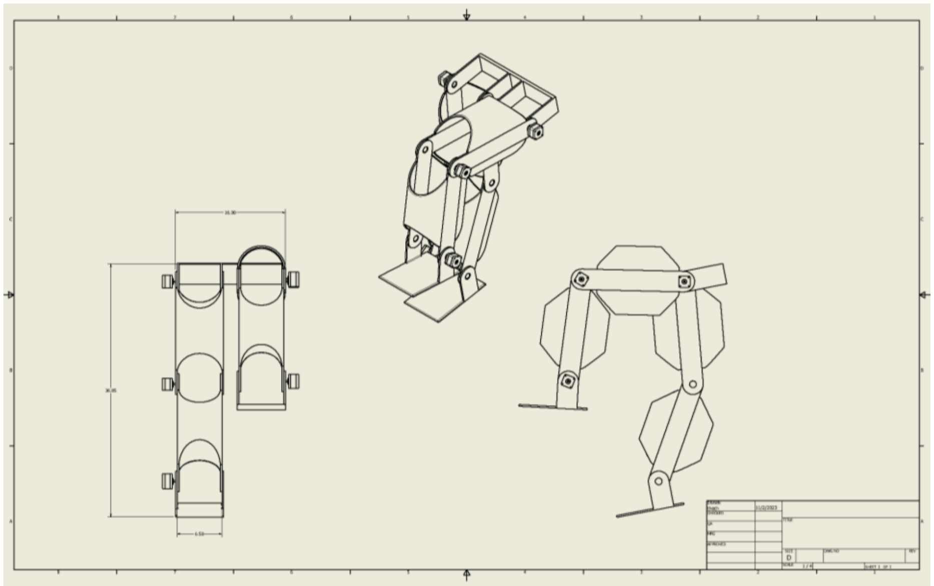

Figure A - 1. Leg Assembly Drawing.

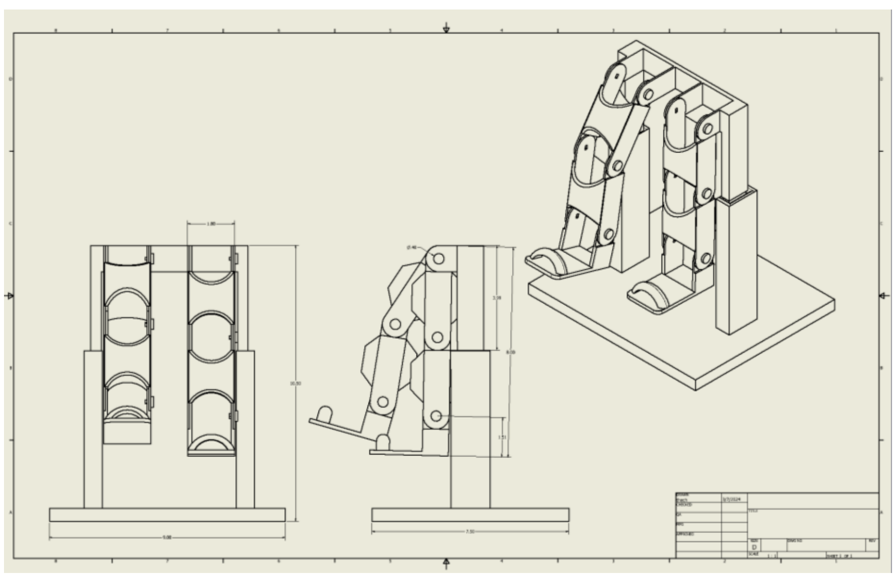

Figure A - 2. Small Scale Prototype – DC – Drawing

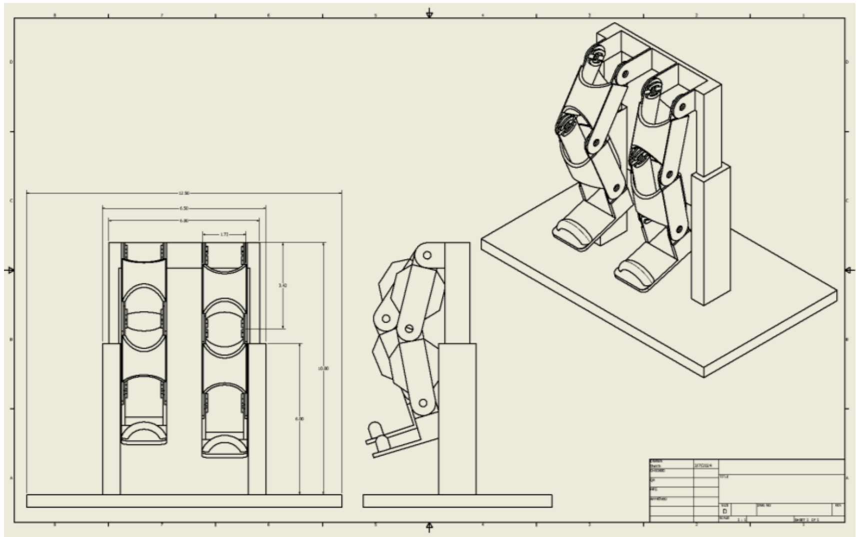

Figure A - 3. Small Scale Prototype – Servo – Drawing

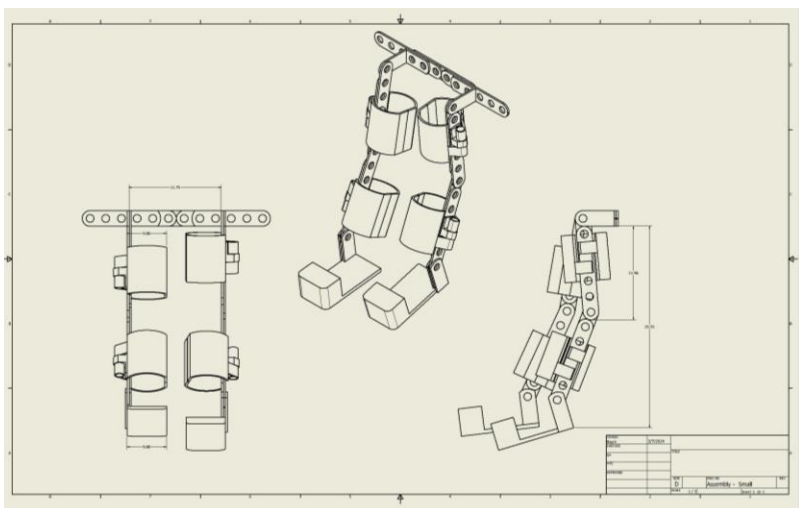

Figure A - 4. Full Scale Adjustable Size Prototype – Drawing

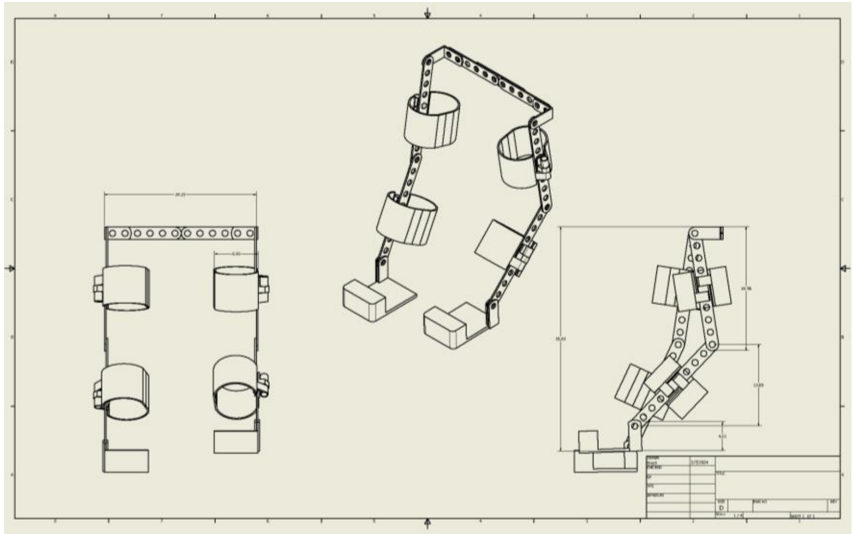

Figure A - 5. Full Scale Adjustable Size Prototype – Drawing

Appendix B. Tables

Table 1: Cost Analysis for Small Scale Prototype.

Item Name	Quantity	Cost
DC Motors	6	$16.99
Accelerometers	6	$18.99
Servo Motors	6	17.99
Arduino Power Supply Module	1	$2.66
Arduino Mega R3	1	$22.99
Steel Socket Head Screws	25	$12.58
	Total:	$74.21

Table 2: Bill of Materials for Exploded View.

ITEM NO.	PART NUMBER	QTY.
1	Hip Attachment Plate	1
2	Long Rod	8
3	Thigh Holder	4
4	Lower Leg Holder	4
5	Foot Base Plate	2
6	Short Pins	12
7	DC Motors	6

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