Development of a Mobile Ankle Joint Attachment For the Universal Prosthesis

Senior Design Project Critical Design Review

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BME 488

ECE 488

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Executive summary

Ideally, a prosthesis allows amputees to recover their walking abilities; however, below-knee amputee patients often have muscle atrophy in their amputated limb, which causes walking complications. Dr. Ha Vo tasked our Senior Design Team with designing a mobile ankle joint prosthetic attachment to promote muscle rehabilitation and improve gait.

Our senior design team is composed of Gabriel Gonzalez, BME, Jenna Hamlin, ECE, and Jackie Harmon, BME. The main and final goal of this project is to create an affordable, operational, and safe mobile ankle joint that can be used in the Universal Prosthesis in order to help amputees who suffer from muscle atrophy to regain their natural gait. This will maximize the efficiency this prosthetic has in assisting amputees who are unable to return to normal gait. In order for this design team to complete this task, a biomedical engineering professor and an electrical engineering professor have been requested and approved as advisors.

After a full development, feasibility analysis, testing, and discussion of the chosen design, Design 15: One Upside Down Ligament Chain Belt Mobile Ankle Joint presented, the team was able to define the design as a successful prototype after the addition of several components such as the backbone.

The deliverables of this project received by the Client were: a 3D printed prototype of the ankle joint, a Nylon prototype fully assembled into the mold of the foot and the electrical component, an informative brochure, and copies of the circuit program, design sketches, CAD designs, and the inventor analysis in metal.

The client will find that the ankle joint designed by this team will not only allow the wearer to return to a normal gait but will also function as a rehabilitation device for lower extremity muscles. This is, however, the very first prototype of the ankle joint for the Universal Prosthesis. It’s well understood that there are to be some more development into this design for it to performed under the weight of an amputee patient. Finally, the design of the prototype itself is functional and stable. It represents a safe device but it needs further work into the production of it in an aluminum version to mesh well with the Universal Prosthesis.

Acknowledgements

Our senior design team could not have come this far without the help of some very important people (VIP):

Dr. Vo, our client for senior design and advisor for Biomedical Engineering. He was able to offer guidelines and advice throughout the project for the biomechanics of the design, as well as specification about the end result of the project and how it would function in Vietnam.

Dr. Fu, our advisor for Electrical Engineering. She was able to help us with the design of the electrical components as far as which were needed and how to calculate which models were necessary.

Dr. Jenkins, the professor over senior design. He taught us how to write and present a Preliminary Design Review (PDR) and Critical Design review (CDR). He also helped us with our design when it came to gears and how they functioned.

Dr. Wright, the assistant professor over senior design and the one specifically over our group. He checked in with us periodically for updates and offered advice for us on how to achieve our goals on this project.

Dr. Ekong, a professor in the Electrical Engineering department. He was able to help us in the area of our circuit design and microcontrollers.

Dr. Hill, a professor in the Mechanical Engineering department. He was able to help us brainstorm designs that would work from a mechanics standpoint, since we did not have a mechanical engineer on the team.

Dr.Choi advised the team on the subject of motors and offered design suggestions to best implement the motor.

Jake Kutrufis offered advice on motors.

Dr. Sumner provided the team with the MasterCam key.

Dr. O'Brien reviewed the design and made several suggestions, including using buttons for the sensors. He also suggested the microcontroller which was used for the final design.

Dr. Kunz advised on the chain design.

Mr. Mullins provided the team with the MasterCam key. He also helped brainstorm chain attachment ideas.

Alec Tabasco and Josh West in the machine shop helped weld and cut pieces for prototyping.

Mr. Jeremy Barker, the Engineering Electronic Laboratory Technician, we could not have 3D printed our prototype.

Ms. Rogers, a secretary for the engineering department. She keeps track of records and scheduling and without her, we could not have scheduled our PDR presentation.

A special thank you goes out to each of the VIPs mentioned above for patience with our team and the personal time they dedicated to help us succeed. Also a thank you to our friends and family members who supported us through this with words of encouragement and motivation.

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Glossary

Dorsiflexion: backward bending of the foot that causes the angle between the foot and the anterior section of the leg to decrease.

Fibula: outer, smaller of the two bones located between the knee and ankle joints.

Flatfoot: the phase of the gait during which the foot is flat on the ground; this phase occurs after heel-strike and lasts until heel-off.

Frontal axis: Line around which the working joint rotates in the sagittal plane.

Frontal plane: vertical plane that divides the body into anterior and posterior.

Heel-off: the phase of the gait during which the heel rises from the ground; this phase occurs after flatfoot and lasts until toe-off.

Heel-strike: the phase of the gait during which the heel strikes the ground; this phase occurs after the swing phase and lasts until flatfoot.

Longitudinal axis: Line around which the working joint rotates in the transverse plane.

Phases of the gait: the segments into which a gait can be separated; these correspond to different positions and movements of the foot during gait and are named as follows: heel-strike, flat foot, heel-off, toe-off, and swing.

Plantar flexion: forward extension of the foot that causes the angle between the foot and the anterior section of the leg to increase.

Sagittal axis: Line around which the working joint rotates in the frontal plane.

Sagittal plane: vertical plane that divides the body into left and right.

Swing phase: the phase of the gait during which the leg has been lifted from the ground and swings to begin a new step; this phase occurs after toe-off and before heel-strike.

Tibia: inner, larger bone of the two bones located between the knee and the ankle joints.

Toe-off: the phase of the gait during which the toe is is lifted from the ground; this phase occurs after heel-off and marks the beginning of the swing phase.

Transverse plane: horizontal plane that divides the body into superior and inferior.

Universal Prosthesis: the below-knee prosthetic leg fitted to amputee patients in Vietnam as a part of the Mercer on Mission program

Introduction/Background

Many obstacles stand between an amputee's stump and the right fit of a prosthesis. Helping patients achieve natural knee and ankle movements has proved difficult within lower-limb prosthetics. Even with the most advanced technology, imitating the nature of human movements proves a great and complex challenge (Dellon and Yoky, 2007). The field of prosthetics is constantly changing and developing, and the fitting process of a prosthesis varies as much with the level of technology used as it does on a patient-to-patient level.

Ideally, a prosthesis allows amputees to recover their walking abilities; however, below-knee amputee patients often have muscle atrophy in their amputated limb, which causes walking complications. Dr. Ha Vo tasked our Senior Design Team with designing a mobile ankle joint prosthetic attachment to promote muscle rehabilitation and improve gait.

Our client, Dr. Ha Vo, MD, Ph.D., DPM, is the Associate Research Scientist with the School of Medicine at Mercer University as well as the Associate Professor in the Department of Biomedical Engineering. Dr. Vo currently offers biomechanics and biomaterials courses for undergraduate biomedical engineering students, as well as graduate courses on Musculoskeletal Injury Mechanics, Advanced Biomechanics, and Advanced Biomaterials of Orthopedic Implants. Moreover, Dr. Vo, in conjunction with other faculty from the biomedical and mechanical engineering departments, leads a Mercer On Mission program to Vietnam in which students are able to take two courses on the mechanics and instrumentation of prosthesis, with a focus on the Universal Prosthesis, shown in Figure 1, that Dr. Vo has himself designed. During this trip students have the chance to shadow Dr. Vo and other professors, get the chance to work on real amputee patients, and provide a service to the Vietnamese community while learning and experiencing their culture.

Dr. Vo focuses his research on several topics from which some are designing orthopedic implants, gait analysis, designing rehabilitative and medical devices for the disabled, and, of course, prostheses and orthotics. Dr. Ha Vo is also the Faculty Advisor for both the Mercer Vietnamese Student Association and the Mercer Prosthetics and Orthotics Club, which are Mercer University student led organizations that focus their time on raising money for the Vietnam cause and developing research on prosthetics and orthotics for amputee patients.

Figure 1: The current Universal Prosthesis

The low-cost Universal Prosthesis, developed by Dr. Ha Vo, is designed to quickly fit to patients with nearly any type of stump. The prosthesis is built of materials that are easy to modify in order to adapt to the specific stump and any other conditions that the patient may have. Even though these materials can be easily modified, they still provide the structure and support necessary for the patient to regain the ability to walk with a more natural gait. The features of the Universal Prosthesis make it effective for its use on the Mercer On Mission trip to Vietnam. However, even with its adaptability, the Universal Prosthesis leaves room for improvement, and complications during the fitting process often occur. The purpose of this project is to design and build the ankle joint for the Universal Prosthesis shown in Figure 2.

Figure 2: Ankle and foot section of Universal Prostheses

A lower-limb amputee's gait will often change during his or her time without a prosthesis. As a result, the patient may experience problems walking with a newly fitted prosthesis.

Depending on the tool that the patient previously used to move, the entire body experiences modifications to compensate for the different dynamics of the patient's movement with that tool. Over time, this compensation of the human body results in a modification of the gait. When a prosthetic leg is to be fitted on the amputee, the fitter must consider the alterations of the patient's gait and develop the fit so that the prosthetic leg will help the patient to get back to their natural gait.

Another common obstacle that fitters encounter is the muscle atrophy that patients experience while unable to walk. While this is not an issue with some patients, with those that have stopped using their lower limb muscle, it tends to be more difficult or impossible to get them walking. The weakness of the lower limb muscles results in a higher difficulty walking after the prosthesis has been fitted. For most of these cases, the prosthetic leg is given to the patient but he or she must practice and gain strength back before being able to walk normally with it (BME 491: *Mechanics Design and Clinical Fitting Prosthetics Class by Dr. Ha Vo).*

Our team aims to create an electrically powered ankle joint that can be attached to the Universal Prosthesis. The implementation of an ankle joint will allow dorsiflexion and plantarflexion of the prosthetic foot, improving patient gait. The ankle joint will help patients who do not have full control of the prosthetic leg by replicating the motion of a natural ankle throughout the gait. This device will improve the rehabilitation of muscle-atrophied patients, allowing them to walk while helping them recover the strength needed to perform a natural gait without aid.

In a prosthetic leg, an ankle joint is meant to go between a pylon, serving as the tibial structure, and a prosthetic foot. The ankle joint will contain a mechanical and an electrical component. Together, these two components will encourage better performance of the patient's gait.

For the electrical component, a microcontroller will control the dorsiflexion and plantarflexion based on the pressure applied to pressure plates. Microcontrollers are computing devices which serve for specific purposes. They can vary in size and complexity depending on their purpose. They contain memory and a central processor, and may take inputs, such as the pressure applied to a pressure sensor, and produce outputs based on the needs of their user. They can be programmable or pre-programmed to serve their function (Dr. Ekong).

Project Description

The main and final goal of this project is to create an affordable, operational, and safe mobile ankle joint that can be used in the Universal Prosthesis in order to help amputees who suffer from muscle atrophy to regain their natural gait.

There are several goals that can be considered indirect, but still contribute to the success of the final result. A secondary, broader goal of the project is the general improvement of the Universal Prosthesis. With the mobile ankle joint, more amputees will be able to regain a more natural gait and increase their muscle strength. By providing aid in these two areas, the mobile ankle joint will develop the Universal Prosthesis into a more adaptable device for amputees, making it even more “universal.” The mobile ankle joint is also meant to serve primarily as a rehabilitation device, improving the patient’s gait and increasing their muscle strength. Once these factors have been fulfilled, it is expected that the mobile ankle joint can be removed and the amputee can then receive a normal ankle joint and continue walking. Furthermore, the team and client want this device to be accepted by the amputee patients. It is essential that the joint fulfill its functions, but is also important that the patients want this product and that it is something they can be proud of and rely on. If the device is not appealing to the patients, they may reject it, then making the mobil ankle joint a pointless project since the patient will not want to use it.

Moreover, this project contains in itself a series of smaller and more specific goals that lead up to such main, final result. This series of steps is essential to the realization of this entire project, as it simplifies the process. Most of these smaller goals are for the device to function as a joint, to power the prosthesis, to work without power, and to represent a safe device for amputee patients.

The device developed by the team is meant to be a joint, and more specifically, an ankle joint. Through this goal, it was defined that the ankle joint must be able to both dorsiflex and plantarflex, shown in Figure 3. For the purposes of the Universal Prosthesis, there is no need for the joint to include any other movement, such as abduction, adduction, external rotation, internal rotation, eversion, or inversion, since these would just decreases the stability of the ankle joint and the entire prosthetic limb. Furthermore, it is a goal for the team to test the final design on the amount of plantarflexion and dorsiflexion that the ankle allows for, and also conduct testing on the constraints to the other planes of motion. Keeping the movements of the joint on the sagittal plane, as shown in Figure 4, will allow for greater stability and simplicity, while still completely fulfilling its function. The joint will only be rotating on the frontal axis, allowing the team to develop a simpler mechanical structure in comparison to an ankle that moves in different planes.

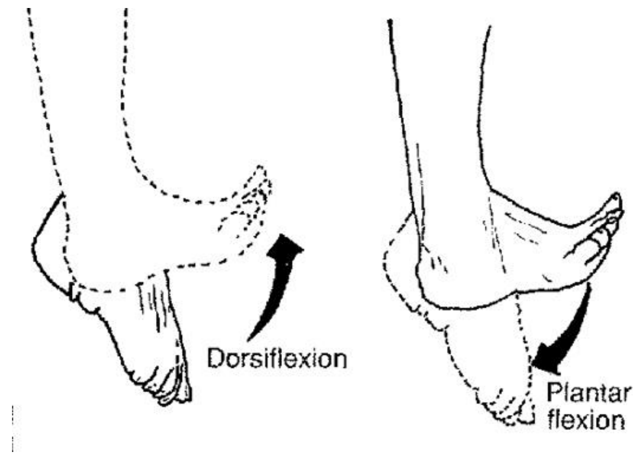

Figure 3: Diagram for dorsiflexion and plantarflexion of the foot

Figure 4: Translational Sagittal Plane over Frontal axis.

The mobile ankle joint is expected to dorsiflex and plantarflex by itself with the help of motors and batteries to power the joint, microcontrollers to program the motions, and sensors to assimilate the natural gait and react at the right points of dorsiflexion and plantarflexion. However, the mobile ankle joint must also provide the patient with a small push created by the momentum from the plantarflexion. This will assist the patient during the amputee's forward movement. This powering assistance given by the mobile ankle joint compliments into its function as a rehabilitation device. Moreover, the motor will get tested on its connectivity with the ankle joint, the amount of power it offers, and it's fluidity when providing the power to the ankle joint. In addition, the system used to connect the motor with the ankle joint will be tested for connectivity, stability, and safety characteristics.

In the other hand, the team concluded that it would be reasonable for the mobile ankle joint to also work while the power is off. In this case if the patient was attempting to practice his or her gait without the help of the motors, they would be able to do it by simply turning off the motor. This would further allow for the battery to last longer since the electrical portion of the device could remain off while it is not being used.

Lastly, it is of major importance that this ankle joint be a reliable and safe device and provide security, trust, and comfort to the amputee patient. As the device will be connected to the person's stump, and entire body structure, it is imperative that the ankle joint is as safe as possible while still performing its functions. A case in which the ankle joint collapses or causes the patient to fall could result in injury. There are several requirements that factor into the safety matters of the prosthetic joint. Stability is key for maintaining structure and confidence. If the device shakes and is not steady, it will be difficult for the patient to walk with it, and it will likely not earn his confidence. The mechanical and electrical system created for the ankle joint must be able to operate without getting stuck or producing any other faults that may interrupt the patient's gait. Wearing is also a factor into the safety of the device. since the patients will be taking this prosthetic leg home and practice on their own with it, the team must make sure that the materials used in the device, specially in the friction areas, does not wear easily since this could further create instability and affect the gait of the patient. It is vital that the electrical component is powerful enough when performing the dorsiflexion and the plantarflexion, but that it is also under control and operating at a really close dynamic with the natural leg. An operation of the joint that is too fast or too slow, could result in injury. Lastly, since the device includes an electrical component, it is necessary for the ankle joint to be weatherproof. Patients may be exposed to different environment such as water, mud, etc. The more protected/covered each of these electrical components are, the sefer the patient will be.

Feasibility Criteria

In order to qualify as a possible mobile ankle joint, a proposed design must fulfill each of the following base criteria. These five criteria has been chosen by the team as a result from the experience with the Universal Prosthesis, its functions, and the expectations of the client.

Durability

To qualify for a good performance, it is expected that the ankle joint will be functional for at least a length of two years incorporated in the Universal Prosthesis. Applying maintenance to the device every several periods should be doable but having to replace the entire joint every year or even two years will not be an option for a possible design. The team does understand however that the time length, a device can last, will change depending on the environment in which the prosthetic is used at. The three year specification applies for normal conditions and it also meets the performance expectation given by the client.

Range of Motion

The device must be able to perform two ranges of motion on the feet, dorsiflexion and plantarflexion. For both movements, the ankle will need to mimic the gait of the patient and work at a rate that simulates the speed of the natural leg. In addition, the device must include a stopping mechanism to restrict the movement to a maximum of 45° of Plantarflexion and 20° of dorsiflexion, as shown in Figure 5.

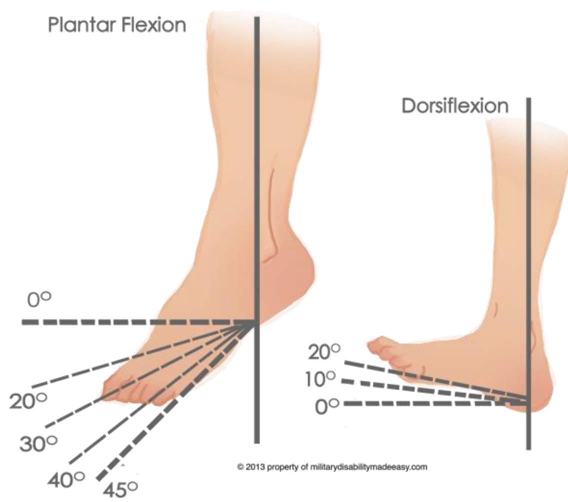

Figure 5: Range of motion for dorsiflexion and plantar flexion

Off-Power Functionality

The device must be able to rotate and operate when the electrical components are turned off. Once the muscles are rehabilitated or anytime the patient is in a static position, the device should be able to go into neutral state in order to save up power and represent a safer device. In addition, if the patient wanted to use this device without the power, the patient should be able to propel the device forward, rather than the motor, as a normal ankle once the patient has regained enough muscle strength.

Universal Prosthesis

For the purpose of this research project, the ankle joint must be able to attach and work proficiently with the Universal Prosthesis. In other words, any design proposed will be restricted to the structure and dynamics of the Universal Prosthesis. The full cost of the ankle joint must allow for mass production and distribution to the clinics in Vietnam. In addition, the materials must be accessible and the production methods must be simple enough that do not demand the need of very specific tools not available in Vietnam.

The ankle joint must not weigh over 5 pounds so that it can be worn by patients with muscle atrophy and other complications. Moreover, the ankle joint must be able to handle a minimum amount of human weight to qualify as a design, since most of the human weight will be applied on the joint at some moments.

Safety

The device must be stable and not cause injury to patients, even in inclement weather. Safety is also extremely important so that the patients are comfortable and trusting of the device they are wearing. This criterion will partly be satisfied by the completion of all above criteria. However, other safety factors that must be accounted for include stability, weatherproofing, control, resistance, and continuous mobility.

Team Roles and Assignments

<u>Gabriel Gonzalez - Biomedical Engineer</u>

Seeking a degree of Bachelors of Science in Engineering with a specialization in the Biomedical field, Mr. Gonzalez is a Senior at Mercer University specifically interested in the field of Prosthetics and Orthotics. Mr. Gonzalez recently participated in the Mercer On a Mission trip to Vietnam, where he was able to develop his knowledge of the prostheses field and his skills in the fitting process of the Universal Prosthesis.

Furthermore, Mr. Gonzalez was primarily focused on the biomechanics of the ankle and the ankle joint. The main assignments for Mr. Gonzalez were the design and development of the ankle joint, conducting the testing and data analysis of the final prototypes, ordering all pieces from the different suppliers, management of the paperwork, scheduling of meetings and the critical design review presentation, write-up and structure of the final document, and creation of the brochure.

Figure 6. Mr. Gabriel Gonzalez

Jenna Hamlin - Electrical Engineer

Ms. Jenna Hamlin is a senior level electrical engineering major at Mercer University. She has experience programming microcontrollers and designing and building circuits. Her areas of work on this project were programming and interfacing the microcontroller as well as designing and testing the circuitry within the prosthesis.

Other specific tasks under Ms. Jenna included development of gear calculations, design and development of the ankle joint, making sure all circuitry was taken care of, developing the program for the microcontroller, connectivity and stability of the electrical components with the ankle joint, and maintaining direct communication with Dr. Fu, the electrical engineer advisor.

Figure 7. Ms. Jenna Hamlin

<u>Jackie Harmon - Biomedical Engineer</u>

Ms. Jackie Harmon is a senior biomedical engineer on track to graduate with a Bachelors of Science and Engineering. Her focus in this project were biomechanics, since she recently completed the course and was fresh on the topics, and CAD designing of the product. Ms. Jackie has worked with several different CAD programs, as well as with 3D printers which will be used to make the prototype.

Other specific areas under Ms. Jackie included the creation of the CAD designs, the development and manufacturing of both the 3-D printed and the MasterCam models of the ankle joint, design and development of the ankle joint, development of the gear calculations, development of the gear backbone and gear structure, manufacturing of the gears themselves and any other parts such as the wheels, pulleys, and pins.

Figure 8. Ms. Jackie Harmon

Design alternatives

Following are the descriptions of sixteen design alternatives our senior design team created while determining a solution for our client. Each of these drawings were sent through a feasibility evaluation, and those which passed were then sent through a merit analysis to be selected for final design. Following is a brief description of the designs considered by the team.

Design 1: Dorsi Gate Front Hinge Mobile Ankle Joint

This design involves splitting the tibia to foot adapter, and installing a hinge on the front of the split adapter. A clamp will be placed inside the joint, with the joined part facing the hinge. The top leg of the clamp is attached to the top piece of the adapter and the bottom leg of the clamp is attached to the bottom piece of the adapter. This clamp is powered by a motor located in the hollow space of the foot, and rotates to open and close the joint, allowing for dorsiflexion of the foot.

Design 2: Plantar Gate Back Hinge Mobile Ankle Joint

This design involves splitting the tibia to foot adapter, and installing a hinge on the back of the split adapter. A clamp will be placed inside the joint, with the joined part facing the hinge. The top leg of the clamp is attached to the top piece of the adapter and the bottom leg of the clamp is attached to the bottom piece of the adapter. This clamp is powered by a motor located in the hollow space of the foot, and rotates to open and close the joint, allowing for plantar flexion of the foot.

Design 3: Gear Ball Driven Mobile Ankle Joint

This design involved a motor with two gears attached to it, which rotate a gear ball to create an ankle joint. The gear ball is an oblique ball with the transverse plane splitting the ball into its two parts. The top part of the ball is smooth, while the bottom part of the ball is lined with gear teeth. The smooth half of the ball has a slightly larger radius that the gear teeth, so that the gears attached to the motor can only rotate so far until physically stopped. An axle runs laterally through the gear ball, with each end attached to the hood surrounding the joint. This hood covers the joint like a baseball helmet, with the sides covered and the front being exposed to allow for rotation. When the gears rotate clockwise, it allows for dorsiflexion of the foot; when the gears rotate counterclockwise, it allows to plantar flexion of the foot.

Design 4: Sliding Pin Driven Mobile Ankle Joint

This design involves a pin connected to a motor. The motor is located in the hollow of the foot, and the pin reaches from there to the middle of the male connector, which is attached to the tibia. The male connector is rounded, but oblique rather than circular. It slides against a female connector which is attached to the prosthetic foot. The pin itself is not straight, but bent slightly and reinforced for stability at the point the male and female connectors touch. It rotates about the center of the male connector. The male connector has a hollow path for the pin to follow when it slides back and forth due to the pushing of the motor.

Design 5: Gear Belt Driven Mobile Ankle Joint

This design involves three gears and a single motor, with two of the gears attached to the motor for powered rotation, and the middle gear attached a free rotating gear. The gear to the right is smaller than the gear to the left because plantar flexion requires more rotation than dorsiflexion. When the left (larger) gear rotates inward, the other two gears rotate freely, allowing for plantar flexion of the foot. When the right (smaller) gear rotates inward, the other two gears rotate freely, allowing for dorsiflexion of the foot. A hood encompasses all of the gears so that the axles have a place of attachment. The motor is located in the hollow of the foot. A belt with gear teeth laterally crossing it, similar to tractor tread, is what is weaving through the gears as the thing that makes the ankle joint rotate.

Design 6: Gear Belt 2 Driven Mobile Ankle Joint

This design involves a chain belt attached to the front and back of the leg and fed down into the foot and around a gear driven by the motor. As the motor rotates one direction, it pulls the foot into a dorsiflexion position. As it rotates the other way, the belt pulls the foot into a plantarflexion position. Springs between the leg are used as spacers and and foot provide necessary resistance in both directions of motion.

Design 7: Wedge Gate Concept Mobile Ankle Joint

This design involves the motor pushing a sliding wedge fitted between the foot and leg. The bottom of the leg would have a smooth surface against which the curved wedge could slide backward and forward to create a varying angle between the foot and the leg. The narrow part of the wedge would correspond to dorsiflexion and the wide part of the wedge would correspond to plantarflexion.

Design 8: Egg Gate Concept Mobile Ankle Joint

This design involves the motor turning an egg-shaped block fitted in the foot. As the egg shape rotates, it pushes against the ankle above, creating a varying angle between the foot and the leg. When the egg is in a vertical position, a large angle is created. When the egg is in a horizontal position, there is a narrow angle created. The egg would be shaped so that it would rotate 360 degrees over one gait cycle, creating the necessary angles of dorsiflexion and plantarflexion at the correct times.

Design 9: One Ligament Wheel Cushioned Mobile Ankle Joint

This design involves one ligament with a motor connected at each end. The ligament will go through the male connection along the sagittal axis. Five wheels are attached to the bottom of the male connection so that the female connection can smoothly rotate. Two wheels are along a front line, one wheel is in the middle, and two wheels are along the back line. There is a frictionless pulley wheel at either end of the male connection where the ligament comes out to reduce friction. There are ledges located at both places where the ligament passes through the male connection that act at a physical barrier for the female connection during dorsiflexion and plantar flexion of the foot. The male connection is joined at the top to the femur, and the female connection is joined at the bottom to the prosthetic foot. Both are longer than they are wide, creating an oblong shape rather than a circular shape for better stability. On the left and right side of the ankle joint, a ligament connects the female and male connection and acts as support so that the joint cannot move laterally. The motors are located inside the hollow space of the foot, and a small opening is made in the front and back part of the foot so that the ligament can pass through. The motors rotate in such a way that as one draws in, the other locks, and plantar flexion and dorsiflexion can occur.

Design 10: Two Ligament Wheel Cushioned Mobile Ankle Joint

This design involves two ligaments with a motor connected at each end. The ligaments are attached to the male connection along the sagittal axis. Five wheels are attached to the bottom of the male connection so that the female connection can smoothly rotate. Two wheels are along a front line, one wheel is in the middle, and two wheels are along the back line. There are ledges located at both places where the ligament connects to the male connection that act at a physical barrier for the female connection during dorsiflexion and plantar flexion of the foot. The male connection is joined at the top to the femur, and the female connection is joined at the bottom to the prosthetic foot. Both are longer than they are wide, creating an oblong shape rather than a circular shape for better stability. On the left and right side of the ankle joint, a ligament connects the female and male connection and acts as support so that the joint cannot move laterally. The motors are located inside the hollow space of the foot, and a small opening is made in the front and back part of the foot so that the ligament can pass through. The motors rotate in such a way that as one draws in, the other locks, and plantar flexion and dorsiflexion can occur.

Design 11: One Ligament Material Cushioned Mobile Ankle Joint

This design involves one ligament with a motor connected at each end. The ligament will go through the male connection along the sagittal axis. Material is located between the male connection and the female connection so that they can rotate against each other smoothly. There is a frictionless pulley wheel at either end of the male connection where the ligament comes out to reduce friction. There are ledges located at both places where the ligament passes through the male connection that act at a physical barrier for the female connection during dorsiflexion and plantar flexion of the foot. The male connection is joined at the top to the femur, and the female connection is joined at the bottom to the prosthetic foot. Both are longer than they are wide, creating an oblong shape rather than a circular shape for better stability. On the left and right side of the ankle joint, a ligament connects the female and male connection and acts as support so that the joint cannot move laterally. The motors are located inside the hollow space of the foot, and a small opening is made in the front and back part of the foot so that the ligament can pass through. The motors rotate in such a way that as one draws in, the other locks, and plantar flexion and dorsiflexion can occur.

Design 12: Two Ligament Material Cushioned Mobile Ankle Joint

This design involves two ligaments with a motor connected at each end. The ligaments are attached to the male connection along the sagittal axis. Material is located between the male connection and the female connection so that they can rotate against each other smoothly. There are ledges located at both places where the ligament connects to the male connection that act at a physical barrier for the female connection during dorsiflexion and plantar flexion of the foot. The male connection is joined at the top to the femur, and the female connection is joined at the bottom to the prosthetic foot. Both are longer than they are wide, creating an oblong shape rather than a circular shape for better stability. On the left and right side of the ankle joint, a ligament connects the female and male connection and acts as support so that the joint cannot move laterally. The motors are located inside the hollow space of the foot, and a small opening is made in the front and back part of the foot so that the ligament can pass through. The motors rotate in such a way that as one draws in, the other locks, and plantar flexion and dorsiflexion can occur.

Design 13: One Ligament Teeth Cushioned Mobile Ankle Joint

This design involves one ligament with a motor connected at each end. The ligament will go through the male connection along the sagittal axis. The space between the male connection and the female connection is occupied by teeth that are pointing downward from the male connection an upward from the female connection. They are quadrilateral in nature, though not rectangular. Instead they get smaller as they get longer, creating a trapezoidal effect. The sides of the teeth do not touch; only the top face of each tooth touches the opposing connection, so that friction is reduced. There is a frictionless pulley wheel at either end of the male connection where the ligament comes out to reduce friction. There are ledges located at both places where the ligament passes through the male connection that act at a physical barrier for the female connection during dorsiflexion and plantar flexion of the foot. The male connection is joined at the top to the femur, and the female connection is joined at the bottom to the prosthetic foot. Both are longer than they are wide, creating an oblong shape rather than a circular shape for better stability. On the left and right side of the ankle joint, a ligament connects the female and male connection and acts as support so that the joint cannot move laterally. The motors are located inside the hollow space of the foot, and a small opening is made in the front and back part of the foot so that the ligament can pass through. The motors rotate in such a way that as one draws in, the other locks, and plantar flexion and dorsiflexion can occur.

Design 14: Two Ligament Teeth Cushioned Mobile Ankle Joint

This design involves two ligaments with a motor connected at each end. The ligaments are attached to the male connection along the sagittal axis. The space between the male connection and the female connection is occupied by teeth that are pointing downward from the male connection an upward from the female connection. They are quadrilateral in nature, though not rectangular. Instead they get smaller as they get longer, creating a trapezoidal effect. The sides of the teeth do not touch; only the top face of each tooth touches the opposing connection, so that friction is reduced. There are ledges located at both places where the ligament connects to the male connection that act at a physical barrier for the female connection during dorsiflexion and plantar flexion of the foot. The male connection is joined at the top to the femur, and the female connection is joined at the bottom to the prosthetic foot. Both are longer than they are wide, creating an oblong shape rather than a circular shape for better stability. On the left and right side of the ankle joint, a ligament connects the female and male connection and acts as support so that the joint cannot move laterally. The motors are located inside the hollow space of the foot, and a small opening is made in the front and back part of the foot so that the ligament can pass through. The motors rotate in such a way that as one draws in, the other locks, and plantar flexion and dorsiflexion can occur.

Design 15: One Upside Down Ligament Chain Belt Mobile Ankle Joint

This design involves one ligament with each end attached to the male connection along the sagittal axis. The middle of the ligament goes through the prosthetic foot through holes drilled in the front and back of the foot. A small gear is located at each opening of the foot to prevent the ligament from making a triangular shape with the motor in the center. There is a larger gear located between the two smaller gears, in the center of the hollow space of the foot, that is directly connected to the motor. The ligament wraps under each small gear and over the large gear. The motor rotates backward and forward in order to create dorsiflexion and plantar flexion of the foot. The ligament has a chain-like appearance, with holes in it that the gear teeth can sink into, and pull the ligament a certain way when rotating. There are ledges located at both places where the ligament connects to the male connection that act at a physical barrier for the female connection during dorsiflexion and plantar flexion of the foot. The male connection is joined at the top to the femur, and the female connection is joined at the bottom to the prosthetic foot. Both are longer than they are wide, creating an oblong shape rather than a circular shape for better stability. On the left and right side of the ankle joint, a ligament connects the female and male connection and acts as support so that the joint cannot move laterally. Five wheels are attached to the bottom of the male connection so that the female connection can smoothly rotate. Two wheels are along a front line, one wheel is in the middle, and two wheels are along the back line. There are ledges located at both places where the ligament connects to the male connection that act at a physical barrier for the female connection during dorsiflexion and plantar flexion of the foot.

Design 16: One Upside Down Ligament Flat Belt Mobile Ankle Joint

This design involves one ligament with each end attached to the male connection along the sagittal axis. The middle of the ligament goes through the prosthetic foot through holes drilled in the front and back of the foot. A frictionless pulley is located at each opening of the foot to prevent the ligament from making a triangular shape with the motor in the center. There is a turning shaft located between the two frictionless pulleys, in the center of the hollow space of the foot, that is directly connected to the motor. The ligament is a flat belt that wraps around the turning shaft, and is attached in the middle so that when the motor rotates backward and forward, dorsiflexion and plantar flexion of the foot occur. There are ledges located at both places where the ligament connects to the male connection that act at a physical barrier for the female connection during dorsiflexion and plantar flexion of the foot. The male connection is joined at the top to the femur, and the female connection is joined at the bottom to the prosthetic foot. Both are longer than they are wide, creating an oblong shape rather than a circular shape for better stability. On the left and right side of the ankle joint, a ligament connects the female and male connection and acts as support so that the joint cannot move laterally. Five wheels are attached to the bottom of the male connection so that the female connection can smoothly rotate. Two wheels are along a front line, one wheel is in the middle, and two wheels are along the back line. There are ledges located at both places where the ligament connects to the male connection that act at a physical barrier for the female connection during dorsiflexion and plantar flexion of the foot.

Engineering Design Analysis

Feasibility Analysis

The feasibility of each criteria with each design was scaled in a GO or NO GO basis. For a design to be considered feasible, it must first receive a GO in each of the criteria. After the feasibility analysis was performed, the study yielded a total of 8 out of the 16 designs that qualified as a GO in each of the feasibility criteria. Designs 9 through 16 all passed, while designs 1 through 8 did not fulfill all the feasibility criteria.

Design 1: Dorsi Gate Front Hinge Mobile Ankle Joint and Design 2: Plantar Gate Back Hinge Mobile Ankle Joint were overall unfeasible designs. These designs were not considered to be durable or safe since the connection/support point was a simple clamp. These designs will also not be able to work without power since they needs a motor to open the clamp. In addition, design 1 had a good dorsiflexion range but it would not be able to plantarflex and design 2 . had a good plantarflexion range but it would not be able to dorsiflex.

Design 3: Gear Ball Driven Mobile Ankle Joint ended up being a decent design but it was not able to pass the Universal Prosthesis and the Safety criteria. This device would not be fitting for the ankle structure of the Universal Prosthesis. In addition, the gear ball mechanisms would not be a safe enough system to operate as the supporting structure of a patient due to the axle having to bear all the weight of the patient.

Design 4: Sliding Pin Driven Mobile Ankle Joint was not a good design since the pin would represent a huge weak point for the ankle. Because of the pin being so fragile and unstable, this design was not able to pass the Durability and Safety criteria. This design was also not able to pass the Off-Power Functionality criterion since the pin would need the motor to create the movement motion. This designed did not pass the range of motion either since the pin would not be able to perform dorsiflexion and plantarflexion.

Design 5: Gear Belt Driven Mobile Ankle Joint failed to meet the Universal Prosthesis and safety requirements. The gear system may be efficient to provide power but it will not operate well in the ankle device, making it also an unsafe option. In addition, since these are gears, the device would not be able to operate without power.

Design 6: Gear Belt 2 Driven Mobile Ankle Joint was an overall good design but it failed to pass the range of motion criteria since this belt system would not be able to reach the necessary degrees of freedom for the ankle joint. Not being able to fully dorsiflex and plantarflex makes the device pretty obsolete.

Design 7: Wedge Gate Concept Mobile Ankle Joint and Design 8: Egg Gate Concept Mobile Ankle Joint were both designs that did not meet the Universal Prosthesis criterion due to their bulky system that would extend out of the ankle joint in order to be able to operate. Since the system would go out of its usual space, this would decrease the safety of the device. In addition, neither of these would be able to have an Off-Power Functionality since the gear systems need the motor to be propelling them.

Deliverables

Beginning with the proposal for this project, the team described the project deliverable sto be as follow:

"At the end of this project, our team will deliver a Universal Prosthesis modified to have a movable ankle joint. We will include a 3-D printed prototype, design sketches, and a brochure in both English and Vietnamese on how to fit and use the prosthesis. We will also include instructions on how to make the device so that more can be produced and distributed in the future. These will be delivered to Dr. Ha Vo."

As far as the deliverables go, the team was able to achieve the following items in combination from the proposal and the preliminary design review.

The team has provided the client with a 3-D printed model of the ankle joint. This model includes both the male and female components of the ankle joint. These components have been set together with the use of small nails that serve as the pins. These pins represented the attachment of both components as well as the two biggest weak points of the design and the axis of rotation for the ankle joint.

In addition to the 3-D prototype, the client was given a nylon prototype of the male and female components to serve as the main deliverable for the ankle joint. This model was assembled and set on a foot mold. This prototype includes the connection with the electrical components through the gear system proposed. The electrical components include the circuit, the motor, the microcontroller, the sensors, etc. This prototype serves as the final product for this project. It is not, however, a finalized design to be used on an amputee.

The deliverables also include a brochure of the mobile ankle joint both, in english and vietnamese. This brochure includes information on the general description of the project, list of deliverables, conclusion of the design, approximate budget for fabrication, the tests performed and the future studies proposed.

Furthermore, the client has access to all schematics of of the circuit and the program used for the electrical components. As well as the design sketches and files of the ankle joint.

Methods and Work Accomplished

When the team first received this project from the client, the first step was to better understand the complex demands of this mobile ankle joint. At the beginning of our work, the team focused on defining the expectations and identifying all parts of the project. The team was clear that it was a necessity for the ankle joint to be specific to the Universal Prosthesis, since this is the device on which the ankle would be used. A further understanding that allowed the team to proceed on the creation of this ankle joint was to set proper boundaries. The mobile ankle joint is a complex project, but for our Senior Design research, it was important to keep the project deliverables limited to the goals in question. Moreover, the first step the team accomplished was the understanding of the mobile ankle joint's purposes, limitations, and expectations. This information was acquired through meetings with our client, Dr. Ha Vo, team discussions, where the team shared knowledge on their respective areas of focus, and the compilation of research articles and published journals related to the topic of study. See the References section for the complete list of sources.

Once this understanding was set and well thought about, the team proceeded into the first line of designs (designs 1-8). This first wave of drawings was useful into visualising the structure, shape, and size that the joint would have. In addition, these first designs also allowed us to define several options of engineering systems in the electrical, mechanical, and biomechanical side, that could represent possibilities on our final designs. Some of the mechanical and biomechanical systems included gears, springs, ligaments, wheels, and hinges. On the other hand, some of the possible electrical components thought about included motors (in specific step motors), push buttons, batteries, and microcontrollers. The first line of designs consisted of 8 models. Descriptions of each of these can be found in the Design Alternatives section.

These design sketches were then presented to Dr. Vo, who, as the client, provided the team with some insight about the ideas proposed so far. At this point, Dr. Vo assigned the team to come up with the feasibility and merit criteria that would be used to evaluate the designs.

In developing the feasibility and merit criteria, the team decided to compile a list for each of these criteria that could possibly apply to the project. In addition, there were three main areas of approach when thinking about plausible criteria, these were: The mechanical component, the electrical components, and the adaptation into the characteristics of the Universal Prosthesis. During the development of the feasibility criteria, the team focused on the vital aspects of the ankle joint. The final feasibility criteria consisted of five criteria: durability, range of motion, off-power functionality, Universal Prosthesis, and safety; these criteria and the feasibility analysis can be found under the Feasibility Criteria section and the Engineering Design Analysis section. Furthermore, the merit analysis was defined by focusing on factors that would create a more efficient ankle joint and increase the comfort and rehabilitation effects for the amputee patient. The final merit criteria consisted of the following six criteria: durability, functioning quality, weight, cost, strength, and complexity; these criteria and the merit analysis can be found in the Merit Criteria section and the Engineering Design Analysis section. Each of the merit criteria was given a weight, which allowed the team to conduct the merit evaluation and assign the most appropriate scores to each design on each criterion. These scores were assigned to each criterion based on the merit curves developed and the team decided how to weight each criterion.

The criteria was then reviewed and critiqued by Dr. Vo, who approved of the existing criteria and recommended adding weatherproofing into the safety section and product lifetime into a durability section.

In addition, after reviewing the feasibility and merit criteria with Dr. Vo, the team met with Dr. Fu from the Electrical Engineering Department, who was chosen to be the project technical advisor with a focus on the electrical side of the device. Dr. Fu provided the team with guidance on the electrical requirements, suggesting types of motors to research and recommending that we conduct power calculations for our design.

After all the criteria were chosen, the team had a more definite approach to the design process. The team decided to brainstorm a second line of designs (designs 9-16). Using both criteria and the experience from the first line of designs, the team developed more plausible and complete designs. These new designs used one model and changed two variables to produce concepts. The two variables were the material or system used in the 'subtalar joint,' and the number of ligaments used to create the motion of dorsiflexion and plantarflexion. The second line of designs consisted of eight models. Descriptions of each of these can be found in the Design Alternatives section. The team presented these designs to the client, who approved and made recommendations, the team was finally able to conduct an analysis on all the designs made.

The feasibility analysis was performed, and all eight designs created in the second session passed the feasibility criteria. For or a design to 'pass' the feasibility criteria, it had to have each of the characteristics demanded by the criteria. Once the team had the eight plausible designs, the merit analysis was performed and the designs were each assigned a total score. Based on these scores and a team discussion, the "One Upside Down Ligament Chain Belt" mobile ankle joint was chosen as the most effective preliminary design. The final sketch for this design, after the selection through the feasibility and merit analyses, is shown in figure 9.

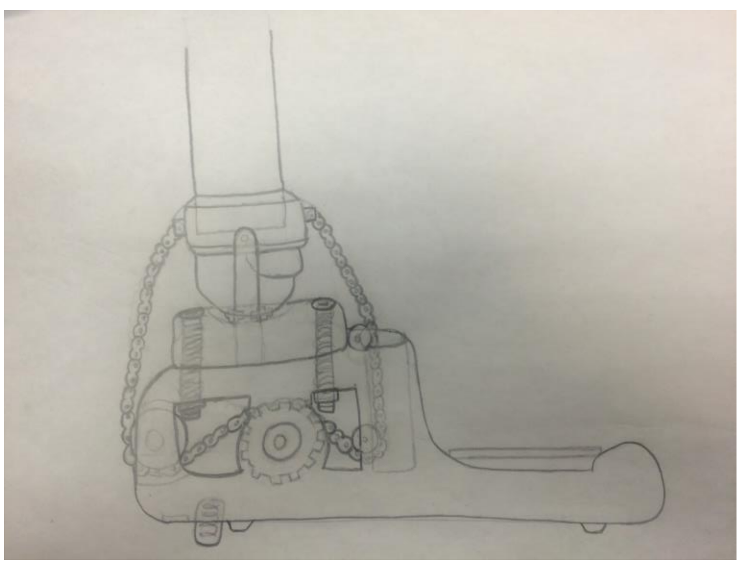

Figure 9. Design 15: One Upside Down Ligament Chain Belt Mobile Ankle Joint

Design 15: One Upside Down Ligament Chain Belt Mobile Ankle Joint will present a good overall design to meet the expectations of our client and the needs of the Universal Prosthesis. The wheel cushion was definitely a prefered trait in any of the designs seen. This will allow for better sliding of the female phalange about the male phalange, while avoiding as much friction as possible. The one ligament component allows to minimize the amount of weak points. In addition, having only one ligament and only one motor decrease the complexity of the device. The use of only one motor connected to a gear is an appropriate system to connect with the step motor. The chain acting as the ligament presents also a good fit due to more grip and stability.

In order to determine the gait phase, the microcontroller must be able to determine the areas of the foot under pressure. There are four gait phases which require unique outputs from the motor: heel-off, swing, heel-strike, and flatfoot. Heel-off requires positive plantarflexion power to drive the patient forward. Swing requires positive powered dorsiflexion to reset the foot to neutral in preparation for the next step. Heel-strike requires that the foot be allowed to plantarflex to the ground. Flatfoot requires negative plantarflexion power to stabilize the patient as he leans forward on his other leg.

This design will use a stepper motor due to its precision of movement and its torque advantages at low speeds. Stepper motors require a sequence of pulses to provide continuous movement. Each pulse produces a discrete amount of rotation. A stepper motor driver can be used to input the correct pulse sequence to the motor. If the voltage applied during a pulse is not released and instead held constant, the motor will resist motion and keep a constant position.

These properties of the stepper motor must be used to write the walking program. During heel-off, the motor must be given the forward rotation sequence at a speed proportional to the speed the user wishes to walk. During swing, the reverse rotation sequence must be applied to the motor to quickly achieve a neutral position of the foot. During heel-strike, the motor can be released so that the natural moments due to gravity can pull the foot to the ground. In a human foot, there is usually a small amount of negative dorsiflexion power during this phase; however, if a permanent magnet stepper motor is used, the natural magnetic resistance should be sufficient to ensure smooth movement during this phase. During flatfoot, the forward motion of the person is due to the shift of weight to the other leg. The flat foot ankle provides negative plantarflexion power the person leans forward. This corresponds to a series of breaking on the motor and releasing of the motor.

Once the team had a design chosen, the team proceeded into creating a CAD version of the design to further create a 3-D printed model of the mobile ankle joint.

The final design has several parts that come together to act as a mobile ankle joint. First, there is the metal pipe that acts as the tibia (Figures 10 & 11), and is already incorporated into the Universal Prosthetic. This connects the ankle joint to the socket which holds the amputee's stump in place. This metal pipe will fit into a hole fitted to it, on the top of the male connector (Figures 12 & 13). This male connector will be where the ends of the ligament connect; in the prototype, a small hook is created on each side in order to allow a ligament to hook onto the connector since the ligament will be represented by a rubber band and the prototype is made of 3D printing plastic material. The actual male connector will be made of stainless steel, as well as the ligament chain, and they will be welded together. The male connector has a ledge on the front of it to physically stop the rotating of the ankle joint during dorsiflexion, if necessary. The four holes at the bottom of the male connector are where the four wheels (Figures 14 & 15) will be inserted. Five wheels were in the original design; however, the middle wheel was removed so that the other four wheels could increase in size and allow for better stability of the joint. Larger wheels are more durable. The female connector is shown in Figures 16 & 17 and follows the original design. However, the prototype will not have the two side ligaments connected to the male connector. Instead they will freely rotate, rather than be screwed in with a washer between the male connector and the side ligament, which will be how the actual ankle joint is manufactured. The female connector will be connected to the prosthetic foot, which already has an existing mold. However, for the prototype, a simple version of the foot was designed, with two hooks on it where the prototype ligament can connect (Figure 18). The assembly of the tibia pipe, male connector, and the wheels is shown in Figure 19. The full mechanical assembly of the ankle joint prototype is shown in Figure 20. The electrical components of this design will be programmed to calibrate and determine which phase of the gait the wearer is in based on this calibration. The flowchart for the calibration program is shown in Figure 21. The flowchart for what happens to the electrical components when the wearer begins walking is shown in Figure 22. The flowchart for walking program itself is shown in Figure 23.

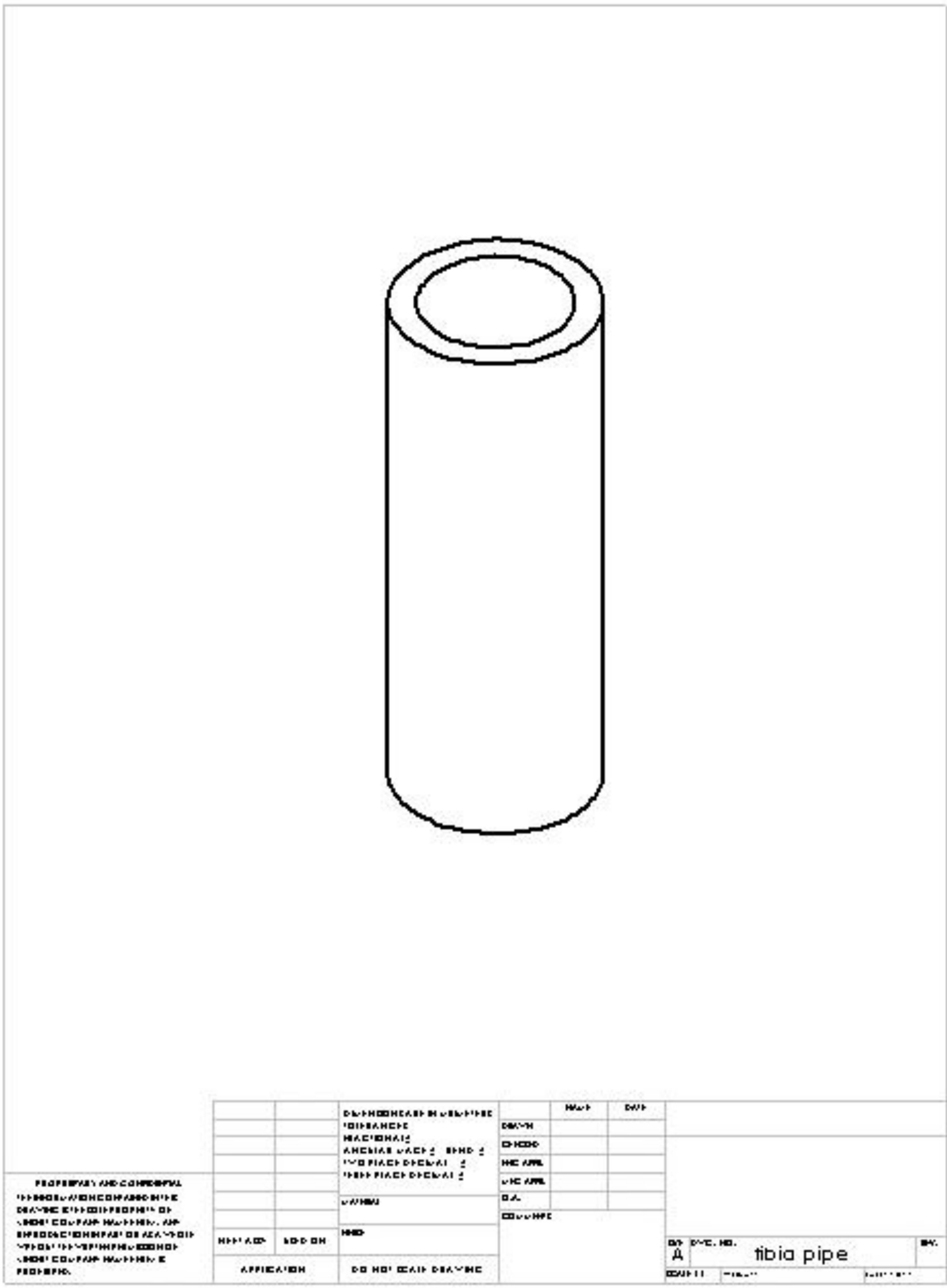

Figure 10: Tibia Pipe CAD isometric view

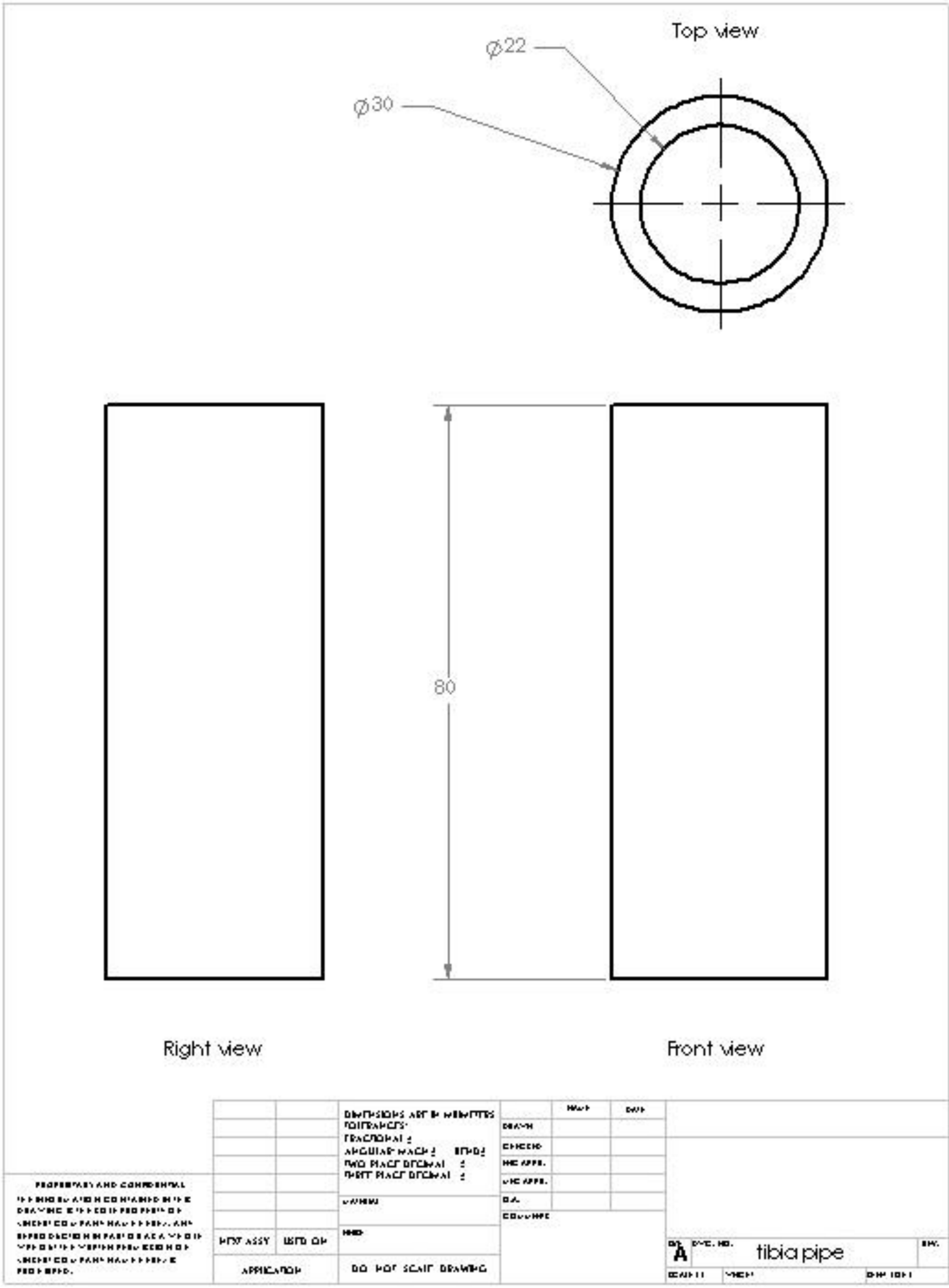

Figure 11: Tibia Pipe CAD drawing with dimensions

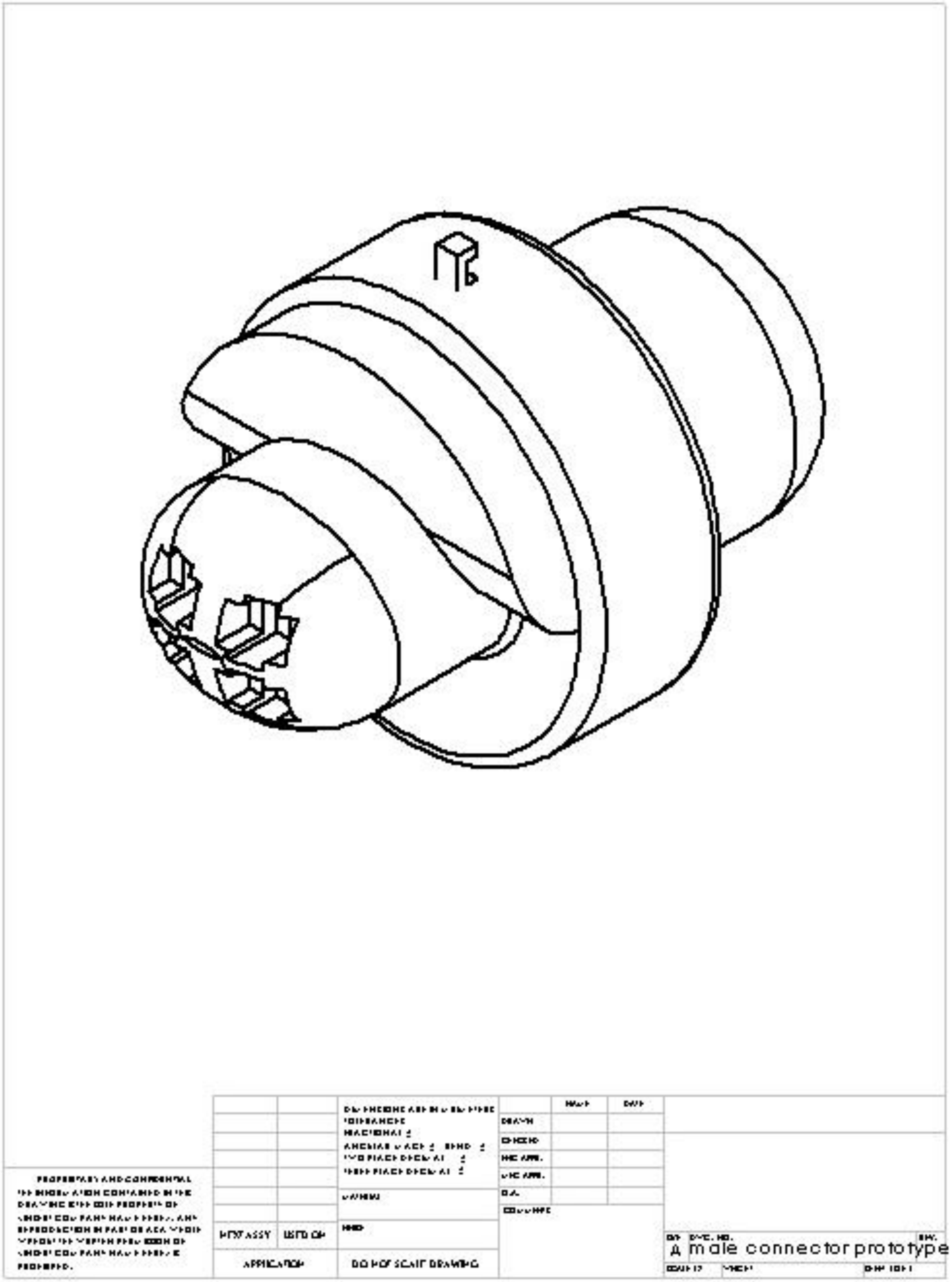

Figure 12: Male Connector CAD isometric view

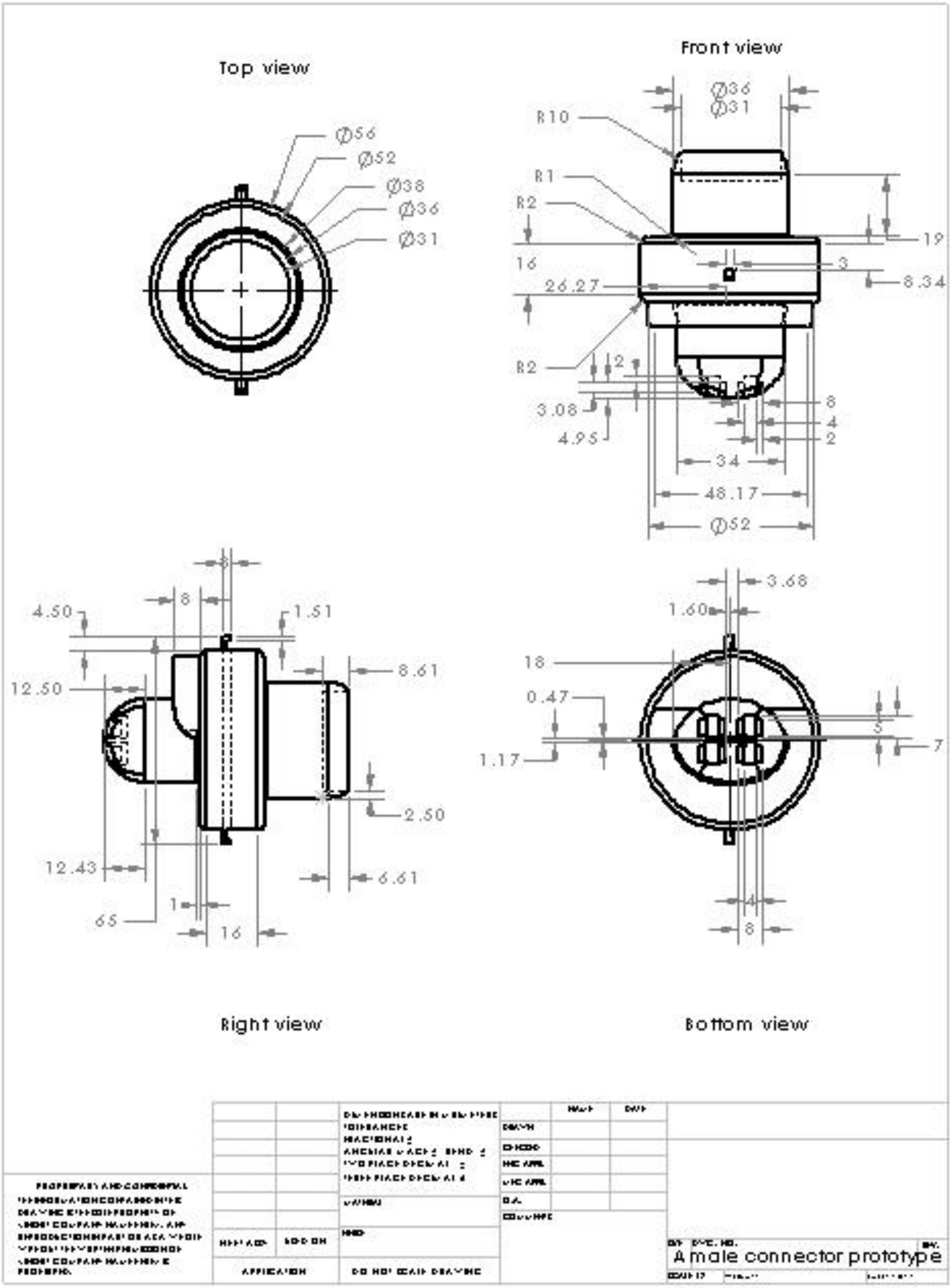

Figure 13: Male Connector CAD drawing with dimensions

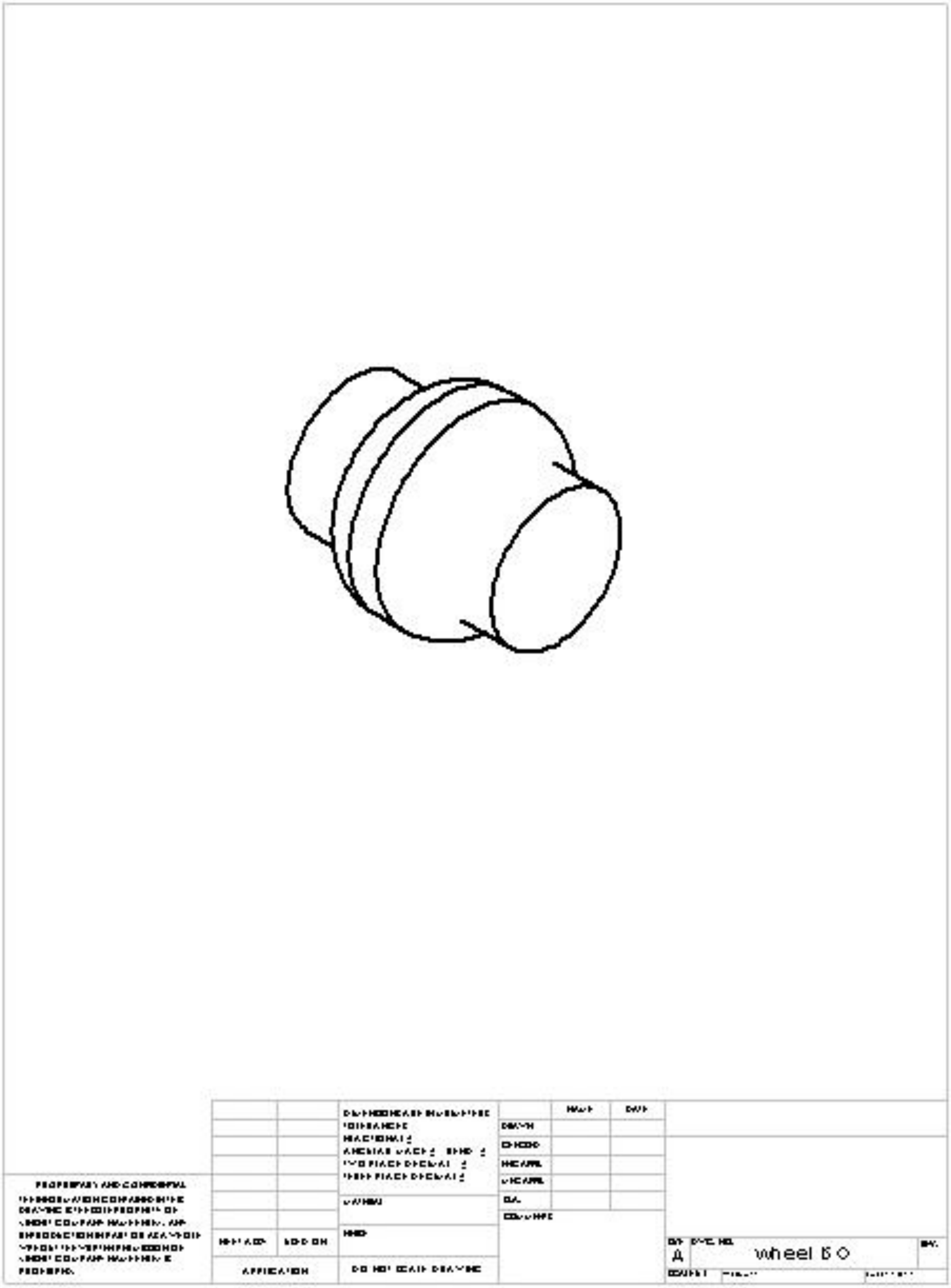

Figure 14: Wheel CAD isometric view

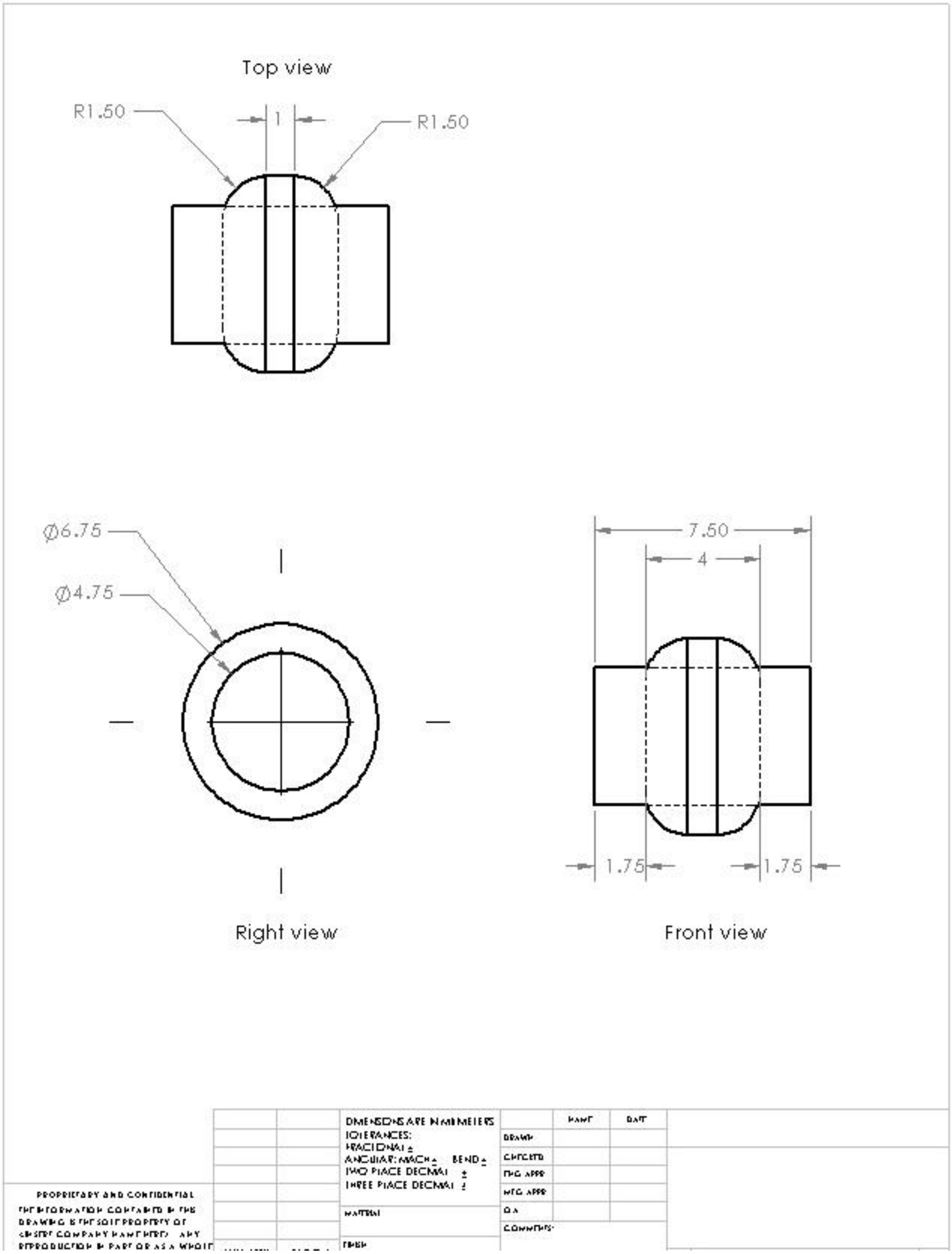

Figure 15: Wheel CAD drawing with dimensions

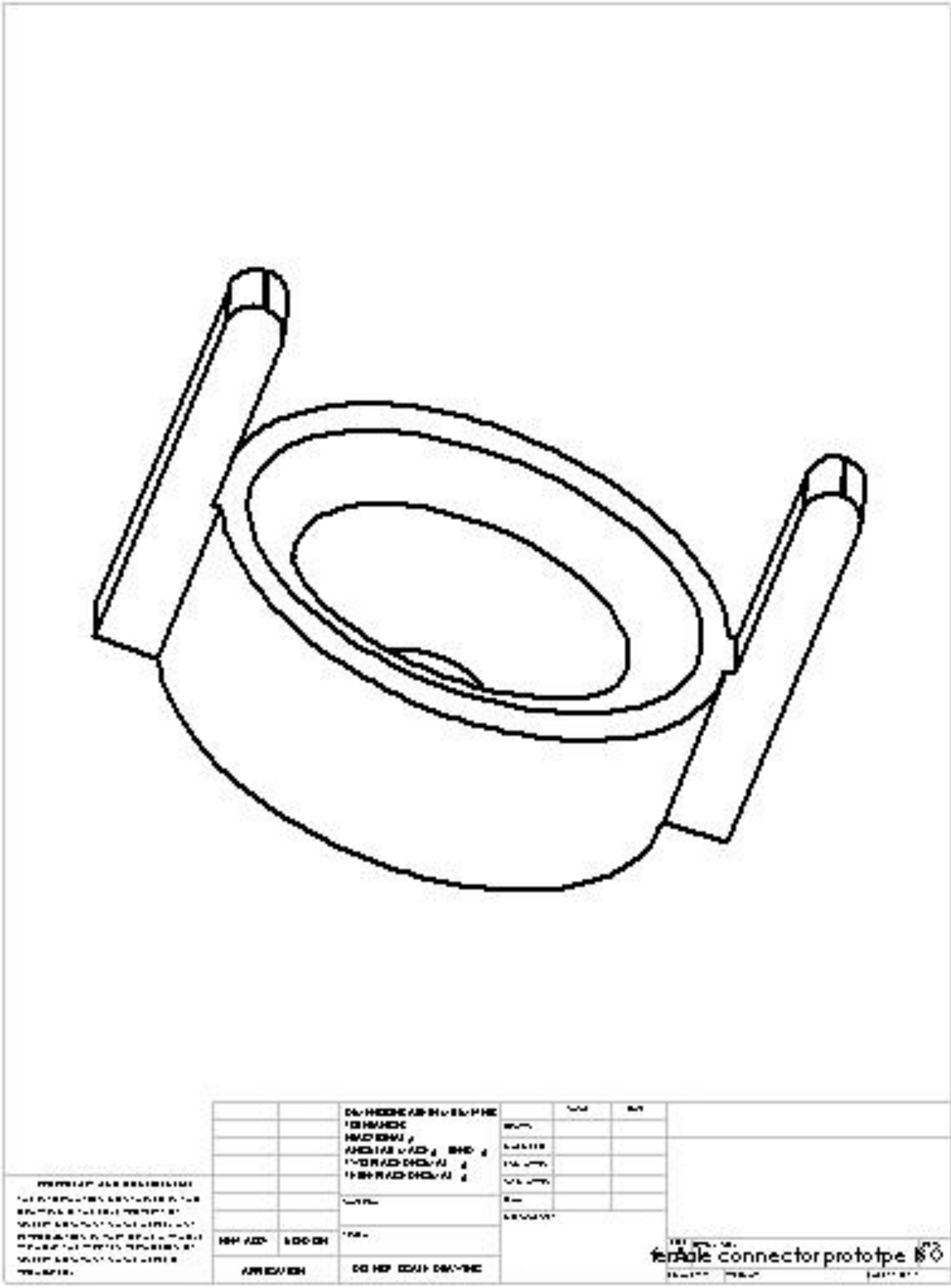

Figure 16: Female Connector CAD isometric view

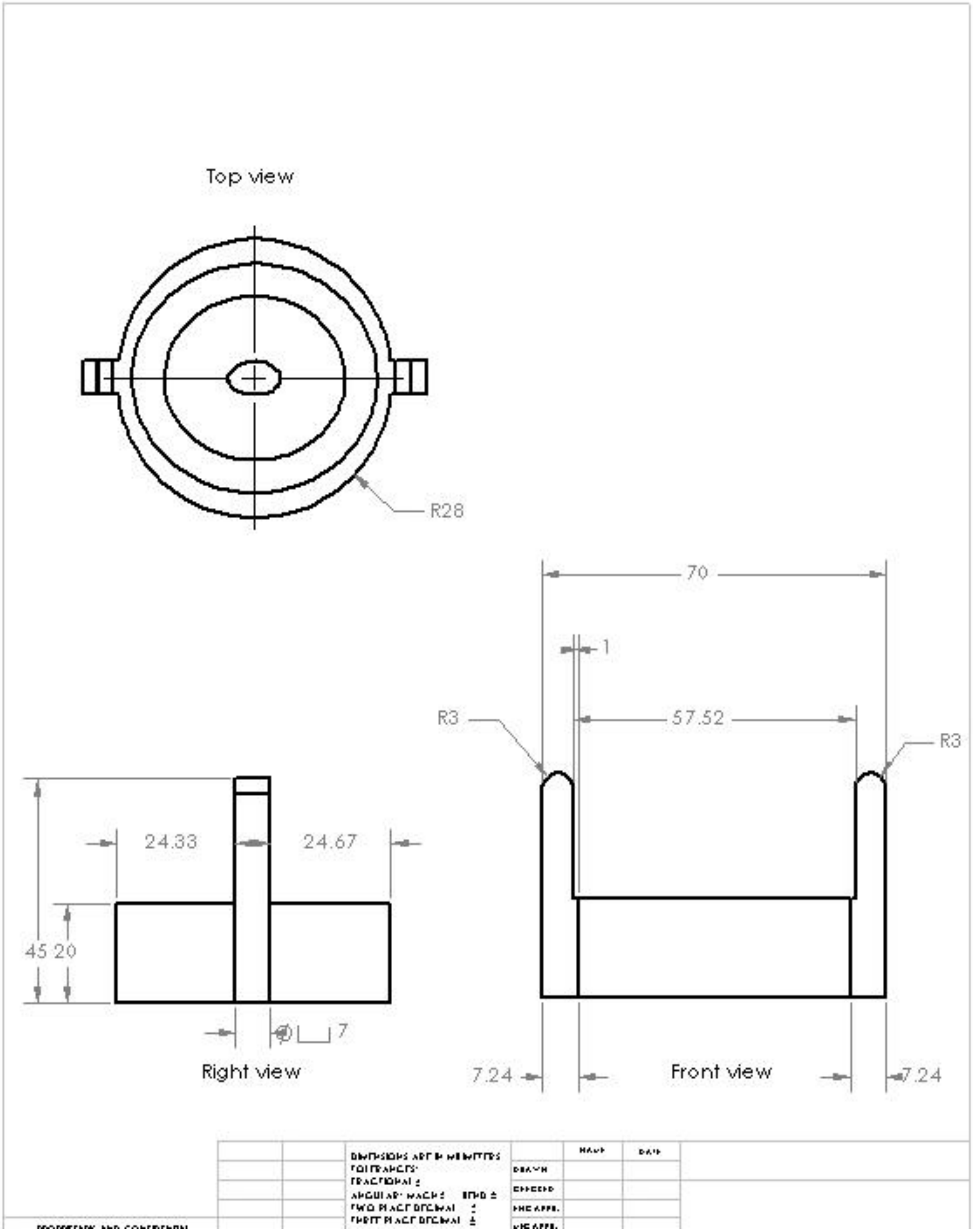

Figure 17: Female Connector CAD drawing with dimensions

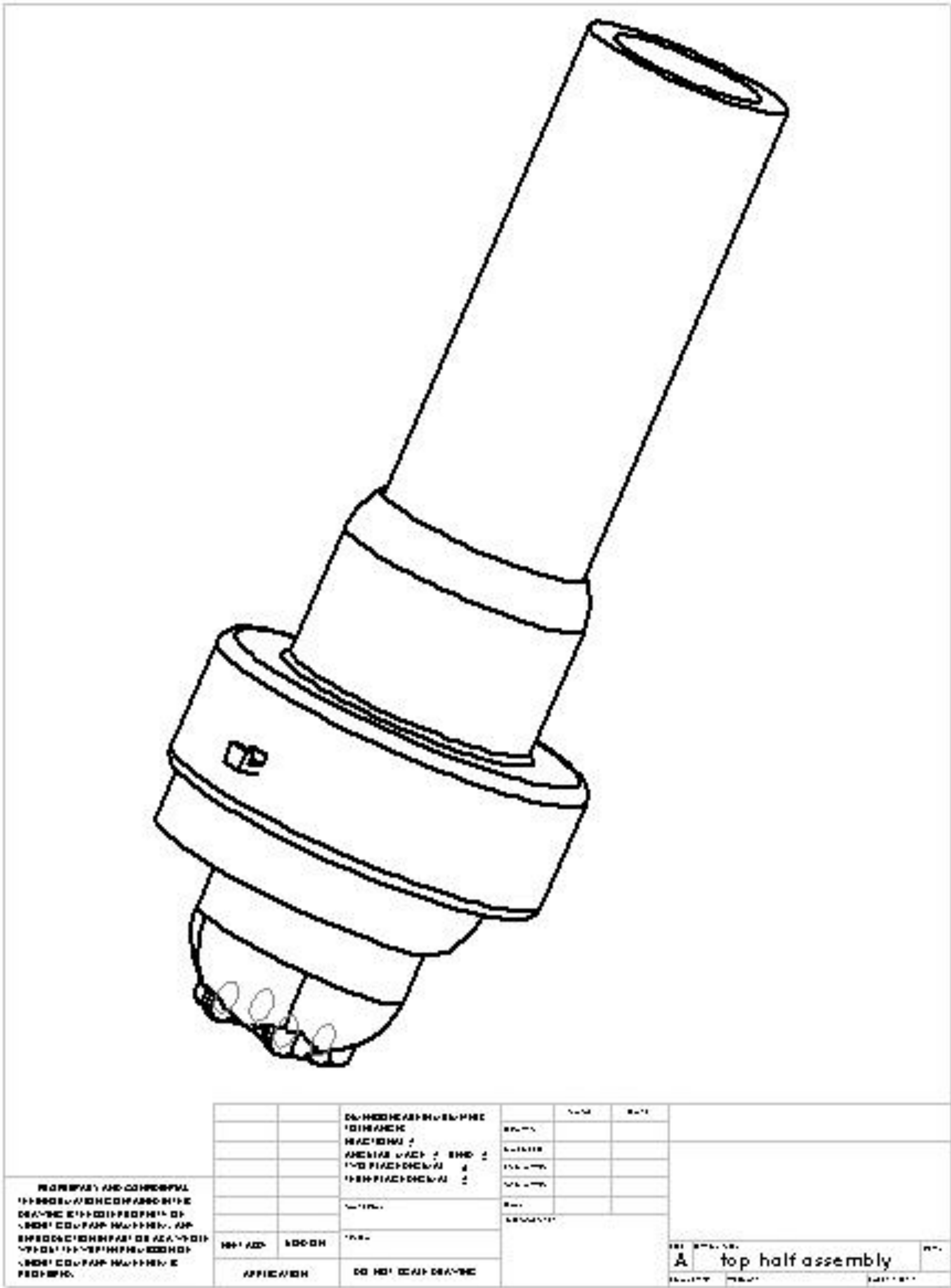

Figure 18: Top partial assembly CAD isometric view, solid

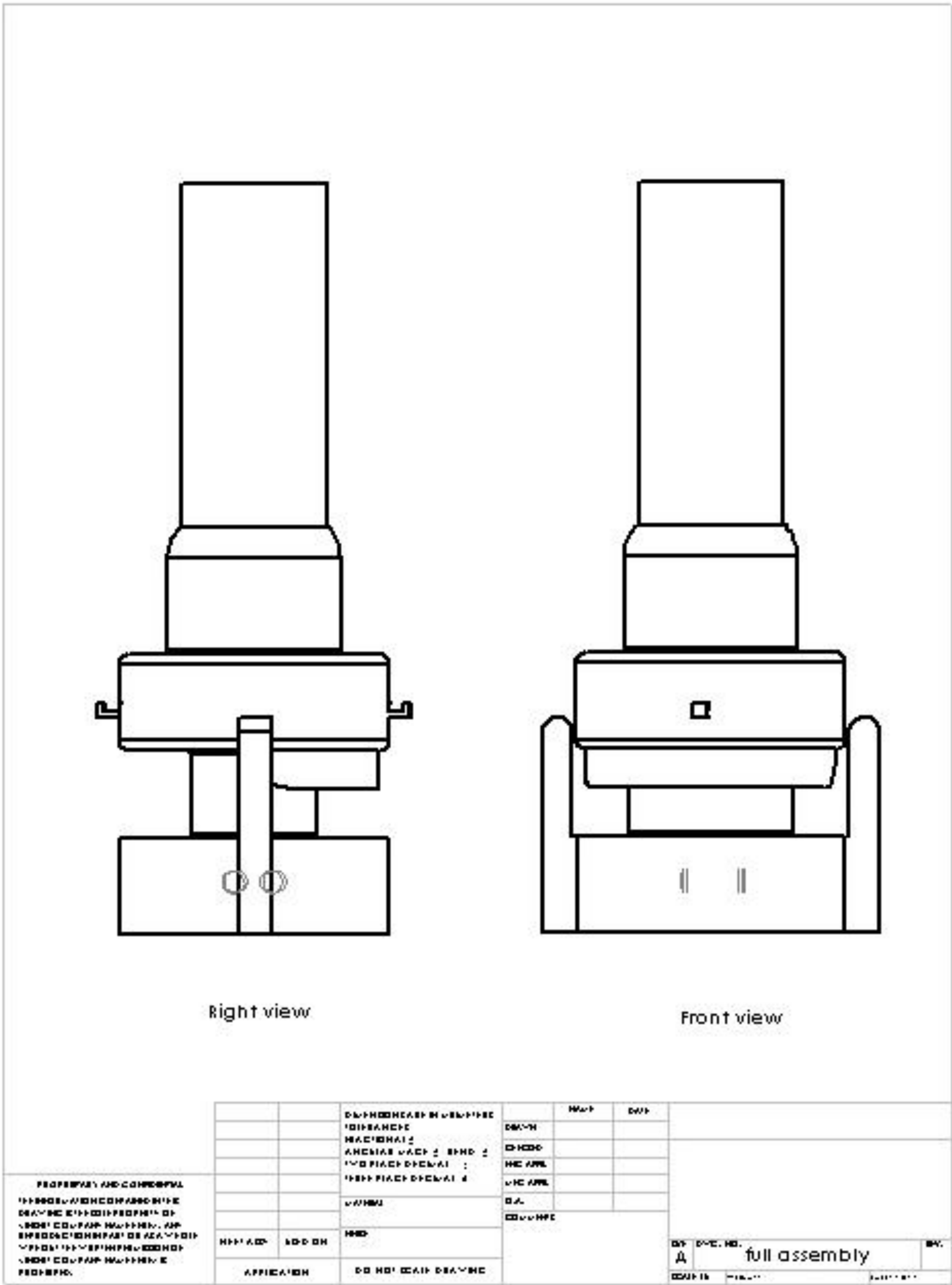

Figure 19: Full assembly CAD isometric view, solid

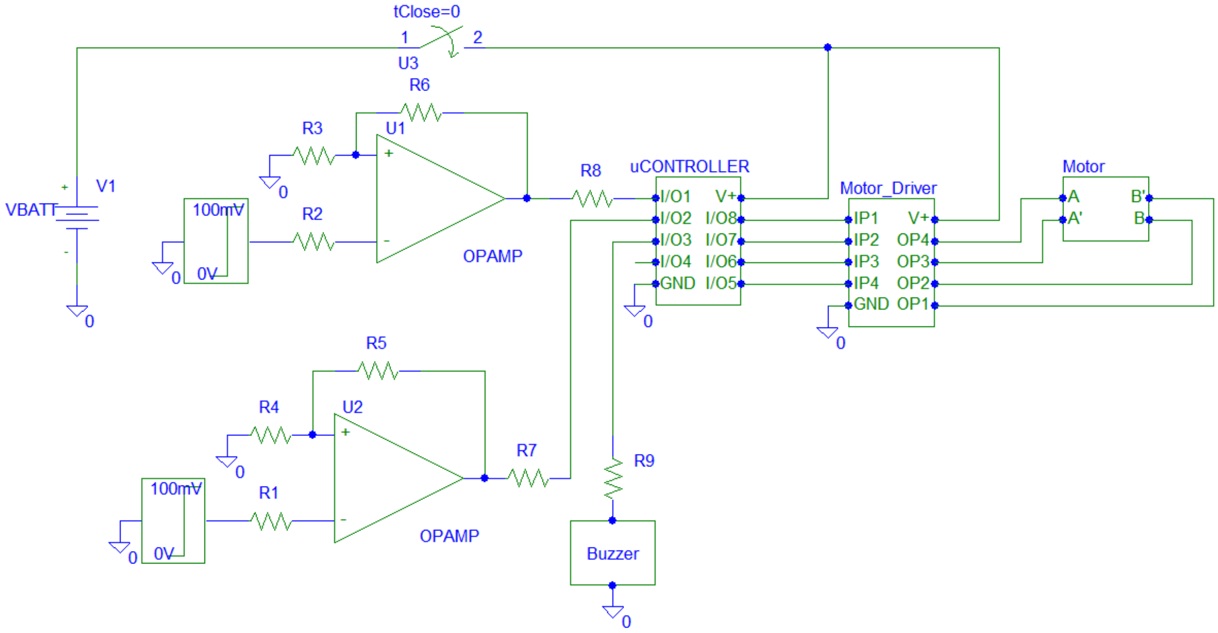

Figure 20: Schematic

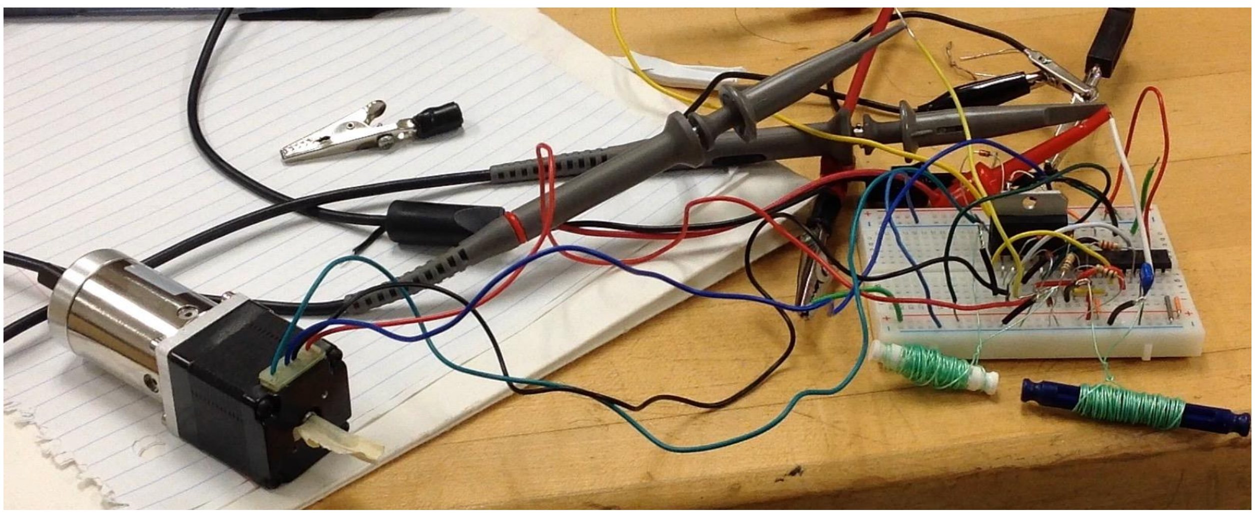

Figure 21: A Test Circuit

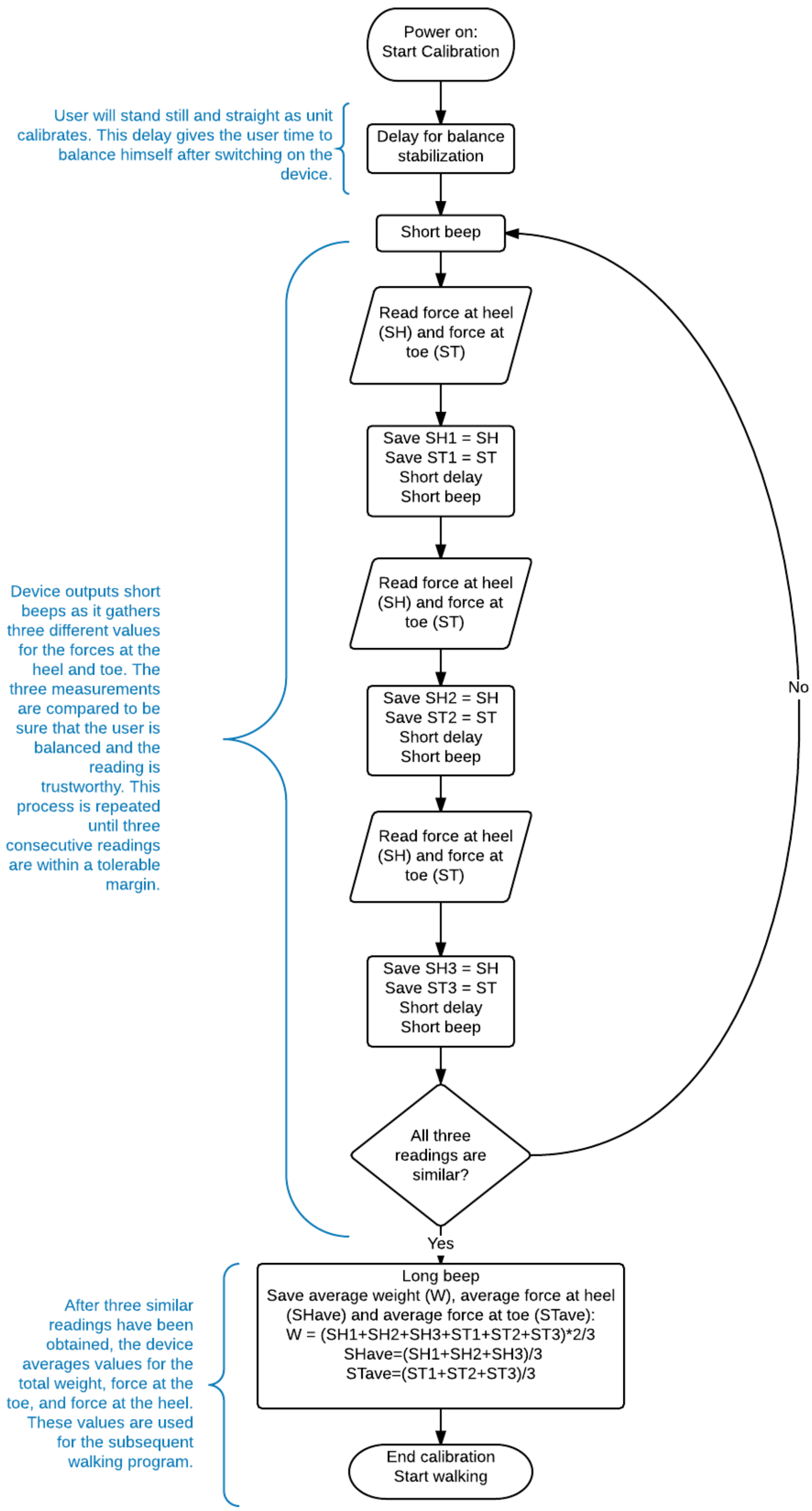

Figure 22: Calibration Program Flowchart

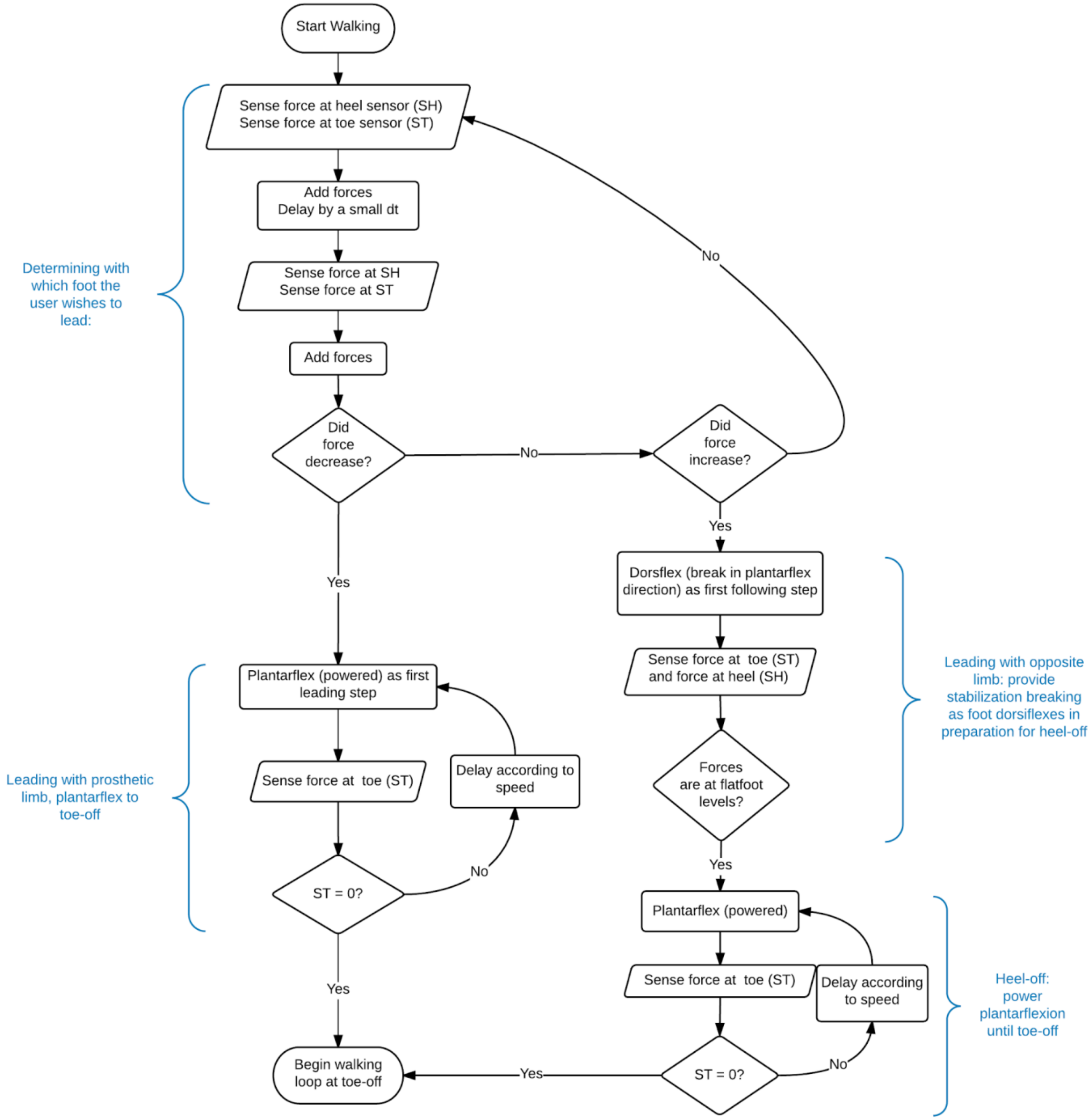

Figure 23: Walking Initialization Flowchart

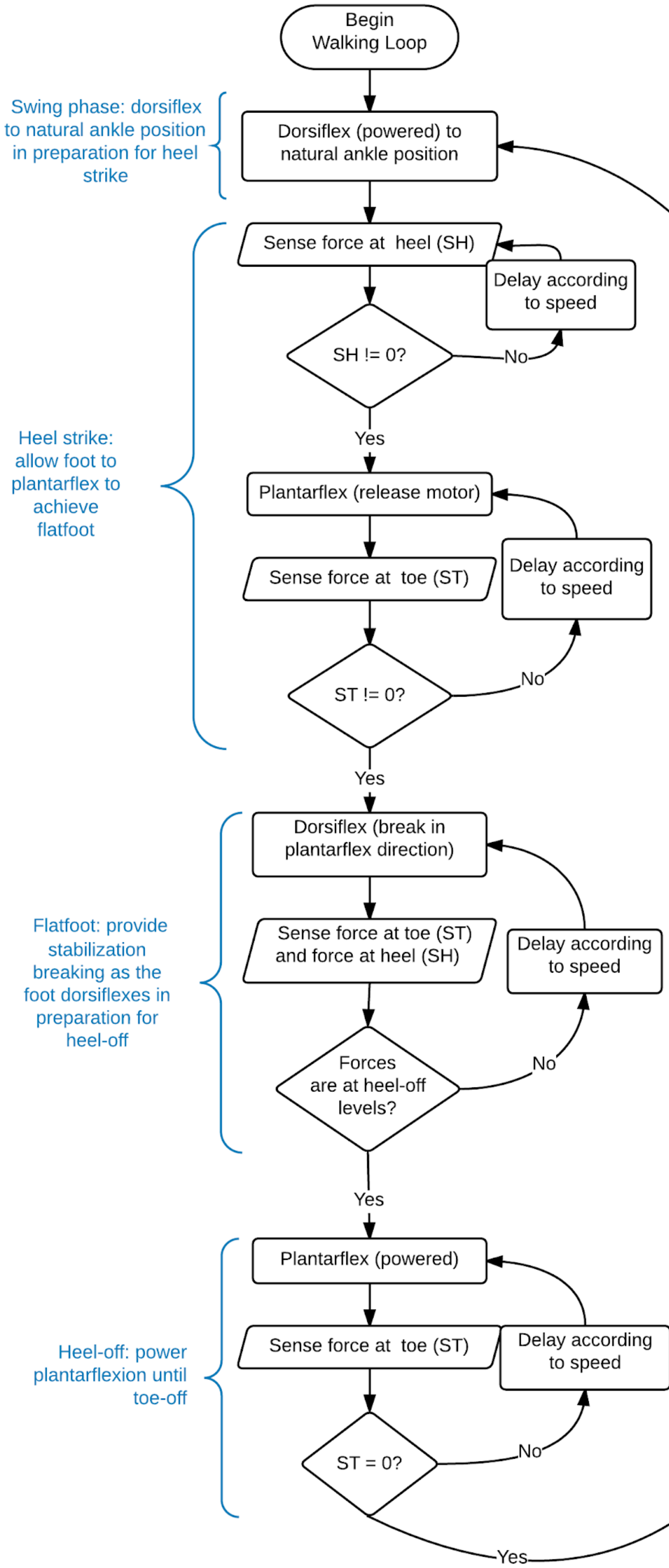

Figure 24: Walking Loop Flowchart

This 3-D printed prototype was used as a first physical design of the ankle joint. This prototypes allowed the team to truly see the characteristics and observe how the general structure of the design works and whether there is a need to make other changes to it before proceeding into its manufacturing.

The first 3-D printed prototype of the female and the male pieces of the ankle joint are shown in Figure 25 and Figure 26. These prototypes were directly made from the CAD designs shown in Figure 10 through Figure 19. The team converted the CAD files into STL files in order to be inputted into the 3-D Printer. Fabrication of the male and the female parts lasted 6 hours and 9 hours, respectively. As observed in Figure 25, the male piece includes the wholes for the wheels, the stopper to control rotation of the ankle, and the ligament attachments.

Figure 25. 3-D printed prototype of male ankle piece.

The female piece, shown in figure 26, includes a nicely concave surface in order to allow for sliding of the male piece. It also includes the side bars to secure the male piece and avoid the male piece from leaving the sagittal axis. By keeping the male piece on the sagittal axis only, the stability and safety of the joint increases. However, the safety side bars of the female pieces are not high or thick enough to secure the male part.

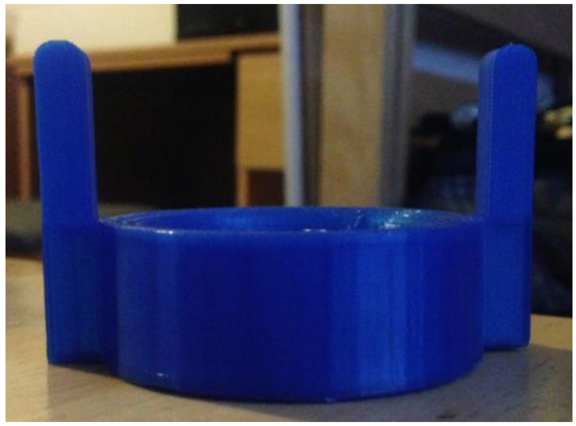

Figure 26. First 3-D printed prototype of female ankle piece.

Due to the female piece's inability to secure the male piece, the team made some alterations to the measurements of the female piece in order to increase the height and thickness of the female part and also increase the main base of the joint. The male piece was kept the same so only a second female piece was created. Figure 27 shows the the second 3-D printed female piece of the ankle joint. In this case the safety side bars represent a much better structure providing both, great stability and support to the male portion. In addition, the sliding surface of the female piece was made wider in order to allow more rotation of the male piece and the edges of the female piece were made steeper in order to secure the ankle joint from going to far forward or backwards. Figures 27 to 33 show several points of view of the ankle joint prototype brought together. The male portion was attached to the female safety side bars by nailing each of the side bars to the male piece, which created the axis of rotation for the male piece.the nails worked perfectly as the axis of rotation for the ankle joint. Surprisingly, these nails did not crack the 3-D printed material.

Figure 27. Second female piece and male piece set together, posterior view.

Figure 28. Second female piece and male piece set together, lateral view.

Figure 29. Second female piece and male piece set together, anterosuperior lateral view.

Figure 30. Second female piece and male piece set together, superior view.

For testing purposes, a rubber band was used to simulate the effects of the chain on the rotation of the ankle joint.

Figure 31. Second female piece and male piece set together with rubber band, posterior view.

Figure 32. Second female piece and male piece set together with rubber band, lateral view.

Figure 33. Shows the 3-D printed wheels and pulleys. These were not able to fit into the ankle joint due to the effects of acetone on the plastic, which swollen the wheels making the too

big for the ankle joint. The acetone was used in order to eliminate the support structures created by the 3-D printer.

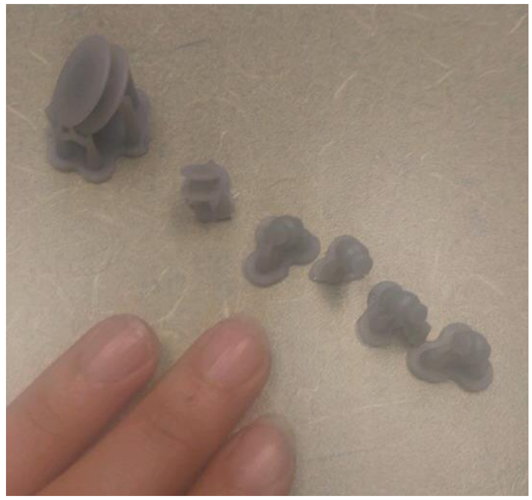

Figure 33. 3-D printed wheels and pulleys.

The process of 3-D printing the pieces brought several complications for the team and the success of this project. The resin printer, which is the one capable of printing such small pieces, kept getting damage and throughout the entire semester, and the team had to postpone the creation of the prototype. Without having any prototype at all, the team did not want to proceed with the creation of the real design in aluminum in order to not waste expensive material.

The team order all materials from different online websites. The total budget remains under the $300 cap as it is (please see the budget in table 5 in the results and discussion section). The following sub-section includes the materials necessary to make this project possible.

Mechanical Components

Most of the mechanical system will be developed at the MUSE Machine Shop. The team has decided to manufacture the male and female components, the stabilizing ligaments, the pulleys, and the wheels. These components will be made of aluminum, which keeps the metal used for the Universal Prosthesis standard and allows for better weight results. The wheels will also include a rubber cover to decrease the friction between both components. Table 2 shows several specifications on the measurements of components that were missing on the PDR. More specifics on these components, including measurements and CAD designs, can be found in the Engineering Documentation (PDR, page 36). The components will be manufactured with the MasterCAM device at the Machine Shop. The team has already received permission from Dr.

Sumner to use this device. In addition, the lab assistants have also offered us help for operating the MasterCAM since none of the team members are certified for it. The chain and the gear will both be order from suppliers. The suppliers for these parts can be found in Table 1 in the Budget section.

Table 1 Complementary Measurements.

Part	Measurements
Large Pulley	Size: 19.05 mm; 9.525 mm radius, 3 mm width between sides of pulley
Small Pulley (x2)	Size: 7.94 mm; 3.97 mm radius, 3 mm width between sides of pulley
Chain	Size: 3 mm in diameter, 391.16 mm long
Aluminum Cylinder	Size: 76.2 mm diameter, 152.4 mm long

Electrical Components

The electrical components include the microcontroller chip, a geared stepper motor, a motor driver, an h-bridge, a 555 timer, and push-button switches. The microcontroller chip was chosen to be a PIC12F629, shown in Figure 34. This microchip has the perfect size and it offers enough the necessary commands to fulfill the program required for the control of the ankle. The motors were chosen to be step motors that will together connect to the shaft and drive the gear.

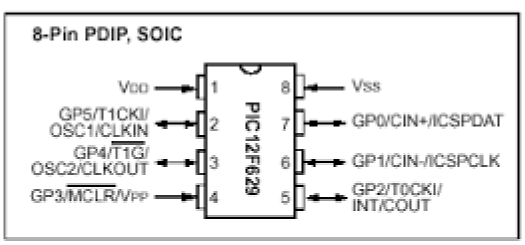

Figure 34: PIC12F629 Chipset Schematic

A program was used to translate states of push buttons on input pins to commands given to a motor driver. Each unique combination of the two input pins corresponds to a different phase of the gait. A table for these inputs is given in Table 2.

Table 2. Inputs vs Motor

Input Buttons	Gait Phase	Motor Action
Heel and Toe both closed	flatfoot	dorsiflex
Heel open Toe closed	heel-off	plantarflex
Heel and Toe both open	swing	dorsiflex to 0 degrees
Heel closed Toe open	heelstrike	plantarflex to the ground

The motor was driven by a L297 and L298N combination. The setup is given in Figure 35. With this setup, a clock input, and enable, and a direction are all that's necessary to drive the motor. The faster the clock, the faster the motor will turn.

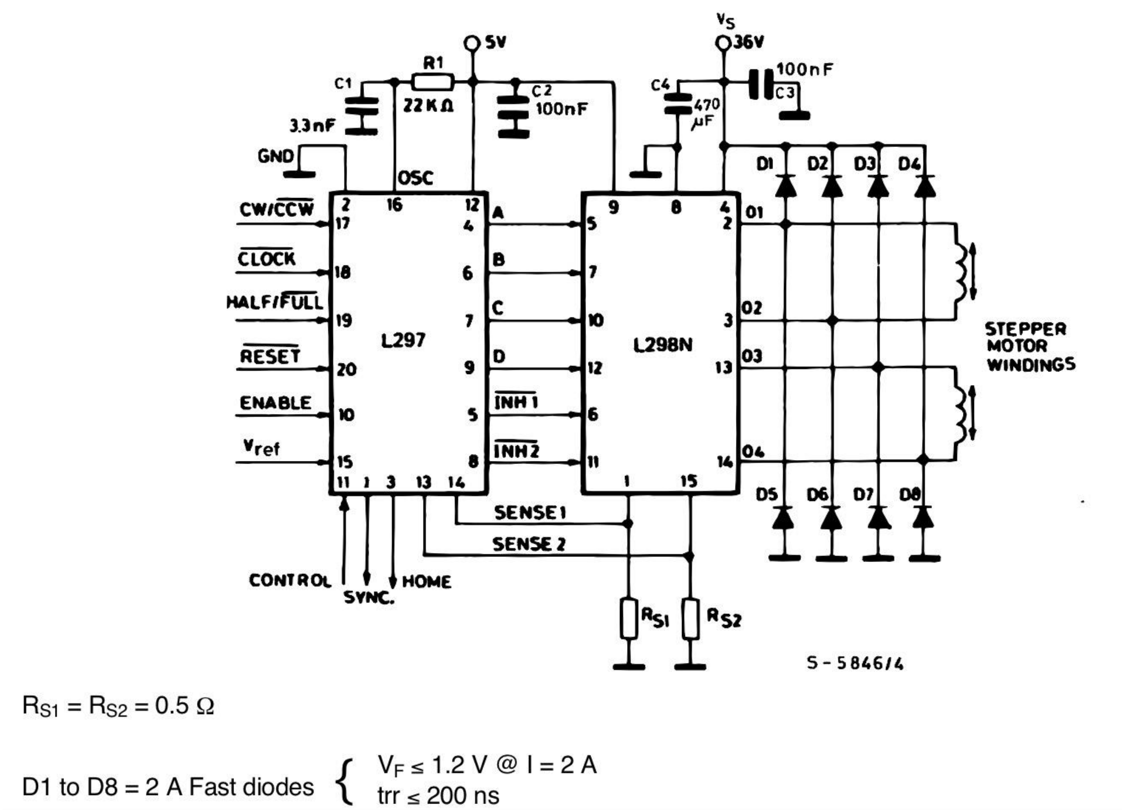

Figure 35. The motor driver circuit

Some challenges in the design were balancing speed with motor performance. Because of the large gearing of the motor, a 100:1 ratio, the motor operated at a fast speed with only a slow shaft speed. The clock frequency was limited to less than 2000 Hz, corresponding to a 0.6 radians per second angular speed of the geared shaft.

The following sections does over the production of the nylon model of the ankle joint and the development of the backbone, gears, axles, holders, and the prosthetic foot.

Making the Gears, Axles, and Holders

First the prosthetic foot was traced on a piece of paper. Then, the area in which the gear would fit was measured. Lastly, the chain was wrapped around that circle and held in place so that it could be traced. This gave the team the number of teeth, along with correct dimensions and spacing. The gears were placed where desired, and it was measured how long the axles would need to be. They were added, and plug were placed at the end opposite of Gear B so that it could be secured from moving left and right. Two axle holders were constructed out of giant paperclips to keep the axle suspended in the air while still being able to rotate.

Making the Backbone

The backbone, shown in Figure 36, was made after the ankle joint was assembled. A Long thin piece of steel was placed beside the foot and joint, and it was measured for height. The box that holds the motor was made to specifically fit the motor's length, width, and height. The box was placed just high enough that it would clear the ankle joint. A hole was drilled at the bottom of the backbone so that the Axle from Gear B to Gear A would fit inside. In order to secure the backbone, a steel pipe was cut into a ring, and that ring was cut in half. The half-ring was placed behind the backbone, and a piece of metal sectioned it off into a third. This was so the metal pylon would have less room to move laterally. Everything was welding in place.

Figure 36. Backbone

Making the Prosthetic Foot

The prosthetic foot, shown in figure 37, was made by tracing out the prosthetic foot molds in the Prosthetic lab. This piece was cut out of 0.5 in plastic, and placed in an industrial oven at 400 degrees for 25 minutes. Halfway through it was sprinkled with baby powder and flipped over. After it was visibly melting, it was placed inside the molds and clamped together. Then, it was placed in water to cool. Afterward, a 0.5cm gap was made at the layover so that flexion could occur. The crepe was traced out by the foot, with additional length given for a toe. Three layers of crepe were cut and each was given a thin layer of rubber cement. The foot was also given a layer of rubber cement, and both were placed in the industrial oven at 300 degrees for 5 minutes. When the time had passed, they were placed together and clamped for security. This was put inside a vacuum seal to prevent it from coming apart as it cooled down and dried. The toe was then sanded into the desired toe shape, and a V was cut into the top two layers of crepe where the plastic ended. This was for toe flexion. Yellow foam was placed in the hole for cover. The holes for the chain to come through the front and back were drilled out. All edges and corners of the plastic part of the foot were sanded.

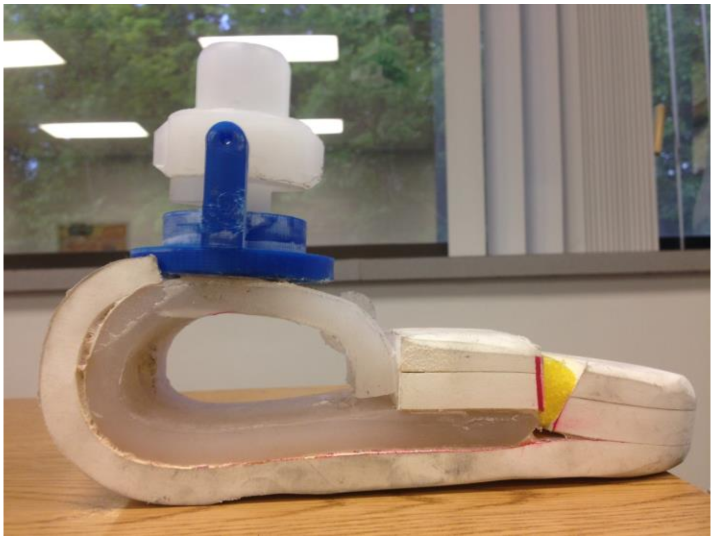

Figure 37. Prosthetic foot with ankle joint.

Making the Nylon Joint Pieces

Each part of the ankle joint made out of nylon was sent to a Roland Model A MDX-40A milling machine. TechSoft VPanel and SRP Player were used to set up each piece. The drill bit used was a ⅛” drill bit, at a rotational speed of 10800 rpm and cutting speed of 1020 mm/min. Material was set to Acrylic. Milling was made to cut for faster time and smooth edges, only from the top.

After the development of the ankle joint, it was necessary to perform various tests to ensure that the device is functional and meets all different requirements/feasibility criteria. The testing selected for this devices included various tests that focused separately on the electrical and mechanical functionability. In addition, there were several more tests proposed that are not possible at this stage, but that would be beneficial for the future development of this ankle joint.

Final Design

All of the pieces fit together to make the final design (Figure 38).

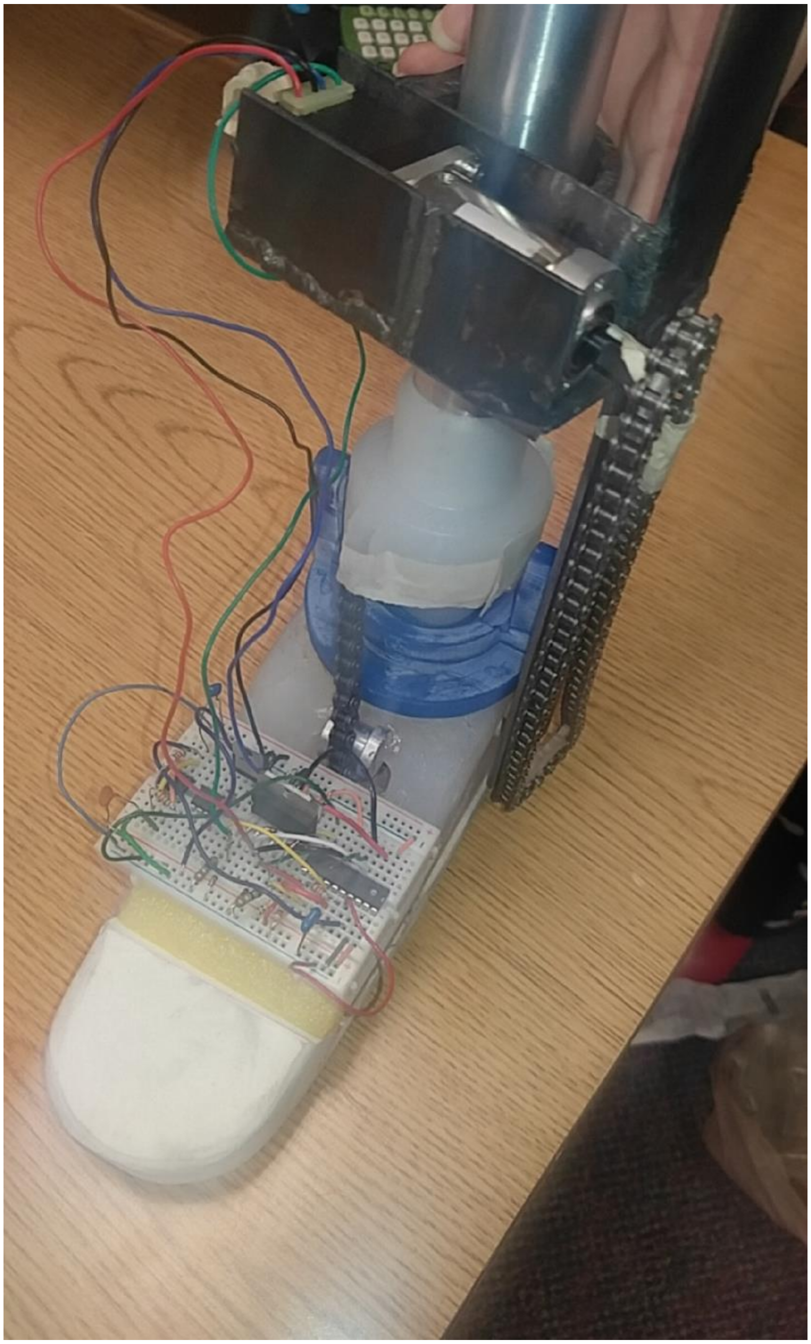

Figure 38: Final Design of Ankle Joint

This final design underwent a series of tests. The selected tests were:

- Materials test.
- Stability and functionality tests
- Degrees of motion test.
- Chain tensile strength test.
- Motor Output Test.
- Current and Battery Life Test

All these combined are perfect to offer the team an idea of the prototype performance. A description and results of all tests is offered in the following section.

Tests and Checks Performed

The following series of tests and checks allowed the team to define the success of the design and its performance as a mobile ankle joint under the specifications given by the client.

Materials Test

A Static Analysis Simulation was made in AutoCAD Inventor. The material for the male connector, female connector, and pylon were set to Aluminum 6061, and the four wheels were set to silicone rubber. The Safety Factor was set to Yield Strength. A load of 150 lbf was applied downward along the y-axis to simulate a person's weight, and gravity was applied. A pulling load of 30 lbf was applied to the plates to simulate a pulling chain.

Stability and Functionality Tests

These test represents more of an overall check of the design and how it works mechanically and fits together with the electrical component. The results for these checks are rather qualitative than quantitative. Throughout these checks the team verified the stability of the ankle joint in the different planes. These checks focused also on analysing the manual mobility and sliding capability of the male component over the female complenet of the ankle joint. In order to performed this test, the team had previously set the rotational axis with the pins for more accuracy. These checks also included the testing of the electrical components on the ankle joint through the gear and chain system.

Degrees of Motion Test

This test focused on finding out the maximum angle of both, dorsiflexion and plantarflexion, for the ankle joint. This test was performed by first setting the prototype at neutral position. Then for checking on the maximum angle of plantarflexion, the male component was slided forward over the female component making the entire feet plantarflex. The angle created by the new positioning of the female component and the neutral positioning was defined as the maximum angle for plantarflexion. The same was done to get the angle of dorsiflexion, but instead of sliding the male component forward, it was slided backwards, which raise the feet, thus making it dorsiflex.

Chain Tensile Strength Test

This test was majorly an analysis of the tensile strength properties of the chain. The tensile strength of a material is the maximum amount of tensile stress that it can take before failure, such as breaking or permanent deformation. Tensile strength specifies the point when a material goes from elastic to plastic deformation. It is expressed as the minimum tensile stress (force per unit area) needed to split the material apart. Appendix A shows a full table for the properties for the chain used in the design.

Motor Output Test

To determine the motor's response to the circuit and program, the circuit was simulated with the clock continuously applied to the motor at the chosen frequency. The time to complete one full cycle of rotation on the geared motor shaft was measured.

Current and Battery Life Test

In order to predict the life of the battery, it is necessary to how much current the circuit draws. To measure this, a small 0.5 ohm resistor was placed between the positive terminal of the battery and the power rail of the circuit. The power was applied to the circuit and the voltage drop across the 0.5 ohm resistor was measured. The current was then found using Ohm's law. This current was then divided into the battery capacity to obtain the expected battery life.

Results and Discussion

After having a full analysis of the final design developed, the team was able to gather all results and perform a full discussions on the final design, the tests, and its performance.

The final the design satisfies mostly all the expectations set by the proposal and the feasibility criteria. All deliverables were developed by the team with the exception of the full setup of the ankle joint into the universal prosthesis. But as far as the design goes, all pieces were combined together making the device complete.

As far as the feasibility criteria goes, the design developed by the team represents a durable design. This can be proven through the material's test that was performed and the safety factor obtained. The ankle joint allows for enough dorsiflexion and plantarflexion for the ankle to have an impact on the patient. Due to the chain design, the ankle joint can also operate while the motor is off. Furthermore, the design does fit into the universal prosthesis. The only reason why this was not delivered was due to the fact that the aluminum version of the ankle joint was not able to be made, given the lack of the mechanical engineer's expertise in the team and such credentials to work in the machine shop. Finally, the design has an overall good safety. The ankle joint is very stable and does not allow for movements on the frontal plane, forcing it to stay on the sagittal plane. It is also very stable, allowing the patient to trust the device and be able to walk on it.

After the design presented on the PDR was reanalyzed, there were a couple of changes made to improve some small details of the final design and make it an even sefar and stronger model. As a first alteration, the female component of the ankle joint was changed to wider and more stable. There was an extra based added to the female piece for more stability. In addition, the side bars that connect to the male component were made bigger and wider since this represents a big weak point of the design. Due to complications with motor placement and power supply, the team developed a backbone that represented the structure holding the motor. The motor was then connected to the chain through a three gear system which allowed for the torque outputted to the ankle to be high enough.

In the side of the electrical component, the two motor design was changed to a one motor design since the team was able to find a decent size motor that outputted the necessary power. This also made it easier to interphase the motor with the driver and the program, since driving two motors at the same time would be a bigger challenge. A 555 timer was added to the circuit with the purpose of supplying a clock to the motor driver. Also, instead of using pressure sensors, the final design uses push buttons as way to know when to dorsiflex and plantarflex.

The following paragraphs show the results of the tests performed on the design.

Materials test

The results of the safety test were as expected. The constricted joint where the pylon fits inside the male connector is under a lot of stress. The plates for the chain are also under a lot of stress. These areas are the weak points in the design (Figures 39 and 40). The pin that was applied to connect the male and female parts did not distribute pressure like it should, but when a load was applied to the pin holes, the simulation would not run. The team knows the support columns of the female piece should not be dark blue.

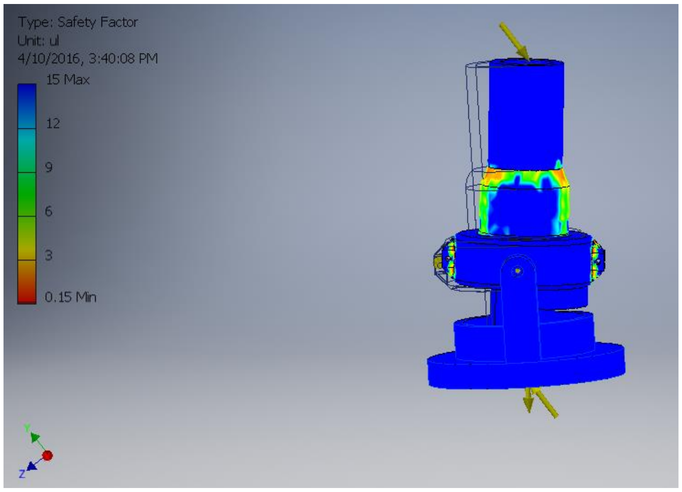

Figure 39: Safety Factor Test, left view.

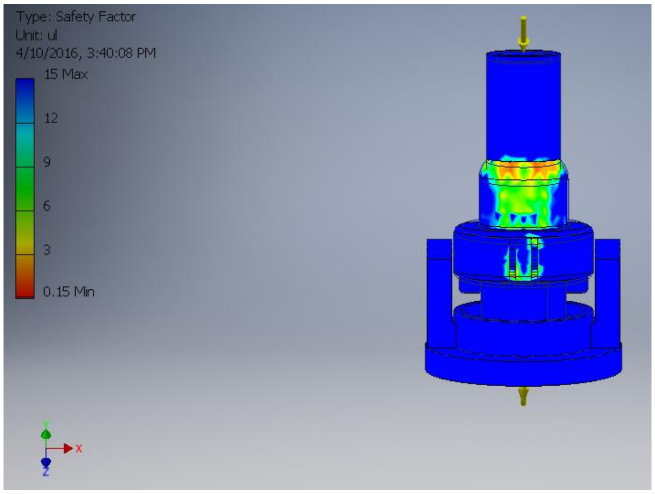

Figure 40: Safety Factor Test, Front View

The female connector was removed so that the wheels and oval head at the base of the male connector could be seen (Figure 41). The wheels are dark blue, but they should be orange or red because the weight of the person is on them when they rotate. However, instead it shows the bottom of the male connector as red, as if the pressure is concentrated there. The team knows this to be not true because the wheels indeed stick out of the oval head when rotating. Therefore, the joints and constraints placed on the wheels must not have been thorough enough. They were re-applied in several different combinations, but the simulation ran the same way.

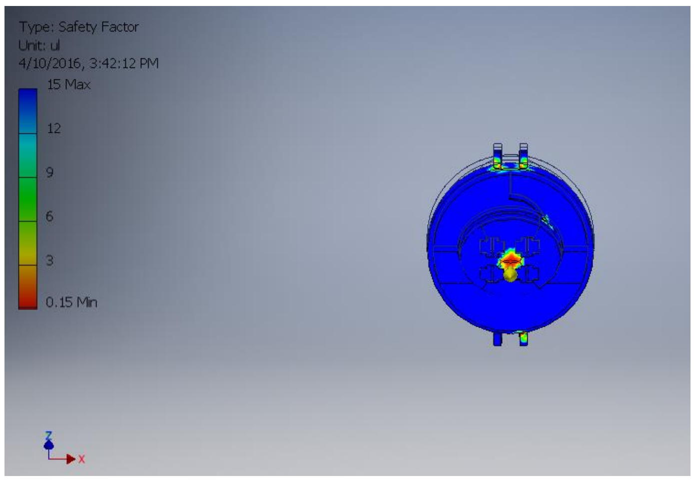

Figure 41 Safety Factor Test, bottom view

Stability and Functionality Tests

The ankle joint resulted to be incredibly stable thanks to the wide side holders of the female component. The male component is also able to slide over the female component without interruptions. The male can only move along the sagittal plane as intended.

Degrees of Motion Test

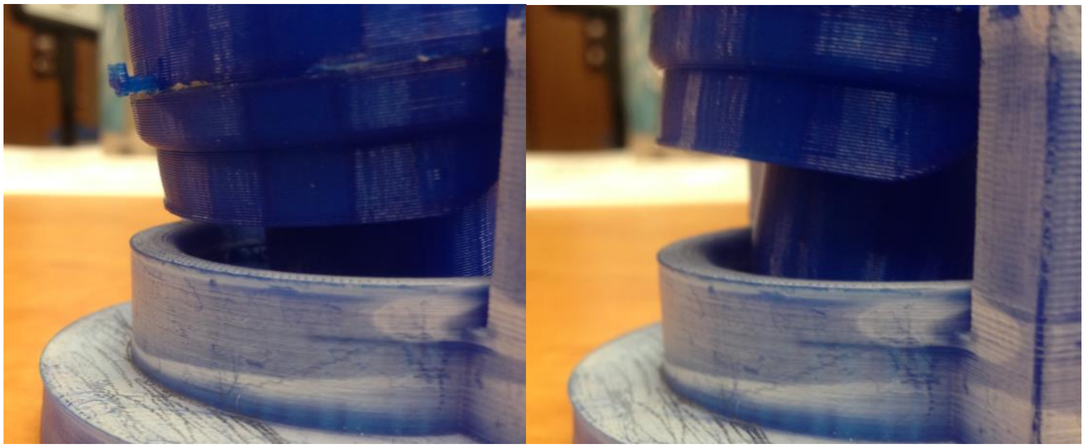

Figure 42. Dorsiflexion and Plantarflexion angles.

Chain Tensile Strength Test

According to the specifications for this chain, shown in Appendix A, the minimum tensile strength of the chain is 780 N/m^2. The Figure 43 shows an analysis of the chain characteristics.

Chain Type	Strength	Wear	Heavy Loads	Shock Loads	High Speeds
Standard ANSI	Good	Excellent	Good	Good	Excellent
XTRA H Range	Good	Excellent	Excellent	Good	Not Suitable
XTRA V Range	Excellent	Good	Good	Excellent	Good
XTRA HV Range	Excellent	Good	Excellent	Excellent	Not Suitable

Figure 43. Standard ANSI chain characteristics.

Motor Output Test

The results of the Motor Output Test is given in Table 3.

Table 3. Results of motor output test.

Frequency	Shaft period	Angular speed
1726 Hz	11 sec	0.571 radians/sec
1900 Hz	9 sec	0.698 radians/sec

This test allows us to know the speed characteristic of the motor. The 1726 Hz clock from the 555 timer was compared with a 1900 Hz signal injected into the circuit. The periods and angular speeds were both measured. It must be certain that these speeds do not pose a safety threat to the user. These results are small enough to be considered safe.

Current and Battery Life Test

Table 4 shows the results of the current and battery life test.

Table 4. Results of the current and battery life test.

Voltage measured	current calculated	expected battery life
0.476 V	0.952 A	1 h 9 minutes

The battery life is expected to be 1 hour and 9 minutes. This means batteries must be changed daily. This results in an undesired amount of waste. It is recommended in future studies to use rechargeable batteries and/or higher capacity batteries which will produce a longer battery life.

<u>Final Budget for the Developed Design</u>

Table 5. Final Budget

Project Budget				
Item Name	#	Item Purpose	Cost	Supplier/Manufacturing.
Prototype printing	1	Prototype creation	$0	3-D printing lab.
Backbone	1	Steel for fabrication	$15	Machine shop
Ankle Creation	1	Fabricate the mechanical ankle	$0	Manufactured in Machine Shop.
Spring Packet	1	Helps motor on plantarflexion	$4.29	[2] Amazon.com
Gear	1	Drives the chain	$0	Machine Shop
Chain	1	10 ft for testing purposes	$30.60	[5] Fastenal.com

Microcontroller PIC12F629 Packet	1	Motor control; programming of dorsiflexion/plantarflexion	$2.65	[7] Ebay.com
Motor	2	Ankle movement	$52.68	[9] Ebay.com
Button sensors	4	Interface with microcontroller	$1.40	[8] Sparkfun.com
Motor driver	1	Control and drive motor	$60.66	[10] Mouser.com
Motor batteries and charger	1	Powers the motor and electronics of ankle joint	$12.95	[11] Batteryspace.com
Other circuit components	x	Connect circuit, limit current, set gain, provide sound, aluminum.	$35.96	N/A
Binding	4	Binding of final papers	$25	[3] Staples
Total			$245.19	

Aspects of the Design

The ankle joint designed by this team is not a safe design to use for rehabilitation at the moment. Optimization of materials, gears, and joint kinetics needs to occur before a person uses it. The design does have several safety precautions in place, such as an electrical and mechanical stopper to keep the ankle from over-rotating. However, this design includes several mechanical pieces that were created and evaluated by engineers in a non-mechanical field, and before use, the design should be approved by the appropriate specialists.

This ankle joint is meant to go to Vietnam during Mercer On Mission trips. It was designed to help rehabilitate those who have not had use of the lower limb for a significant amount of time. The electrical components of this design could also be optimized, such as a smaller or lighter motor, in order to provide a better rehabilitation experience and quicker recovery of muscles. However, ethically, this design is sound and should help as it says.

The social aspects of this design are in the impact it will have on the children and adults living in vietnam. It will help them get their lives back together, because they will be able to move and function like everybody else. Without good lower limb muscles, the prosthetic must be drug on the ground,which can create other bodily issues from gait change. Without a good prosthetic, the people cannot work, and are seen as lower-class citizens.

Because this design is made out of metal, its lifespan should be just as long as the current prosthetic, after mechanical and electrical optimization. It will be more expensive that the current prosthetic due to more mechanical pieces and added electrical pieces, but it is not so expensive the design cannot be sustained over time.

Summary and Conclusions

Ideally, a prosthesis allows amputees to recover their walking abilities; however, below-knee amputee patients often have muscle atrophy in their amputated limb, which causes walking complications. Dr. Ha Vo tasked our Senior Design Team with designing a mobile ankle joint prosthetic attachment to promote muscle rehabilitation and improve gait.

Our senior design team is composed of Gabriel Gonzalez, BME, Jenna Hamlin, ECE, and Jackie Harmon, BME. The main and final goal of this project is to create an affordable, operational, and safe mobile ankle joint that can be used in the Universal Prosthesis in order to help amputees who suffer from muscle atrophy to regain their natural gait. This will maximize the efficiency this prosthetic has in assisting amputees who are unable to return to normal gait. In order for this design team to complete this task, a biomedical engineering professor and an electrical engineering professor have been requested and approved as advisors.

A total of 16 designs were proposed and Design 15 was the one to be chosen. This design further underwent some alterations to improve in several factors that would make it even a better design, such as the addition of the gear system and the backbone. The the design was manufactured in two ways, first as a 3-D printed model and then as a nylon model. The device was then tested and analyzed based on the results of the tests.

The deliverables of this project received by the Client were: a 3D printed prototype of the ankle joint, a Nylon prototype fully assembled into the mold of the foot and the electrical component, an informative brochure, and copies of the circuit program, design sketches, CAD designs, and the Inventor analysis in metal.

In summary, the team concluded that this model is a strong design for the mobile ankle joint to be used on the Universal Prosthesis. The movement of the joint is very fluent and stable. The joint itself is also a extremely stable component due to the inclusion of the side ligaments that eliminated any movement in the front or transverse planes. The chain represents an excellent way to drive the joint back and forth. The gear connection from the motor to the chain allows for the achieving the right amount of torque to drive the joint. The circuit developed operates well and puts controls the movement from dorsiflexion to plantarflexion of the ankle joint. The full cost of the design does not go over $300, making it a very cheap and affordable device in comparison to other technology offered out there. Overall this device is very well-rounded and represents a strong design for the mobile ankle joint.

Despite the development that has been done to this device, this mobile ankle joint is yet to be ready for patient use. This design doesn't have the required materials necessary for the joint to hold the weight of a patient or sustain the wear to too pressure. Fabrication of the aluminum design was not possible due to the lack of a mechanical engineer in the team. Even though the device is not fully ready for patient use, this design does present a potential device for mass production.

Finally, further development of this device would definitely bring it to a possible point for patient use. In the following section the team has presented a series of recommendations that may serve as future studies for this device and will definitely contribute to the final goal of making it possible for patients to use.

Recommendations

Since this design represents the first model created for this device, there are a good number of recommendations made by the team for future development of this mobile ankle joint.

One of the major complications of connecting the electrical and the mechanical components together was that there was no motor size in the market that would appropriately adapt to the needs of the device and at the same time output enough power to drive it. It would be of great interest if as a separate project, one mainly electrical engineering focus, a future team focuses on creating a motor that offers the perfect output to drive the ankle joint and also has the right measurements and weight to allow for a better structure of the connection between the electrical and the mechanical components. This would directly solve the need for a backbone since by outputting enough power will also eliminate the need for a gear ration.

Further electrical engineering focused studies should look at the possibility of developing a more complex program and circuit. If these electrical components were able to conduct a weight analysis through pressure sensors, rather than push buttons, the whole device would be able to create the right amount of output power necessary for each specific weights.

In a materials standpoint, finding a better material that does not increase the cost of the device for too much would be ideal to increase the safety and lifespan of the ankle joint. From a mechanical standpoint, the gears could be made out to be more efficient than the ones done for this stage. A future study should definitely look into focusing of the creation of mechanically better gears to increase their efficiency.

One of these ideas was to make a battery that operates as a solar energy charger. The purpose of this is that then the device would eliminate the constraints of battery life, as it could constantly remain charged through the absorbance of solar power during the day. Another future study for this device is the idea of placing all the connections within the prosthetic itself. The team has considered that it would be possible to place the battery inside the socket and connect the cables that connect the battery to the motor, through the pylon and into the foot, where the motor is located. This method would allow for more protection to the device and also less risk of outside structures getting caught with the outside environment. In addition, future studies should also consider the reshaping of the current prosthetic foot in order to allow for better room for the electrical components and the inclusion of the ankle joint. If the design of the foot was to have a bendable foot at the phalanges section, this would allow for less work to be required from the electrical components. This method would actually resemble the correct anatomically structure of the foot and provide better support and impulse. Finally, created an ankle cover to make sure all components are protected from the environment would ensure both, the safety of the device and the patient wearing it.

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[10]http://www.mouser.com/ProductDetail/STMicroelectronics/L298N/?qs=gr8Zi5OG3Mj6jDtNclcF9Q%3D%3D&gclid=Cj0KEQiA-ZSzBRDp3ITHm5KO_JYBEiQA1JjHHHv-RsGklPV47fgCArVTEZWxi_KzQmJKJ5wT1rOJbukaAjSq8P8HAQ

[11]http://www.batteryspace.com/ch-p228compact9vcharger2pcs9vnimh200mahretangularbattery.aspx?gclid=Cj0KEQiA-ZSzBRDp3ITHm5KO_JYBEiQA1JjHHCq-GyaWJqFb14FOLkR0aY1OHuDWXWqRlQDkcr_E9Q8aAtMF8P8HAQ

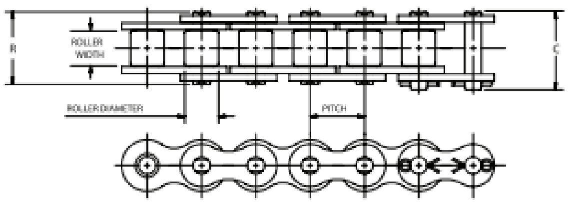
Appendices

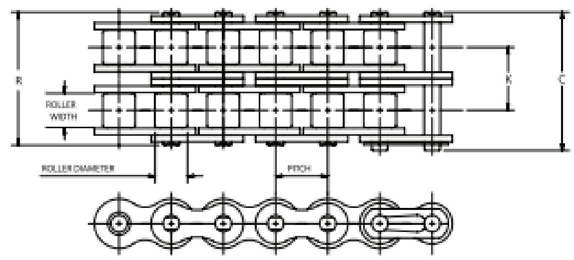
Appendix A. Table of chain properties.

ASME / ANSI SERIES CHAIN

SINGLE AND MULTI-STRAND

Sapphire Standard series chains are built to ASME/ANSI B29.1 standards.





Dimensions in Inches

ASME/ANSI Number	Pitch Inches	Roller Width	Roller Diameter	Pin Diameter	Link Plate Thickness	C	R	K	Pounds Per Foot	Minimum Tensile Strength
25	1/4	1/8	*.130	.090	.030	0.37	0.34	....	0.084	780
35	3/8	3/16	*.200	.141	.050	0.56	0.50	....	0.210	1760
35-2	3/8	3/16	*.200	.141	.050	0.96	0.90	0.399	0.450	3520
40	1/2	5/16	.312	.156	.060	0.72	0.67	....	0.410	3125
40-2	1/2	5/16	.312	.156	.060	1.29	1.24	0.566	0.800	6250
40-3	1/2	5/16	.312	.156	.060	1.85	1.80	0.566	1.200	9375
41	1/2	3/4	.306	.141	.050	0.65	0.57	....	0.260	1500
50	5/8	3/8	.400	.200	.080	0.89	0.83	....	0.680	4880
50-2	5/8	3/8	.400	.200	.080	1.60	1.55	0.713	1.320	9760
50-3	5/8	3/8	.400	.200	.080	2.31	2.26	0.713	1.980	14640
60	3/4	1/2	.469	.234	.094	1.11	1.04	....	0.990	7030
60-2	3/4	1/2	.469	.234	.094	2.01	1.94	0.897	1.950	14060
60-3	3/4	1/2	.469	.234	.094	2.91	2.84	0.897	2.880	21090
80	1	5/8	.625	.312	.125	1.44	1.32	....	1.730	12500
80-2	1	5/8	.625	.312	.125	2.59	2.47	1.153	3.370	25000
100	1 1/4	3/4	.750	.375	.156	1.73	1.61	....	2.510	19530
100-2	1 1/4	3/4	.750	.375	.156	3.14	3.02	1.408	4.910	39060
120	1 1/2	1	.875	.437	.187	2.14	2.00	....	3.690	28125
120-2	1 1/2	1	.875	.437	.187	3.93	3.79	1.789	7.350	56250
140	1 3/4	1	1.000	.500	.219	2.31	2.14	....	5.000	38280
140-2	1 3/4	1	1.000	.500	.219	4.24	4.07	1.924	9.650	76560
160	2	1 1/4	1.125	.562	.250	2.73	2.54	....	6.530	50000
160-2	2	1 1/4	1.125	.562	.250	5.04	4.85	2.305	12.830	100000
180	2 1/4	1 13/32	1.406	.687	.281	3.15	2.88	....	9.060	63280
180-2	2 1/4	1 13/32	1.406	.687	.281	5.87	5.51	2.592	17.510	126677
200	2 1/2	1 1/2	1.562	.781	.312	3.44	3.12	....	10.650	78125
200-2	2 1/2	1 1/2	1.562	.781	.312	6.26	5.94	2.817	21.500	156250
240	3	17/8	1.875	.937	.375	4.06	3.72	....	16.400	112500

*Chains are rollerless - dimension shown is bushing diameter.

Appendix B General Calculations

$Average\ Vietnamese\ weight: 150\ lbs\ =\ 68.038\ kg$ **Equation 1**

$Total\ work\ done\ (by\ ankle): 0.13\ J/kg\ =\ 8.845\ J$ **Equation 2**

$Max\ torque\ (of\ ankle): -1.5\ Nm/kg\ =\ -102.057\ Nm$ **Equation 3**

$Max\ power\ (of\ ankle): 3.68\ W/kg = 250.379\ W$ **Equation 4**

$Angular\ speed\ (of\ ankle)\ =\ \frac{Power}{2\pi * Torque} =\ 0.3904\ rad/sec$ **Equation 5**

$20\%\ of\ ankle\ torque\ = joint\ torque\ =\ -20.411\ Nm$ **Equation 6**

$\boldsymbol{20\%}\ of\ ankle\ power = joint\ power = \boldsymbol{50.076}\ W$ **Equation 7**

$Motor\ torque\ =\ \frac{joint\ torque * sprocket\ radius}{radius\ of\ rotation * cos(angle\ of\ chain\ pull)} = 6.869\ Nm$ **Equation 8**

$Battery\ power\ = Potential * Current\ Drawn\ =\ \boldsymbol{82.8}\ W$ **Equation 9**

$PE_{spring} = \boldsymbol{\frac{1}{2}} kx^{\boldsymbol{2}} = \boldsymbol{0.00005232}\ J$ **Equation 10**

Table 1 Spring specifications

Spring constant (Nm)	Free length (mm)	Load length (mm)
5.479	12.7	8.33

Appendix C Gear Calculations Table

Parts Group	Variable Needed	Name Variable	Given Value	Calculated Value	Equation Used	Units
Motor Shaft	radius	MSR	3	3	given	mm
	length	MSL	18	18	given	mm
	work (torque)	MSW	4	4	given	Nm
Gear C (motor)	torque	GCT	4	4	given	Nm
	pitch diameter	GCPD	8.085071109	8.085071109	GCPD=AGCP*GCN/pi (limit 8mm max)	mm
	diametral pitch	GCDP	0.4947390006	0.4947390006	GCDP=GCN/GCPD	teeth/mm
	outside diameter	GCOD	12.12760666	12.12760666	GCOD=(GCN+2)/GCDP	mm
	number of teeth	GCN	4	4	GCN=(GCPD/AGCP)*pi	teeth
	tooth thickness at the pitch	GCTTP	3.175007425	3.175007425	GCTTP=1.5708/GCDP	mm
	inertia	GCI	3.40E-12	3.40E-12	0.5*GCD*pi*AGT*(GCPD/2)^4	g/mm^2
	circumference (outside of teeth)	GCC	38.1	38.1	GCC=GCOD*pi	mm
	tooth whole depth (height total)	GCWD	4.359874596	4.359874596	GCWD=2.157/GCDP	mm
	tooth addendum (height above pitch)	GCA	2.021267777	2.021267777	GCA=1/GCDP	mm

	tooth dedendum (height below pitch)	GCD	2.338606818	2.338606818	GCD=GCWD-GCA	mm
	cylindrical volume	GCCV	154.0206046	154.0206046	GCCV=pi*AGT*(GCPD/2)^2	mm^3
	Density	GCDn	0.0027	-	given	g/mm^3
Calf chain	pitch diameter	CCPD	0.25	-	given	mm
Gear B (outside)	pitch diameter	GBPD	26.2764811	26.2764811	GBPD=AGCP*GBN/pi	mm
	diametral pitch	GBDP	0.4947390006	0.4947390006	GBDP=GBN/GBPD	teeth/mm
	Outside diameter	GBOD	30.31901666	30.31901666	GBOD=(GBN+2)/GBDP (Limit 31mm)	mm
	number of teeth	GBN	13	13	GBN=(GBPD/AGCP)*pi	teeth
	tooth thickness at the pitch	GBTTP	3.048	3.175007425	GBTTP=1.5708/GBDP	mm
	inertia	GBI	2.37E-11	2.37E-11	0.5*GBDn*pi*AGT*(GBPD/2)^4	g*mm^2
	circumference (outside of teeth)	GBC	95.25	95.25	GBC=GBOD*pi	mm
	tooth whole depth (total height)	GBWD	4.359874596	4.359874596	GBWD=2.157/GBDP	mm
	tooth addendum (height above pitch)	GBA	2.021267777	2.021267777	GBA=1/GBDP	mm
	tooth dedendum (height below pitch)	GBD	2.338606818	2.338606818	GBD=GBWD-GBA	mm

	cylindrical volume	GBCV	1626.842636	1626.842636	GBCV=pi*AGT*(GBPD/2)^2	mm^3
	Density	GBDn	0.0027	0.0027	given	g/mm^3
Gear A (inside)	pitch diameter	GAPD	18.19141	18.19141	GAPD=AGCP*GAN/pi	mm
	diametral pitch	GADP	0.4947390006	0.4947390006	GADP=GAN/GAPD	teeth/mm
	outside diameter	GAOD	22.23394555	22.23394555	GAOD=(GAN+2)/GADP (Measured 19mm)	mm
	number of teeth	GAN	9	9	GAN=pi*GAPD/GACP	teeth
	tooth thickness at the pitch	GATTP	3.175007425	3.175007425	GATTP=1.5708/GADP	mm
	inertia	GAI	5.44E-12	5.44E-12	0.5*GADn*pi*AGT*(GAPD/2)^4	g*mm^2
	circumference (outside of teeth)	GAC	69.85	69.85	GAC=GAOD*pi	mm
	tooth whole depth (Total height)	GAWD	4.359874596	4.359874596	GAWD=2.157/GADP	mm
	tooth addendum (height above pitch)	GAA	2.021267777	2.021267777	GAA=1/GADP	mm
	tooth dedendum (height below pitch)	GAD	2.021267777	2.338606818	GAD=GAWD-GAA	mm
	cylindrical volume	GACV	779.7293109	779.7293109	GACV=pi*AGT*(GAPD/2)^2	mm^3
	density	GADn	0.0027	0.0027	given	g/mm^3

Ankle Design	load (weight of person)	ADLOAD	68038.8555	68038.8555	given 150 lbs	g
All gears	Thickness	AGT	3	3	given	mm
	chain pitch	AGCP	6.35	6.35	given	mm

Appendix D. Resumes

Redacted