Ankle Exoskeleton Preliminary Report

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Monday, October 3, 2017
ME 476C
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DISCLAIMER

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Contents

1 Background

1.1 Introduction

The project the team was assigned is to create an ankle exoskeleton device that will help individuals with equinus deformities to improve gait. Equinus is a condition in which an individual suffers from restricted ankle motion, often leading to an inefficient "toe-walking" pattern, in which the patient walks on the balls of the feet. The exoskeleton device the team is creating will assist in re-distributing weight across the foot, and will provide a propulsive force to help the patient walk. The team must design an appropriate drive system to provide propulsion and must design the device to allow for adjustment for a range of equinus severities. Ultimately, the project should help equinus patients manage their condition by helping them establish a more energy-efficient pattern of walking.

1.2 Project Description

The team client, Dr. Zachary Lerner, is the director of the Biomechatronics Lab at NAU. The Biomechatronics Lab uses robotic exoskeletons to improve walking biomechanics in individuals with neuromuscular disorders. Some individuals with cerebral palsy walk with a pattern known as equinus, which has an inefficient energy expenditure. These individuals have limited ankle range of motion, so assistance must be applied in series to the ankle joint. The goal of this project is to design an ankle exoskeleton attachment that supports the foot and will be used improve walking economy.

2 Requirements

Dr. Lerner is the client for this project. The intended consumer, and stakeholder, of this project will be people, specifically children, with equinus deformities. The project is not intended to help people with extreme cases; rather, it is meant to assist with management of milder deformities. The target age range is for children between 5 and 12 years old. Since the team is attaching the device to patients, high stability and a high factor of safety are needed.

Requirements of the project include completing a finite element analysis (FEA), using computer aided design (CAD) to compare 2-3 different devices, and deliver a working prototype that meets the constraints. One such constraint includes using a Bowden cable transmission system. A Bowden cable is similar to a bike break cable, and supplies tension. The device must interface with footwear and have an orthotic attachment to the calf. The device must be adjustable for a range of sizes and for a range of equinus severity. The target severity range is between 0-30 degrees. This angle is measured from the ground to the foot of the subject. The applied propulsive torque should lie within a range of 10-15 Nm. The device must include a torque sensor to gauge how much assistance the device is giving. The device must be comfortable and must soften heel strike. The entire device must be lightweight, no more than 0.25 kg for each foot. Requirements specific to the control box also include a Bluetooth connection. This will allow streaming of data to and from the device. The ultimate goal of the Bluetooth data stream is to take the real-time processing off the microcontroller and moving it to a device that has more processing power.

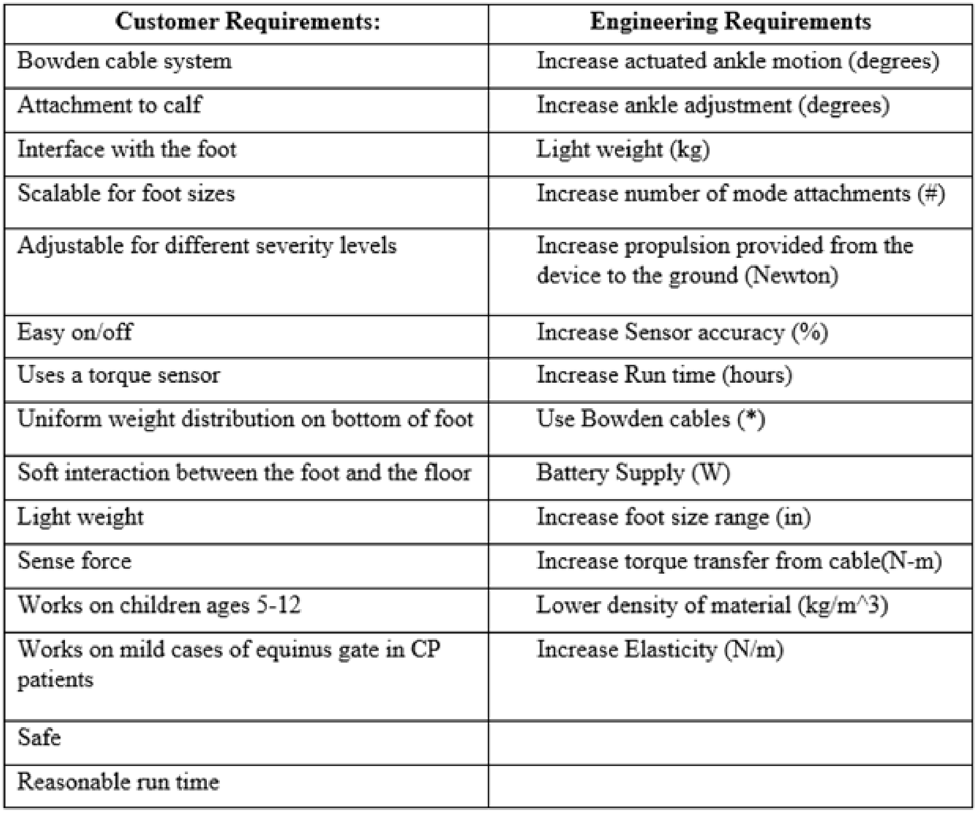
2.1 Customer Needs

Customer requirements outline what the client expects from this project. A Bowden cable is wanted for force transmission from the motor to the device. The device must attach to the calf and foot of the patient. The device will be scalable to meet various patient foot lengths and sizes. The device will be scalable based on the severity of equinus gait, and will have features to allow easy attachment. Torque sensors must be used to collect feedback from movement. The device will need to evenly distribute weight across the foot, will need to be comfortable, and must be lightweight. The device will need to sense force during use for feedback. The device will be used for children ages 5 to 12. The device will need to be safe and have a sufficient run time.

2.2 Engineering Requirements

Engineering requirements provide a unit of measurement as to how the device satisfies the customer needs. The actuated ankle can have an angular motion between 25-30 degrees. Static ankle adjustments can range from 0-30 degrees. The material of the device should have low density, to minimize weight. Modes of securing the device (orthotics) can be increased. Propulsion should be supplied between 10-15 Newtons. Sensor accuracy can be between 10-20 percent. Battery life should allow for at least a 2-hour run time. Motor/actuator force must interface with the device through Bowden cables. The device must be adjustable for foot sizes appropriate for ages 5 to 12.

Table 1: Customer and engineering requirements



Customer Requirements:	Engineering Requirements
Bowden cable system	Increase actuated ankle motion (degrees)
Attachment to calf	Increase ankle adjustment (degrees)
Interface with the foot	Light weight (kg)
Scalable for foot sizes	Increase number of mode attachments (#)
Adjustable for different severity levels	Increase propulsion provided from the device to the ground (Newton)
Easy on/off	Increase Sensor accuracy (%)
Uses a torque sensor	Increase Run time (hours)
Uniform weight distribution on bottom of foot	Use Bowden cables (*)
Soft interaction between the foot and the floor	Battery Supply (W)
Light weight	Increase foot size range (in)
Sense force	Increase torque transfer from cable(N-m)
Works on children ages 5-12	Lower density of material (kg/m^3)
Works on mild cases of equinus gate in CP patients	Increase Elasticity (N/m)
Safe	
Reasonable run time	

2.3 House of Quality

After the customer requirements and engineering requirements were decided, they were integrated into a house of quality (QFD), shown in Appendix A. A QFD allows for a visual interpretation of the relationship between the customer requirements and the engineering requirements. It also shows the correlation between the different engineering requirements. The customer requirements were placed on the left side of the QFD and the engineering requirements at the top center. The customer requirements were rated by the team relative to their importance. It is also important to note that the highlighted cells indicate absolute requirements by the client. They may be rated at a lower importance, due to the fact that they may not relate to the management of equinus gait as heavily as other requirements. The relationships are weighted 1 through 9 (9 being the highest weight). The top portion relates engineering requirements. The bottom portion indicates the required range and the importance of the engineering requirements. It can be seen that the top three engineering requirements are as follows: to increase actuated ankle motion (degrees), to increase sensor accuracy (%), and to increase propulsion provided from the device to the ground (Newtons). This indicates important aspects that should be kept in mind when designing.

3 Existing Ideas

3.1 Design Research

During the preliminary stages of the project, research focused on medical background for equinus. The research established a clear understanding of the condition. Consulting a variety of medical journals and articles helped define the mechanics of equinus, a useful foundation for the eventual design of a device intended to help patients manage the disorder. Patients suffering from equinus tend to plantarflex (bend the foot downward) excessively, and are unable to dorsiflex (bend the foot upward). The result is some degree of “toe-walking,” as defined previously. This causes unbalanced muscle development and severe wear on the forward areas of the foot, which are not intended to carry the weight of the entire body. If the ankle could bend sufficiently, weight could be redistributed towards the heel, and such problems could be avoided.

The focus of this project is equinus management, not treatment. Accordingly, research was directed at helping patients live with the condition, without trying to improve the condition. The prevailing medical opinions on managing equinus emphasize redistribution of weight away from the front of the feet. Ideally, a device employed to assist a patient will help restore balance when walking, will provide increased comfort, and will help to correct problems in gait. Orthopedic specialists and physical therapists employ combinations of orthotic devices and exoskeletal attachments to meet these requirements.

A comfort constraint requires consideration of the materials used in an orthotic or exoskeletal device. The majority of prosthetic devices utilize composite materials, including carbon fiber, Kevlar, and fiberglass. Ideally, the materials used in such a device will have both durability and an ability to flex. When the patient walks, the device will provide sufficient structural support without restricting natural movement of ankle and foot joints.

Further research indicated that current devices used to manage equinus vary in terms of mobility. Some orthotic and exoskeletal devices are static, locking the patient's ankles and feet into a fixed position, with the intent of restricting plantar flexion while forcing dorsiflexion. Other devices allow for some range of motion, so that a dynamic element (natural to walking) is still present. This may allow for some plantarflexion to remain, as long as the heel is taking more weight than the forefoot.

Even in devices that allow for adjustment or range of motion, motorization and propulsion are absent. A propulsive device could, theoretically, apply an assistive force to a patient's feet and ankles, making walking easier. A propulsive exoskeleton for equinus is an original concept, with limited technological basis in any current orthotic or exoskeletal equinus management devices. However, the components utilized by such a device (such as the motors, cables, sensors, and orthotic attachments) can be found in use elsewhere, and were researched thoroughly.

3.2 System Level

Because this project is attempting to create a device that does not currently exist, the team researched system level designs of exoskeletons and prostheses that represent design components relative to our project goals.

One exoskeleton design that was researched was US patent No. 8876123, an exoskeleton and foot attachment system. This device can be used to attach standard footwear to sporting equipment such as skis or snowboards. The exoskeleton is specifically intended for minimizing the time and hassle of changing boots during outdoor activities, while still providing the necessary support and function. The device involves a multi-strap system to attach the exoskeleton to the boot. It has two over-the-foot straps that hold the top of the foot to the rigid base, a front strap to adjust the ankle cuff, and two back straps to secure the heel to the boot. The rigid ankle cuff provides support for the ankle, and the rigid base allows for the exoskeleton to be attached to sporting equipment [1].

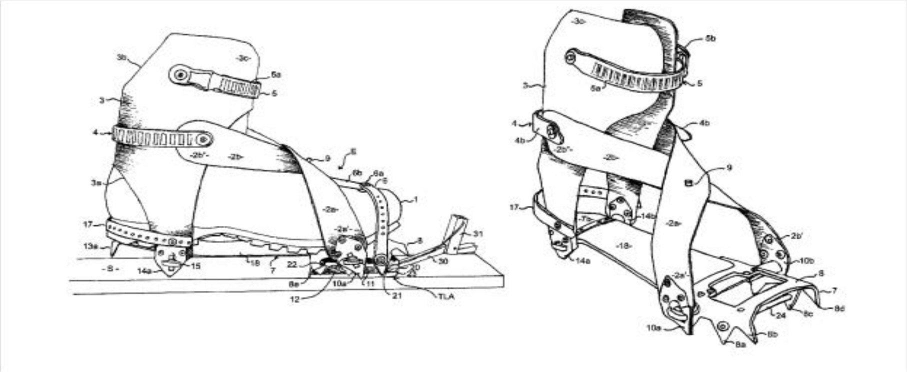


Figure 1: Exoskeleton and footwear attachment system [1]

This over-the-foot exoskeleton is applicable to our design in that it provides a way to connect a device to any standard shoe type, and is adjustable to accommodate different shoe and ankle sizes.

Another exoskeleton design that was researched was US patent 20160331557, which describes an ankle exoskeleton that assists in gait for users in different walking conditions. This patent describes, in detail, control algorithms and different types of sensors that can possibly be used. The patent stresses the need for two sensor types, force sensors and motion sensors. The sensors are used to determine which part of the gait cycle the user is in. Multiple sensors are employed to differentiate between different parts of the cycle. The force sensors' intended use is to see if all, some, or none of the user's weight is loaded onto a particular foot. The control algorithm takes in sensor input to determine the walking intent of the user. The following flow chart is from US patent 20160331557, which outlines a basic algorithm defining when assistance should be given to the user. The patent requires any external wires to be located physically within the exoskeleton, to avoid any wire pinching or tangling. This patent can serve as a resource for the electronics portion of the design. It can be used as a basis for developing the control algorithm, and also for a basic mechanical design [2].

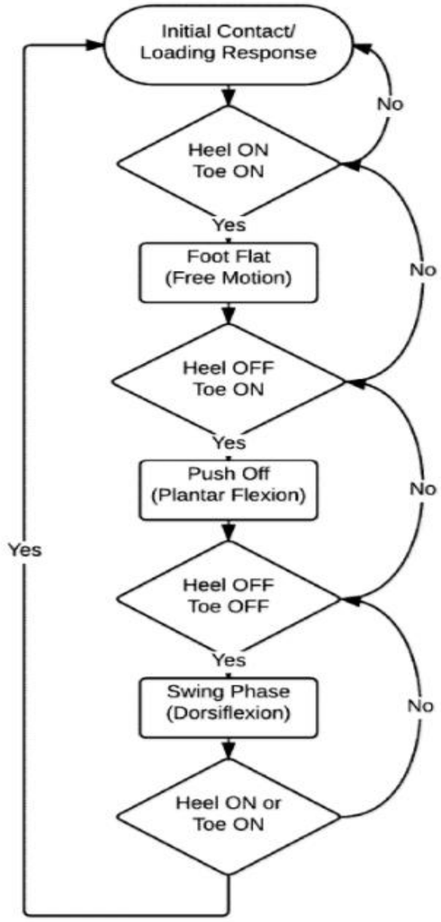


Figure 2: Flowchart of the basic assistance algorithm from US Patent 20160331557 [2]

A third exoskeleton design that was researched was the Berkeley Lower Extremity Exoskeleton (BLEEX), as it is presented in the conference paper. The paper describes the difference between anthropomorphic and non-anthropomorphic design. What these describe is how much the exoskeleton fits onto the body of the user. A fully anthropomorphic exoskeleton tends to be more complex, as the space is more limited within them. A fully anthropomorphic exoskeleton completely incorporates all of the user's degrees of freedom. Essentially, the natural mobility of the user is not limited. The non-anthropomorphic exoskeletons are loose-fitting on the body, and are much less discrete. They also tend to limit the natural mobility of the user, as the exoskeleton is only designed to be moved in very specific ways. The paper describes why the authors chose a pseudo-anthropomorphic design, as the exoskeleton fits onto the user, but is not able to replicate all of the body's degrees of freedom. The pseudo-anthropomorphic BLEEX incorporates the degrees of freedom at the hip, one degree of freedom on the knee, and three degrees of freedom at the ankle. The patent describes how each of the components were designed in order to help augment the user's movements. The team can use this paper to understand why the Berkeley team chose to design their exoskeleton the way they did. The team may be able to foresee problems that the Berkeley team already solved, thus saving time in the design process [3].

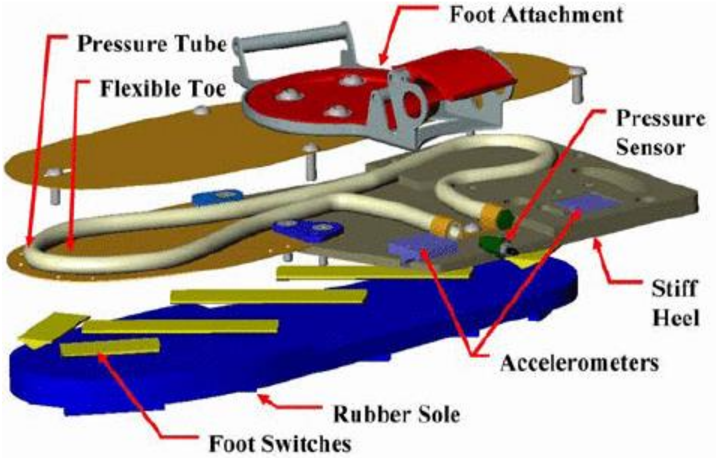


Figure 3: Sensors embedded in the foot portion of the BLEEX [3]

3.3 Functional Decomposition

The functional decomposition of this project returned simpler results than expected. The project begins with numerous deliverables and constraints, but condensing all of the requirements into the basic physical functions of the product improved the team's understanding of the task. The black box model shown below (Figure 4) details inputs and outputs, while the functional model below (Figure 5) shows the process and the feedback loop controlling the product.

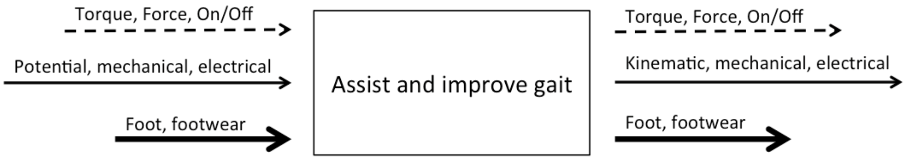


Figure 4: Black box model

The black box model focuses on the task of the product - provide support and gait assistance to the user. Given this simplified task, the team could focus on the minimum inputs and outputs in their most basic form. Each of these inputs contributed to developing systems and subsystems, as we were able to map out signals to movements. Further, the functional model provides the real-time function of the product. Timing is crucial to the success of the product, as the walking cycle must be measured for each user. The process of how information is generated and sent to the controller dictates speed and productivity.

When simplified, the product is a feedback loop - sensors provide information that the controller uses to know when to provide assistance to the user. The loop repeats multiple times during a single gait phase, even though the actual mechanical propulsion will only be provided once on each foot per cycle.

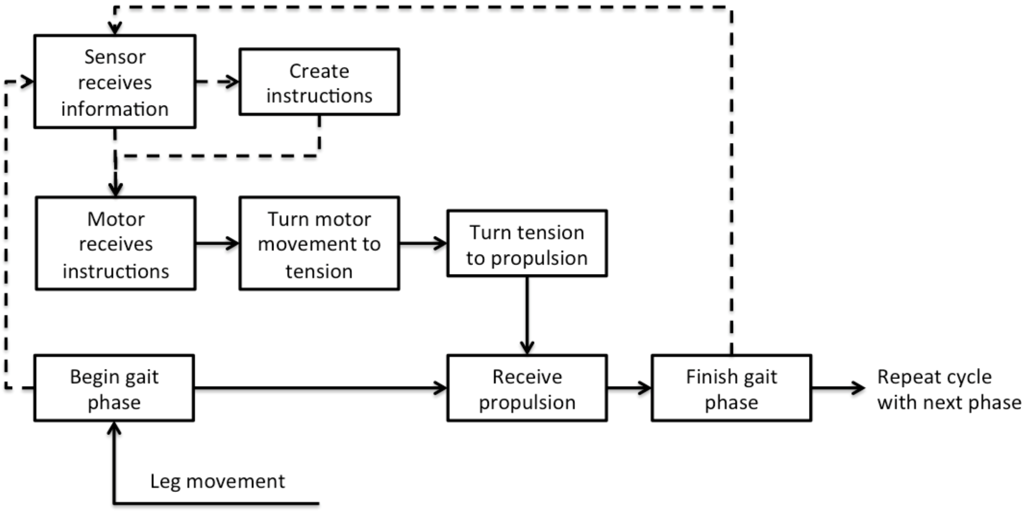


Figure 5: Functional model

3.4 Subsystem Level

Three major subsystems of this design are the mechanical aspects of the exoskeleton, the orthotics, and the electronics of the exoskeleton. The mechanical aspects of the exoskeleton include the propulsive device, the Bowden cable system, and the actuation method. The orthotics subsystem incorporates the interface between the device and the user, including the adjustable heel height and any method to provide added comfort. The electronics subsystem involves the sensors, the signaling processing system, and the control system.

<u>Exoskeleton Subsystem</u>

Propulsion

The primary goal of the device to supply an assistive propulsive force to the user during the propulsive phase of the walking gait. This force needs to push the foot upward and forward. One example of a foot propulsion device is the BiOM prosthetic ankle. This prosthetic mimics the human muscle/tendon system to provide a propulsive force during walking by rotating the ankle joint. This is achieved using a series-elastic actuator, comprised of a brushless motor and ball-screw transmission, which is in series with a carbon-composite leaf spring. Rotary motion from the motor is converted into linear motion through the ball-screw transmission. The in-series leaf spring is used to improve motor efficiency, which it does by storing, then returning, some of the energy that comes from the motor [4].

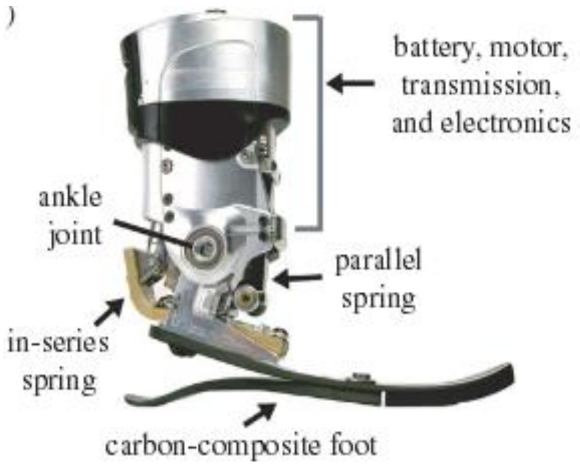


Figure 6: BiOM exoskeleton [4]

Bowden Cable

One of the design constraints for this project requires that the design must interface with a Bowden cable system. A Bowden cable is a cable within an outer cable housing. When the inner cable is tensioned, a force is applied to the other side of the cable. Kirby Witte has previously done work with ankle exoskeleton devices that incorporate Bowden cables to give propulsion to the ankle. The Bowden cable was attached to a plate at the bottom of the ankle. By pulling the Bowden cable superiorly at the heel of the foot, a net force directed anteriorly and superiorly is created. The device had a range of motion of 30 degrees for plantar flexion and 20 degrees for dorsiflexion. These are measured relative to when the foot is flat on the ground. This would pose a problem for our device, as we need to accommodate up to 30 degrees of equinus severity, which is the base limit for this device. Thus, the device would have to be altered in order to accommodate our project requirements [5].

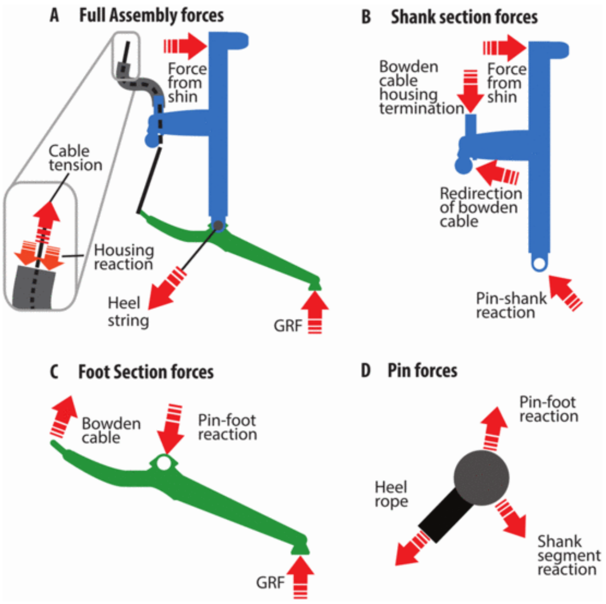


Figure 7: Bowden cable system applied to an ankle exoskeleton [5]

Actuation

The Massachusetts Institute of Technology (MIT) created an ankle robot that is actuated through two brushless motors. Actuation is important, since it moves the device, which translates into an assistive force. There are different types of actuation options, including hydraulic, pneumatic, and motorized. Series elastic actuation is also commonly used in lower extremity exoskeleton devices [gatech]. Series elastic actuation offers advantages such as greater shock tolerance, lower reflected inertia, and more accurate and stable force control [gatech]. MIT locates the motors near the hip, and uses two linear screw actuators to provide forces at the ankles. The MIT design can be extrapolated [6].

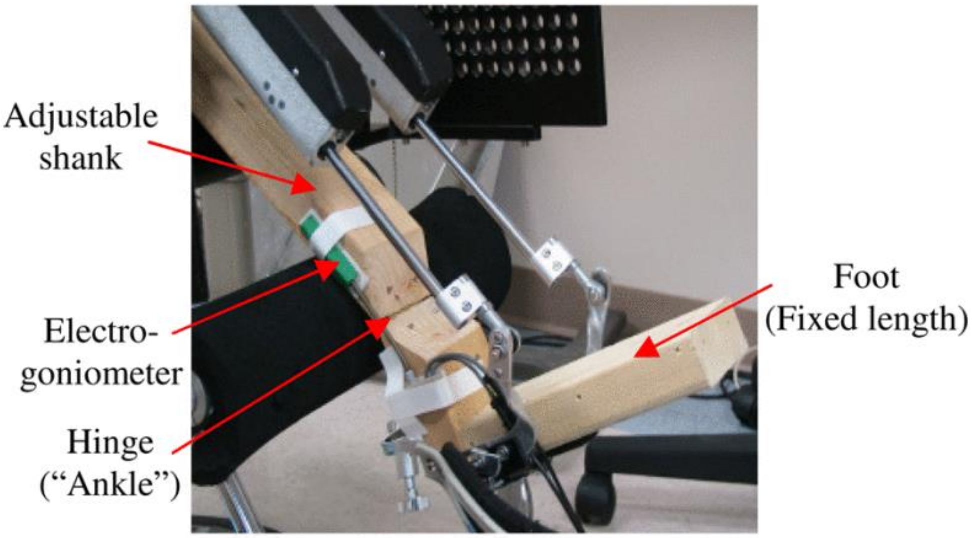


Figure 8: MIT linear actuated ankle exoskeleton [6]

Pneumatics have also been used as an actuation system. In 2011, Shorter published a paper showing the feasibility of pneumatic actuators in ankle exoskeletons. Shorter used liquidized carbon dioxide to provide the force. For pneumatic actuators, a pressure regulator would need to be included in order to control the pressure being released by the liquidized carbon dioxide. The design changes the direction of the torque using two solenoid valves. We could use Bowden cables to control the opening and closing of these valves. We could also use Bowden cables to interface with the pressure regulators. Utilizing a pneumatic design like this would be disadvantageous, as it would increase the complexity of the design [7].

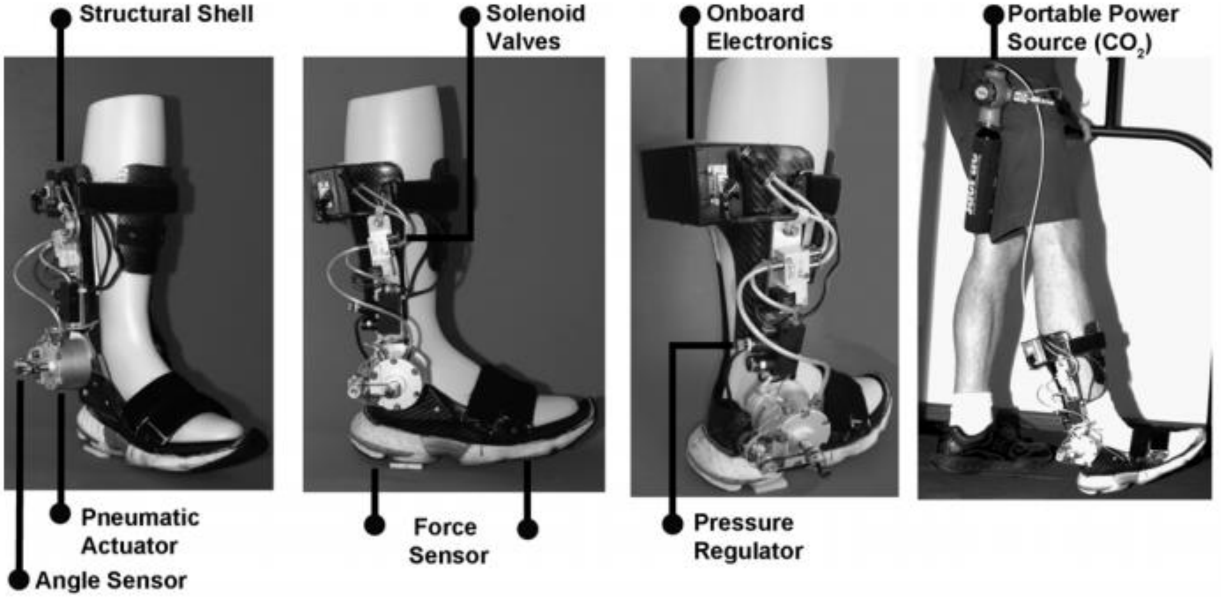


Figure 9: Ankle-foot orthosis for rehabilitation [7]

Orthotic Subsystems

Heel lift

Using stackable shoe insole orthotics is a common method for providing heel lift for equinus and other gait deformities. The heel inserts provide a way to increase the heel angle and offer a comfortable interface between a shoe and the wearer. Patent 5732481 illustrates this concept with a design of stackable heel lifts that progressively increase in hardness, with the top layer being softest to maximize user comfort. The insoles increase in hardness to provide stable support under the heel. The insoles are designed to fit in a shoe and can adjust the heel height proportionally by the number of inserts that are added [8].

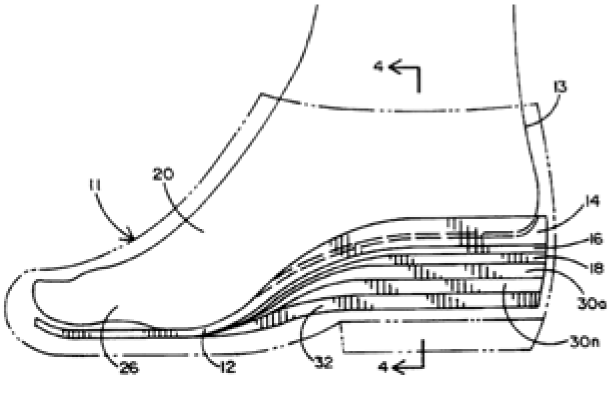


Figure 10: Adjustable height insole system [8]

Another form of heel lift is adjustable shoe heel height. This is most commonly seen in women’s fashion heels. An example of this type of design is Patent 3464126, which presents the design of a shoe with mechanically adjustable heel height. The shoe heel is hinged to the toe portion of the shoe, while a support member rests on the ground, extending rearward from the back of the shoe. The hinge is held in place by a lock that holds the heel at different positions relative to the support member. The heel is adjusted by freeing the locking mechanism and adjusting its angle about the hinge [9].

FIG I

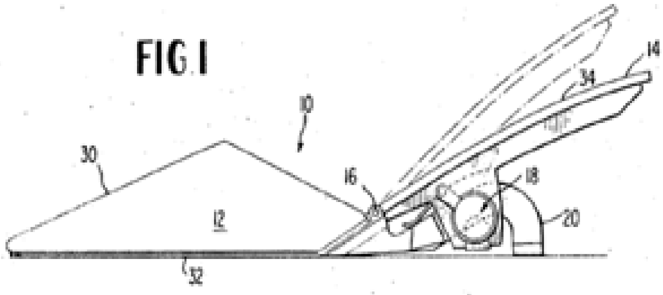


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Figure 11: Shoe with a hinged mechanically adjustable heel [9]

Attachment of mechanical parts to the body

Besides providing heel lift and comfort to the user, the orthotics need to provide a way to attach mechanical components and be stiff enough to transmit force. For equinus deformity, ankle foot orthotics (AFO) are the most commonly used form of orthotics. Depending on their application, they can be permanently formed at a 90 degree ankle angle (where the plane of the foot forms a right angle with the leg), have an adjustable locking angle joint, or have a free-moving joint. Most of these orthotics are made by taking a mold of the leg, then forming the orthotics out of plastic to fit the individual. The orthotics are worn inside the shoe and are secured to the leg by Velcro straps. The purpose of these orthotics is to provide support or resistance to the leg. While this is not a required function for our device, it does offer a way to attach components to the body and provide additional support to the ankle [10].

Figure 12: Plastic ankle foot orthosis [10]

Electrical Subsystems

Sensor subsystem

In order to actuate the ankle sufficiently and still have a human in the loop control, different sensors are required to determine the user's intent of motion. Zhang describes different sensors that are used in a lower extremity exoskeleton design. Zhang describes two different types of sensors - force sensors and position sensors. The force sensors are used to tell if the user has their feet on the ground, and to indicate what part of the gait cycle the user is in. The motion sensors tell the device what positions the legs are in. Combining the information received from both of these sensors, the controller implemented within the device can determine which phase of gait the user is in [11].

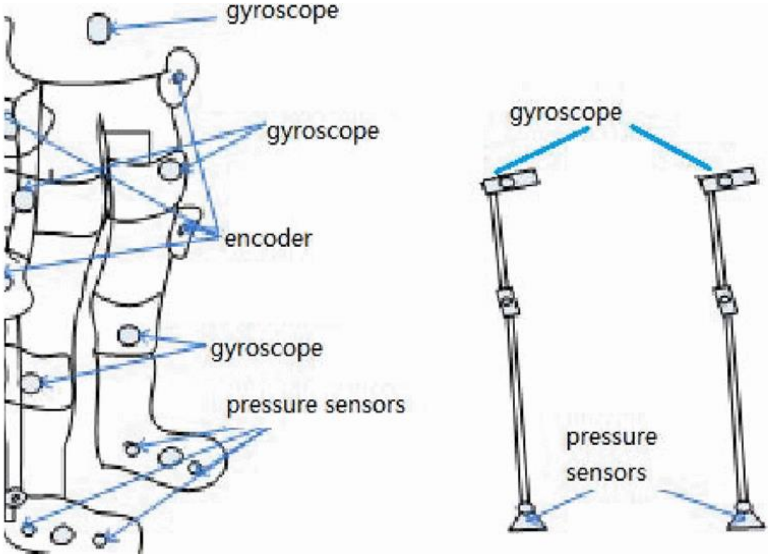

Figure 13: Sensors layout on exoskeleton [11]

Signal Processing Subsystem

Aleksandr Sergeyv describes an exoskeleton system that uses an electromyographic (EMG) sensor. This EMG sensor senses the electrical inputs directly from the muscles, as opposed to sensing the secondary movement caused by the muscles. Sergeyv describes in detail the process for taking the voltage signal and preparing it for processing in a microcontroller to control an exoskeleton. The process involves running the signal through an instrumentation amplifier, unity gain amplifier, filters, and a half-wave rectifier. The signal from the EMG is extremely small, and thus requires amplification for the microcontroller to be able to interpret what the muscles are doing. Sergeyv decided to use an instrumentation amplifier because instrumentation amplifiers tend to have a much higher common mode rejection ratio, and has a controllable gain. This means that it accomplishes two tasks: it filters out noise, and the output signal can be set within a range depending on the desired gain. The positive input of the amplifier is attached to the muscle of interest, while the negative input of the amplifier is placed on the kneecap, where there are no muscles. This ensures that the difference being amplified is the signal to the muscle relative to no signal to a muscle. This paper can possibly apply to the device in the following ways: the device is required to use a certain torque sensor, and the torque sensor puts out microvolts across a bridge configuration. The output voltage of the torque sensor is similar to the EMG sensor in that they are both small signals, with the possibility for significant noise to be introduced. The same type of signal processing can be used to ensure that the device's microcontroller reads what the torque sensor is outputting, and nothing else. The second way this paper can apply to the device is that we can choose to use EMG as our signal to see the intent of the user as the user is moving, and not an after-effect of the user moving [12].

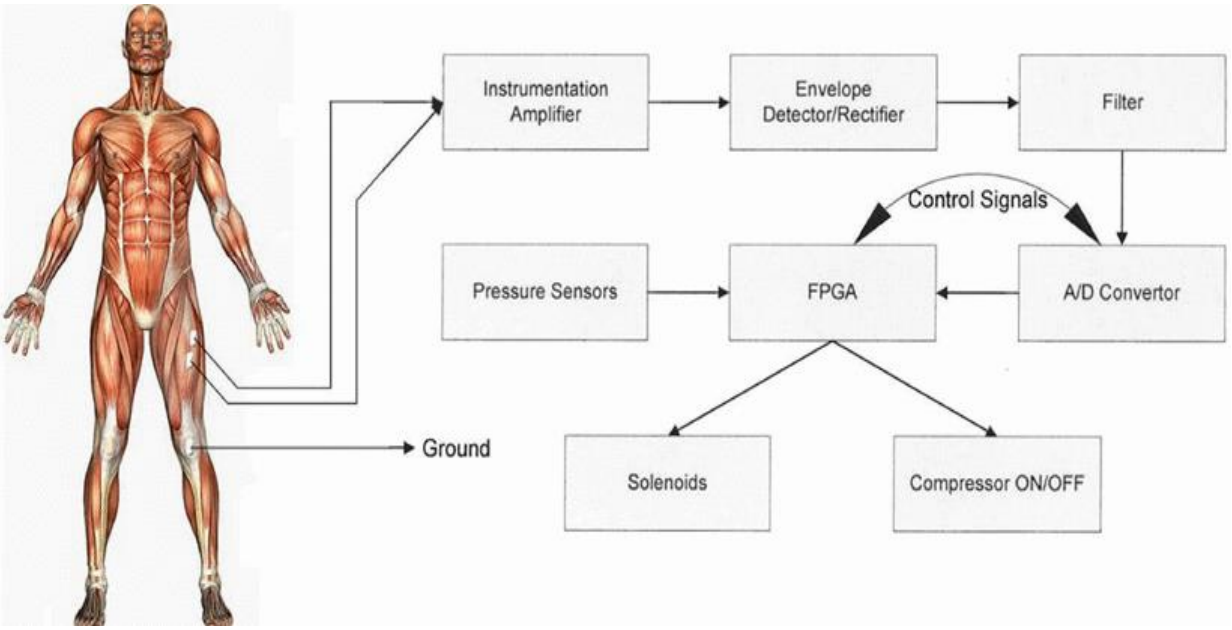

Figure 14: Flow of Signal Processing for EMG Subsystem [12]

Control System

US patent 20160331557 describes a control algorithm that can be applied to many lower extremity exoskeleton designs. The control algorithm described is vague enough that if the device includes at least one type of each of the aforementioned sensors, then the information contained within this patent applies. The sensors are read into a microcontroller for data interpretation. The patent advises that there is a calibration phase for any exoskeleton, to determine the output of the force sensors when the user is putting all of their weight onto each individual leg, and both legs combined. This is to determine threshold values for when the user lifts his or her feet from the floor. The patent then goes on to describe how the controller should interpret the different sensor readings into movement intention of the user. For instance, if the entire weight of the user is on a single foot, and the motion sensors detect that the velocity of the other leg is in a direction that is opposite of the ground, the user is most likely in the mid-swing. If the weight of the foot is concentrated on the ball of the foot, and the acceleration of the other foot is decreasing, the microcontroller would assume that the gait cycle is ending, as one foot is preparing to lift off the ground, and the other foot is setting down onto the ground. However, this patent only describes an algorithm that is applicable to people who do not have equinus, or any other sort of gait deficiency. This limits the applicability of this patent to the design. The design can still use the algorithm as a baseline to determine what the gait of the child *should* be, and try to match it as much as possible.

4 Designs Considered

Using the researched subsystems and other research, the team generated several ideas for each of the major subsystems of our design. The concepts for each of these subsystems are displayed in the following table.

Table 2: Subsystem concepts

Propulsion	• Cam in contact with ground • Spring under foot • Pull up from the back of the heel • Cams on each side of foot • Pressurized air • Pneumatic balloon
Actuation	• Motors • Coiled nylon actuators • Linear actuators • Stepper motors
Ankle lift	• Propulsion device adjustable along bottom of foot • Linear lift from calf connection • Stackable shoe insoles • Ratcheting hinge joint • Push pin angle • Bolt hinge angle
Orthotics	• Shoe built into device • Over-the-shoe device • Toe support • Adjustable heel • Thermoplastic calf cuff • Composite foot support plate • Aluminum supports • Soft shoe inserts • Velcro straps • Elastic straps
Sensors	• Torque sensors • Potentiometers • Optical encoders • Gyroscopes • Accelerometers • Linear force sensors

Multiple design concept drawings that incorporate these subsystem ideas are presented in the figures in Appendix B.

Criteria that was considered while generating and evaluating propulsion concepts included the ability to generate 10-15 Nm of torque, weight, and control. The propulsion concept for a single cam under the foot is advantageous in that it supplies force directly between the foot and the ground. A disadvantage of this concept is that it takes up considerable space under the foot. It is also heavy, since the material would need to be strong and durable. The propulsion concept for the spring under the foot is beneficial for providing simple linear propulsion, it is lighter, and it can fit easily under the foot. However, a spring may deflect to the side if it is not stiff enough. Supplying tension to the back of the foot (pulling the heel upwards) is beneficial in that it is a simple linear force, easy to control. The drawback is that the patients using it may have little to no range of rotation in their ankle joints, in which case this method would provide no propulsion. The concept for cams on each side of the foot is similar to the concept for a single cam. The cams on each side provide more stability, do not add extra bulk directly under the foot, and provide more power for propulsion. However, they take up substantial space and add weight. The pressured air concept involves releasing compressed gas (either air or CO2) under the foot to initiate propulsion. This concept is potentially lightweight; however, it is impractical for generating the required 10-12N of force. The last propulsion concept that was considered was the pneumatic balloon that provides propulsion by inflating a bladder under the heel. This concept is advantageous, in that it is lightweight and can fit under the foot without adding extra bulk, but it requires another source of power (CO2), it is difficult to control, and the bladder could potentially breach easily.

Criteria that was consider during the generation and evaluation of heel lift concepts included the ability to accommodate an ankle angle between 0-30 degrees, weight of the device, and the even distribution of weight across the foot. One way to achieve ankle lift is to make the propulsion device adjustable along bottom of the foot. The advantage of this design is that the placement of the applied force can be adjusted. The disadvantage is that because the device rests under the foot, it cannot be adjusted to the lowest severity case of 0 degrees. Another concept considered was linear lift from a calf connection, where the heel would be held up by a cable from the back of the calf. The benefits of this concept are that it is lightweight and allows for full range of desired adjustment. However, it does not meet the criteria for redistributing the weight under the foot. Stackable insoles are another concept that was considered. The advantages of the insoles are that they can achieve 0-30 degrees of lift, and are comfortable. The disadvantage is that they take up a large amount of space. A ratcheting hinge joint could also be used to achieve different heel heights. The advantage of this concept is that it could achieve 0-30 degrees of lift, without adding extra bulk to the design. The drawbacks are that it would need to be made out of a sturdy material, such as titanium, so that it is strong enough to bear the full body weight of the user. Push pin angle is a concept that uses buttons (such as those in crutches) to set an angle of the heel. The advantages of this design are that it is easy to use and does not add unnecessary bulk to the design. A disadvantage is that it will have large angle step sizes, due to the buttons, making it harder to get precise angles. It also may not be sturdy enough to bear the user’s weight. Another concept is a bolt angle, an angle with a bolt set in a slide that is used to adjust and fix an angle by tightening the bolt. The advantages of this design are that it is lightweight and can achieve the full 0-30 degrees of lift, and because it is adjusted by a bolt in a slide, it can achieve very precise angles. However, the bolt in the slide may not be able to provide a clamping force large enough to prevent unwanted movement of the bolt in the slide.

Orthotics defined for this project are the parts of the exoskeleton that provide the interaction between the mechanical and electrical components with user. Criteria considered when analyzing these concepts included adjustable for foot sizes of children 5-12 years old, lightweight, and easy to get on and off. The first concept for orthotics considered was a shoeless device. In essence, the exoskeleton would act as a shoe. The advantage of this concept is that it would provide a static connection between the device and the user. The disadvantages are that it would be difficult to adjust to the foot size range, and it would be heavy. The second orthotic idea considered was an over-the-shoe device. The advantages of this concept are that because it could fit over the shoe of the user, the device would feel more comfortable and familiar, and it would be lighter. There are no evident disadvantages for this concept. The toe cover concept involves the use of a toe cover on the device to keep the foot from sliding forward off the device. The advantage of this device is that it better secures the device to the foot. The disadvantages are that it adds weight to the design, and may be difficult to adjust for foot sizes. The adjustable heel guard concept is similar to the toe guard, except it attaches to the back of the device and helps secure the heel. The advantages are that it supports the heel and is easy to adjust. There are no apparent disadvantages for this concept. Another concept for orthotics is a thermoplastic calf cuff. This cuff would be used to guide the Bowden cables and secure the exoskeleton to the foot. Advantages are that it is lightweight and stiff. Its disadvantages are that it may slide off the leg (due to its stiffness) and it may be difficult to make one that adjusts for an age range. Composite support plates under the foot is another concept for the orthotics. The advantages of this concept are that it is extremely lightweight, and can be made in a variety of shapes. The drawbacks are that it is challenging to attach other devices to it, and it is difficult to manufacture. Various devices such as soft shoe inserts, Velcro straps, elastic straps, and structural material types were also considered; however, until the design is developed further, it will be difficult to gauge which of these will be most practical for the design and in what capacity they may be used.

In order to effectively ascertain the user's walking intent, we must have both pressure sensors and motion sensors. The two pressure sensors that the team considered were force sensitive resistors and foot switches. Either of these sensors would be placed beneath the subject’s feet in order to sense when the user has his or her feet on the ground. An advantage of the foot switch is that it would give more accurate measurements. The foot switch is also larger, and would provide some cushion to the foot. This has a possibility to contribute to our comfort requirement. Size is also a disadvantage. Since foot switches are relatively large, it would limit the space that the team has to work with when placing both the orthoses and the propulsive subsystems. Most foot switches also have large input voltage requirements, upwards of 30 V. The switches would consume a significant amount of power, and the battery would have to be larger to accommodate the voltage. Since foot switches are larger, they also weigh more than their force sensitive resistor counterparts. Force sensitive resistors (FSRs) are very lightweight, which is advantageous for staying within our weight constraint. FSRs are also much smaller, able to fit inside a shoe. This allows more room for the mechanical aspects of the design. They also can be used with virtually any voltage, as they are simply a variable resistor. Since FSRs are just resistors, the circuitry is also simple, which is an advantage. A disadvantage is that the FSRs are not as accurate as foot switches.

Motion sensors are also an integral part of exoskeleton designs. One motion sensor that the team considered is an accelerometer. An advantage of using an accelerometer is that it can generate more exact measurements. In contrast to other sensors considered, accelerometers tell the controller exactly how the leg is moving. With other sensors, the motion of the leg has to be inferred. Accelerometers give a direct motion measurement. Another advantage is that an accelerometer can be mounted nearly anywhere, and it will still work. The main disadvantage of using an accelerometer is that if an external force acts upon the leg, then it could disrupt the controls. Other sensors may be needed in conjunction with the accelerometer, to ensure that what is being measured is the user's movement. Another disadvantage is the complexity of accelerometers. The number of wires, interpretation of the outputs, and coding of the accelerometer are all complex. The additional sensors needed to confirm the accelerometer data also add to the complexity. A potentiometer can also be used to infer the motion of the leg. In contrast to accelerometers, the potentiometer is a much simpler circuit. It is just a simple resistor circuit. It must be attached near the knee in order to measure the knee angle. Since it has to be attached to the knee, it is limiting where it can be placed. This would infer the motion of the leg based on the bend of the knee. Potentiometers are disadvantageous in that they are not directly measuring the motion, but are inferring it. They also do not give exact measurements, while the accelerometer would. A torque sensor can also be used to detect motion, though it is a constraint that our design must incorporate one. The torque sensor would most likely be placed on the shunt of the knee, or on the actuator of the device. This would measure the torque of the leg, and would infer direction. By placing the torque sensor directly on the actuator, one could infer the motion that is being produced by the actuator. Other sensors were considered, but these are the sensors that are most readily available, and the ones that the team is most familiar with.

Some of the full design concepts presented in Appendix B explored the possibility of using different actuation methods besides motors. These methods included stepper motors, coiled nylon actuators, and linear actuators. However, after further discussion with Dr. Lerner, the team decided to use DC motors, because this is what is currently used in the Biomechatronics Lab, and the team wanted to keep the control methods the same.

5 Design Selected

After different designs were considered, one final design was chosen for further consideration. Customer needs informed the design selection, so that the final design fulfills the project's goal and satisfies the client.

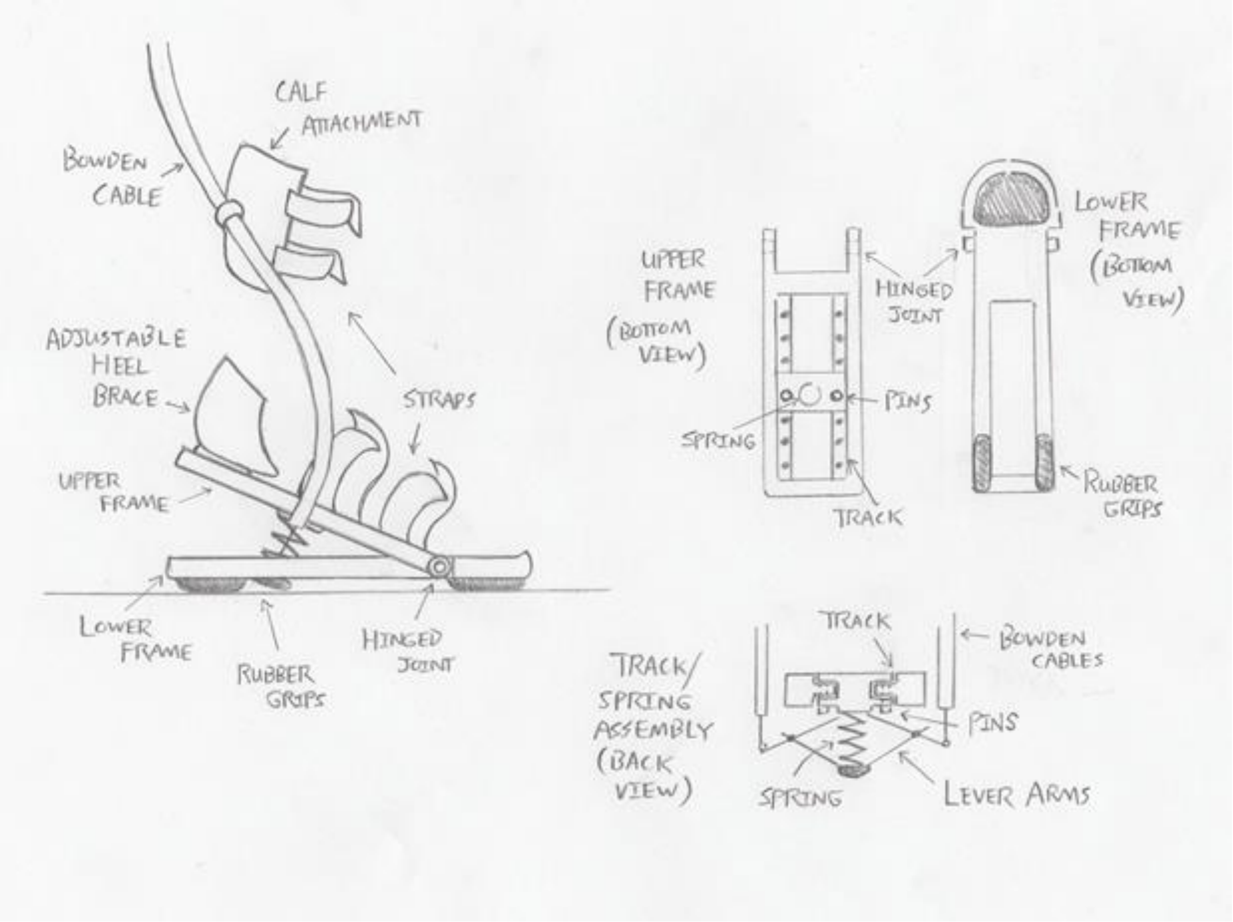

Figure 15: Selected design concept

The current final design, shown in Figure 15, above, employs a spring to provide propulsive force. Attached to the spring are lever arms, which in turn are connected to the Bowden cables. When the motor applies tension to the cables, the cables pull upward on the lever arms, compressing the spring. Then, when the foot is ready to push off the ground (for the propulsive phase of the gait cycle), the tension in the cables is released, allowing the spring to extend. When the spring extends, it strikes the ground, and a propulsive force is exerted on the foot. The motors can then re-compress the spring, until propulsive force is needed again when the gait cycle repeats.

The spring, lever arm, and cable assembly are adjustable. The entire assembly slides along a track, parallel to the bottom of the foot. Pins fix the assembly in place at the appropriate location along the track. This location is dependent on the angle between the track and the horizontal. The track, which forms the upper frame of the device, includes an adjustable heel brace above the track, where the heel rests. This brace, like the spring assembly, can slide up and down the length of the frame. This allows for the securement of a range of foot sizes. The upper frame is hinged at its lower end, where a joint connects it to the lower frame (the lower frame comes in direct contact with the ground). The lower frame includes a cutaway, so that the spring may strike the ground. The joint is located at the ball of the foot, and can be fixed at different positions within a range of 0-30 degrees. The underside of the lower frame, as well as the bottom end of the spring (the end making contact with the ground), feature rubber grips. These will increase friction between the device and the ground, functioning similarly to the sole of a shoe.

The team decided that a force sensitive resistor (FSR) would be the most feasible sensor for the pressure sensor. The FSR is incorporated at the underside of the lower frame (below the heel). The purpose of the FSR is to detect when the foot is on the ground or when it is off the ground. This will hint at what part of the gait cycle that the user is in. In the design, an accelerometer is incorporated at the shunt, though it realistically could be put anywhere. It would make most sense to attach it to existing components, so the team would not have to build a specific mount for any of the sensors. A potentiometer is installed at the lever arms of the spring assembly. The combination of sensors allows the device to determine which phase of the gait cycle the patient is currently in, and when to apply torque.

The Bowden cables are secured to a calf attachment, then run up the length of the leg to the motors, which are situated at the waist. The overall device is bilateral, with one attachment for each foot.

5.1 Rationale for design Selected

The final design was chosen because it satisfies the customer’s needs. As specified in the customer requirements, the device incorporates a Bowden cable system, a calf attachment, a foot interface, and sensors. The device utilizes a simple system of straps (likely Velcro) to secure the device to the foot and calf, enabling easy attachment and removal for the user. The requirement for adjustment based on severity levels is met by the adjustable joint at the ball of the foot, as well as the adjustable spring assembly. The device can be fixed at various angles between 0-30 degrees. Scalability is accounted for in the moveable heel brace, which can be adjusted to secure feet of different size.

The upper frame allows for more uniform weight distribution on the bottom of the foot, since users will rest their body weight across the entire frame back to their heel, instead of concentrating their weight forward. Additionally, the incorporation of rubber attachments on the underside of the device allows for softer interaction between the foot and the floor. The device should weigh less than other designs considered, largely due to the use of a spring instead of a cam.

6 Conclusion and Future Work

The initial assignment was to develop an exoskeleton to assist individuals suffering from equinus deformities. The primary goal is to provide propulsion to the foot, to increase the efficiency of the gait cycle. At this point, a final design concept has been developed. This was achieved by defining the customer and engineering requirements. The team then used the criteria that were defined to narrow the scope of research to focus on methods and mechanisms applicable to the project goal. Several major subsystems that the team generated included propulsion, actuation, attachment, heel lift, signal processing, control, and sensors. The team then combined these subsystem concepts into complete designs. The final design was chosen based on the customer requirements, in order to satisfy the stakeholders.

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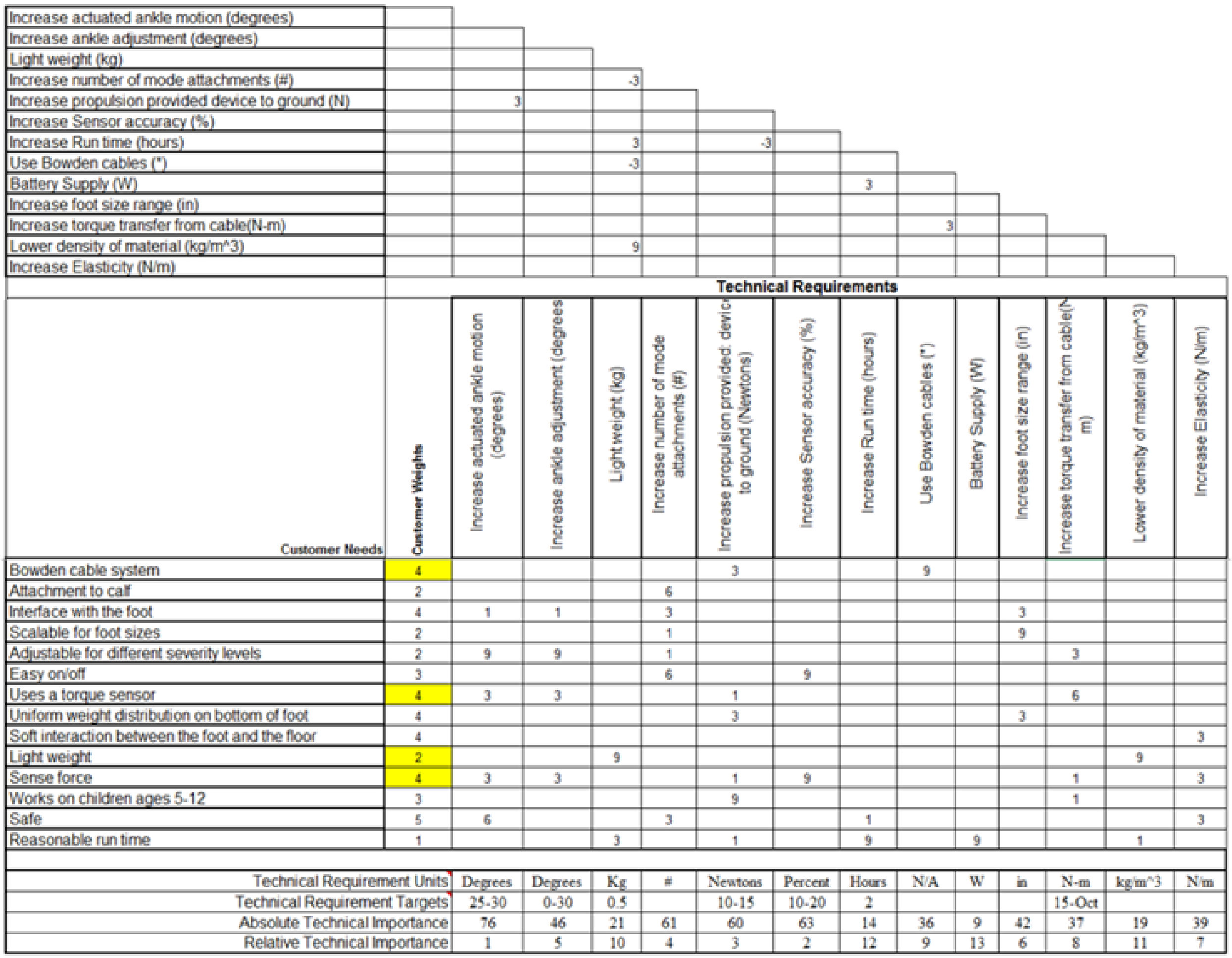
Appendices

Appendix A: QFD



	Increase actuated ankle motion (degrees)	Increase ankle adjustment (degrees	Light weight (kg)	Increase number of mode attachments (#)	Increase propulsion provided: devic to ground (Newtons)	Increase Sensor accuracy (%)	Increase Run time (hours)	Use Bowden cables (*)	Battery Supply (W)	Increase foot size range (in)	Increase torque transfer from cable(N m)	Lower density of material (kg/m^3)
Increase actuated ankle motion (degrees)												
Increase ankle adjustment (degrees)												
Light weight (kg)												
Increase number of mode attachments (#)			-3									
Increase propulsion provided device to ground (N)	3											
Increase Sensor accuracy (%)												
Increase Run time (hours)			3		-3							
Use Bowden cables (*)			-3									
Battery Supply (W)							3					
Increase foot size range (in)												
Increase torque transfer from cable(N-m)								3				
Lower density of material (kg/m^3)			9									
Increase Elasticity (N/m)												

Technical Requirements

Customer Needs	Customer Weights	Increase actuated ankle motion (degrees)	Increase ankle adjustment (degrees	Light weight (kg)	Increase number of mode attachments (#)	Increase propulsion provided: devic to ground (Newtons)	Increase Sensor accuracy (%)	Increase Run time (hours)	Use Bowden cables (*)	Battery Supply (W)	Increase foot size range (in)	Increase torque transfer from cable(N m)	Lower density of material (kg/m^3)	Increase Elasticity (N/m)
Bowden cable system	4					3			9					
Attachment to calf	2				6									
Interface with the foot	4	1	1		3						3			
Scalable for foot sizes	2				1						9			
Adjustable for different severity levels	2	9	9		1							3		
Easy on/off	3				6		9							
Uses a torque sensor	4	3	3			1						6		
Uniform weight distribution on bottom of foot	4					3					3			
Soft interaction between the foot and the floor	4													3
Light weight	2			9									9	
Sense force	4	3	3			1	9					1		3
Works on children ages 5-12	3					9						1		
Safe	5	6			3			1						3
Reasonable run time	1			3		1		9		9			1	
Technical Requirement Units		Degrees	Degrees	Kg	#	Newtons	Percent	Hours	N/A	W	in	N-m	kg/m^3	N/m
Technical Requirement Targets		25-30	0-30	0.5		10-15	10-20	2				15-Oct		
Absolute Technical Importance		76	46	21	61	60	63	14	36	9	42	37	19	39
Relative Technical Importance		1	5	10	4	3	2	12	9	13	6	8	11	7

Appendix B: Design Concepts

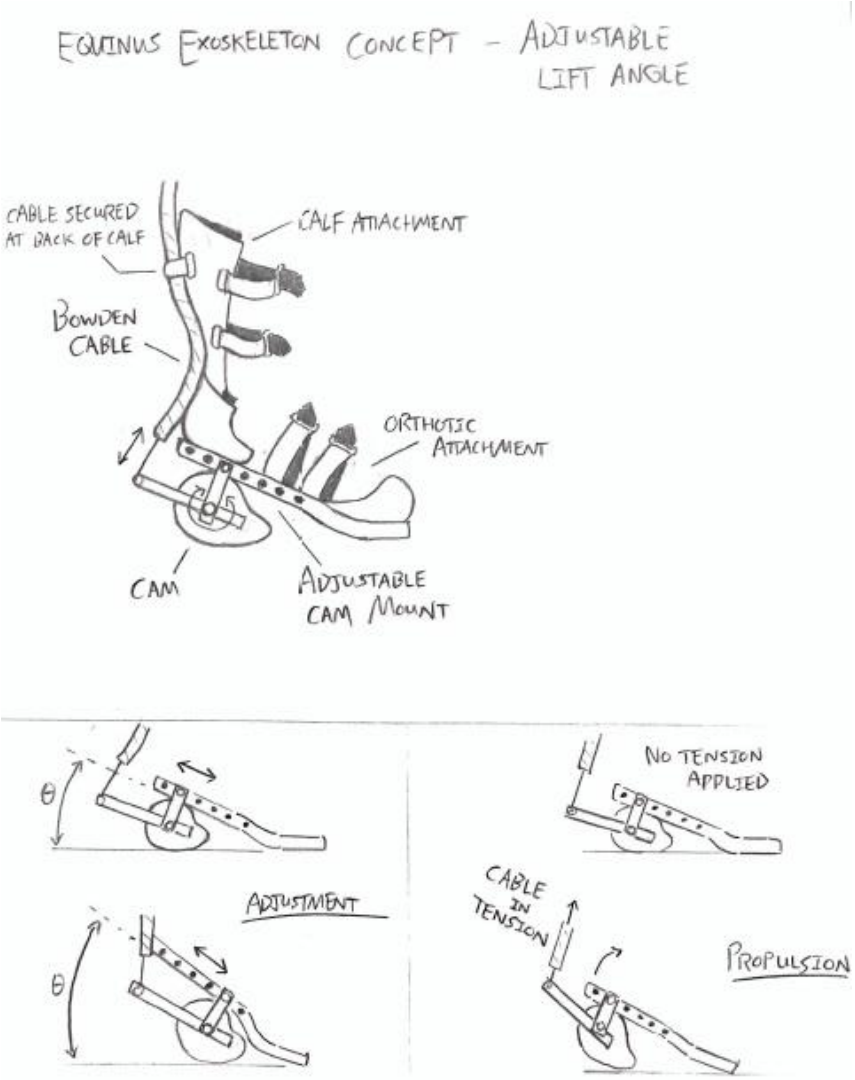


Figure 16: Full design concept incorporating propulsion generated from a cam, heel adjustment from sliding cam, plastic molded orthotic supports, and Velcro attachment straps

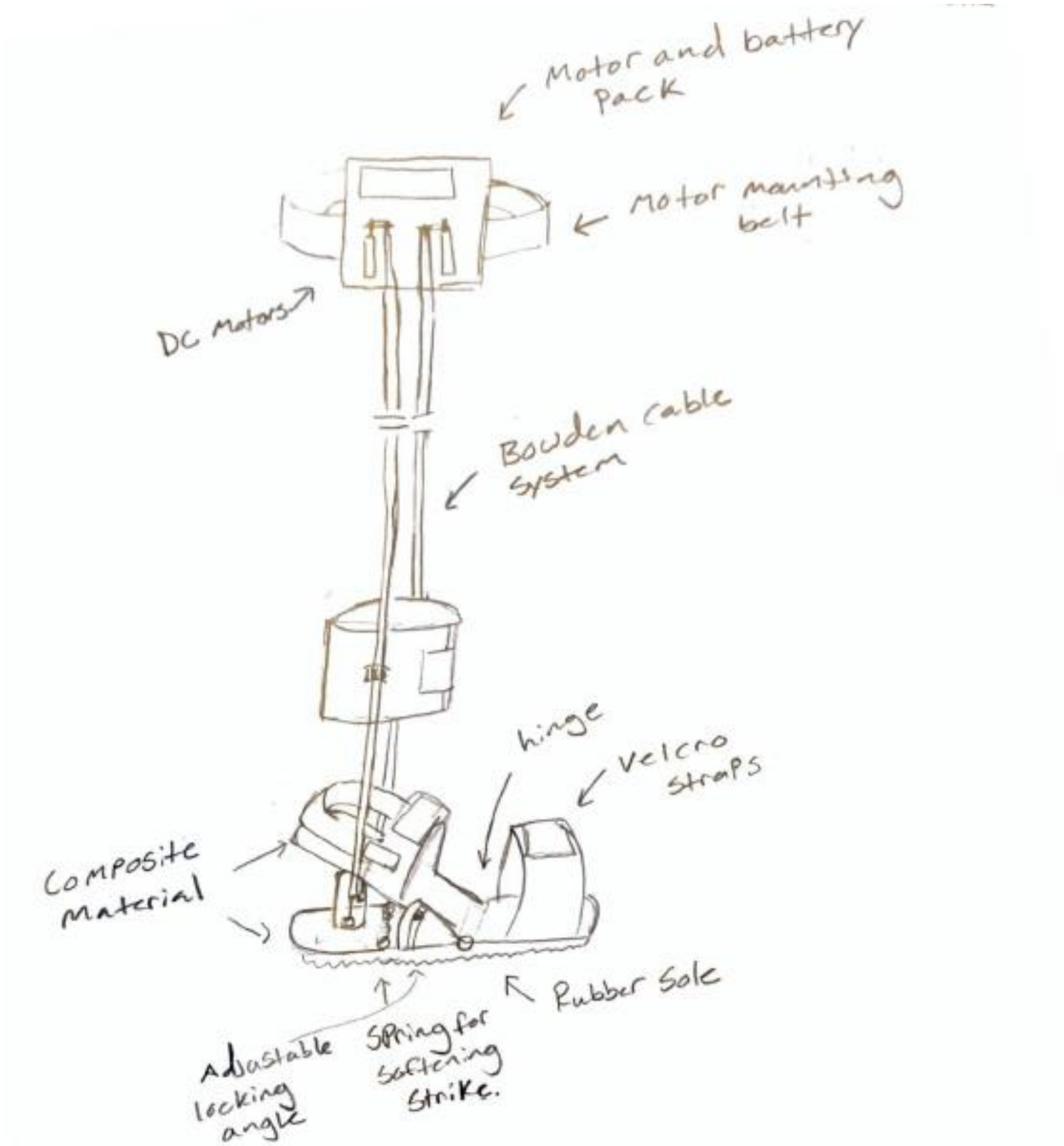


Figure 17: Full design concept incorporating the bolt locking angle for heel lift, and over the shoe orthotic attachment

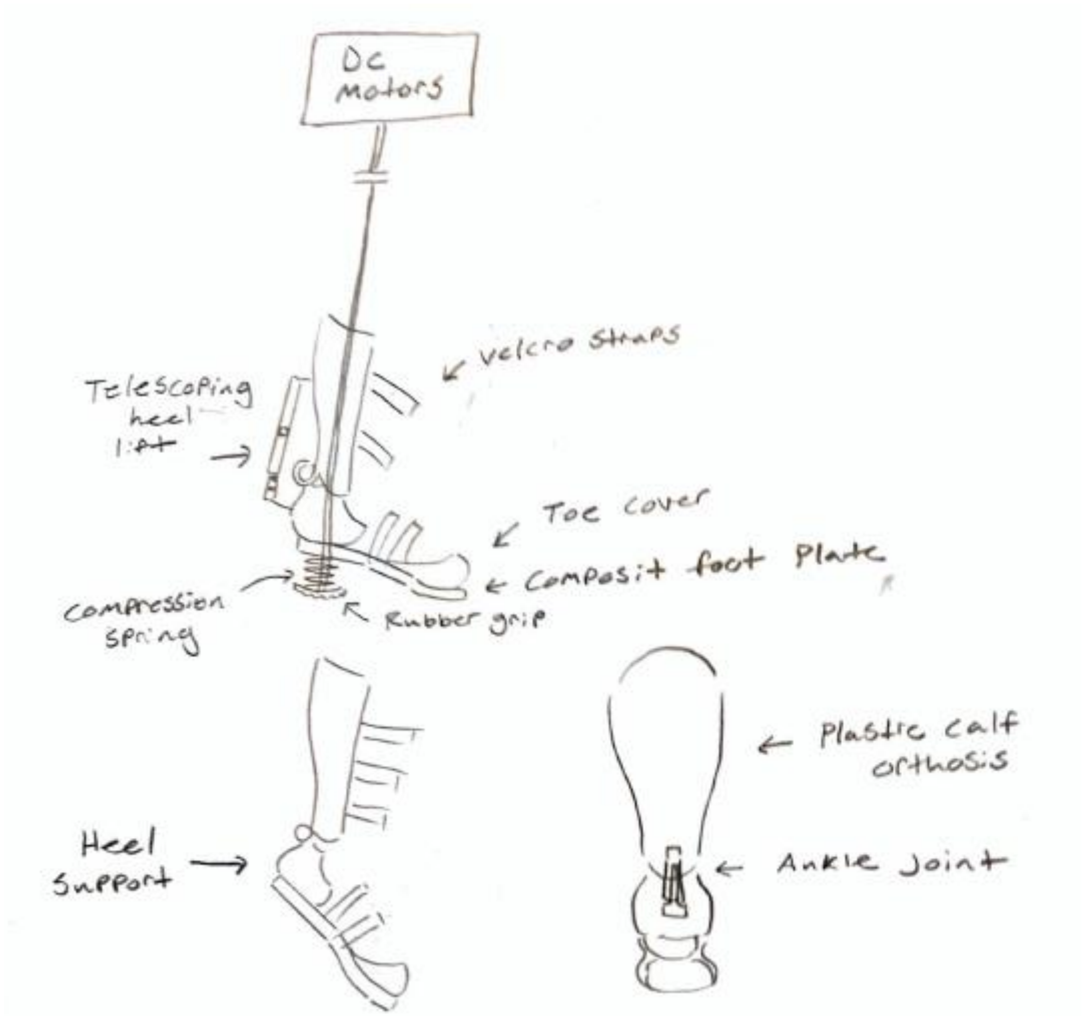


Figure 18: Design concept which uses a spring for propulsion, telescopic adjustment, and plastic AFO

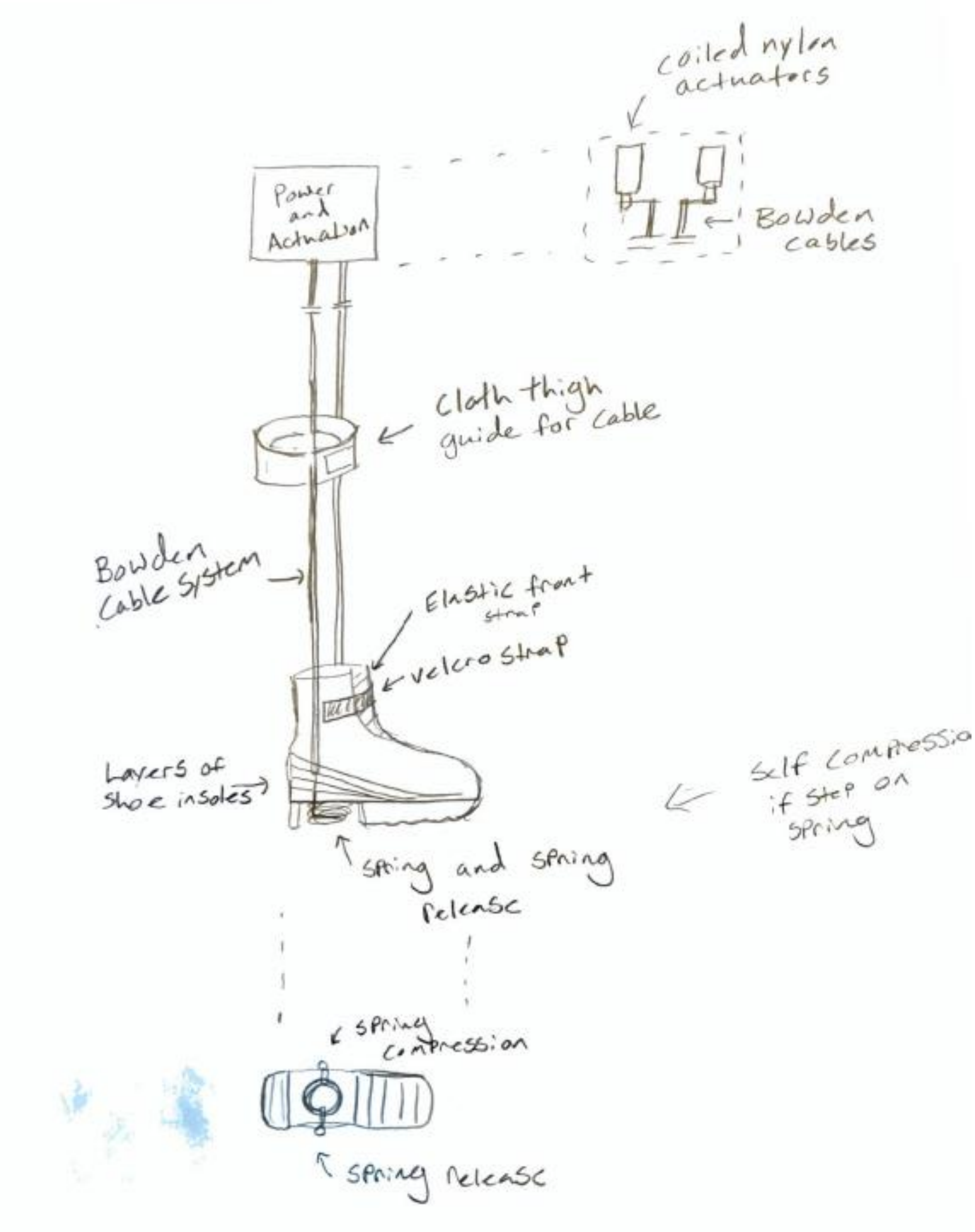


Figure 19: Full design concept incorporating spring propulsion, stackable insoles, and built in shoe orthotic

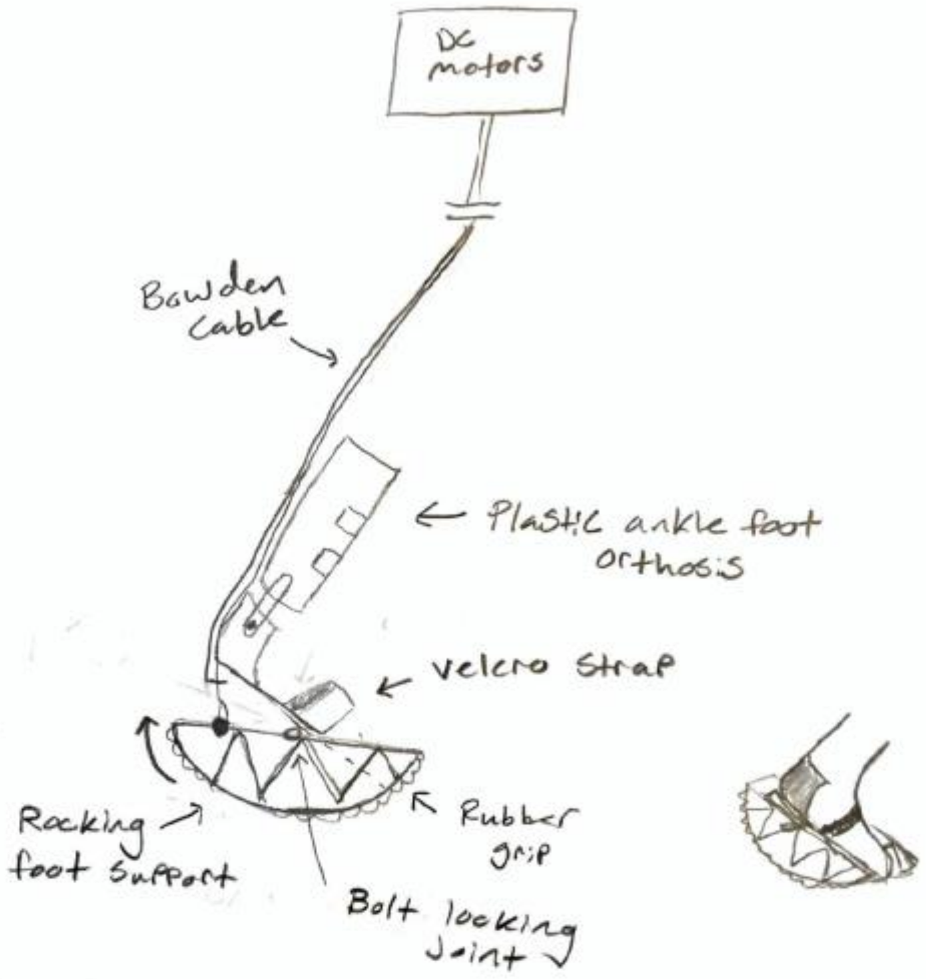


Figure 20: Design concept incorporating rocker propulsion and heel height adjustment

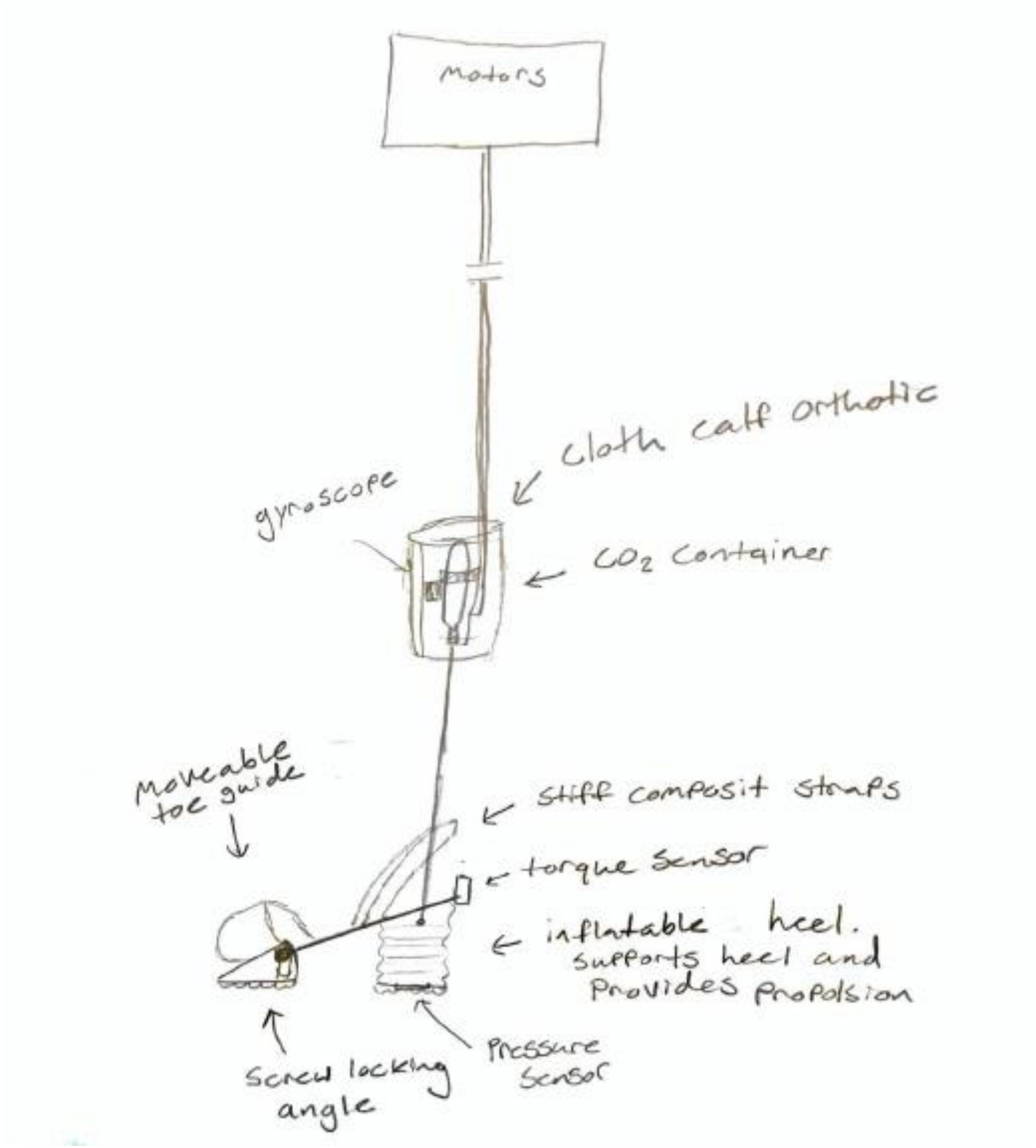


Figure 21: Design concept incorporating sensors, pneumatic bladder for propulsion and locking angle

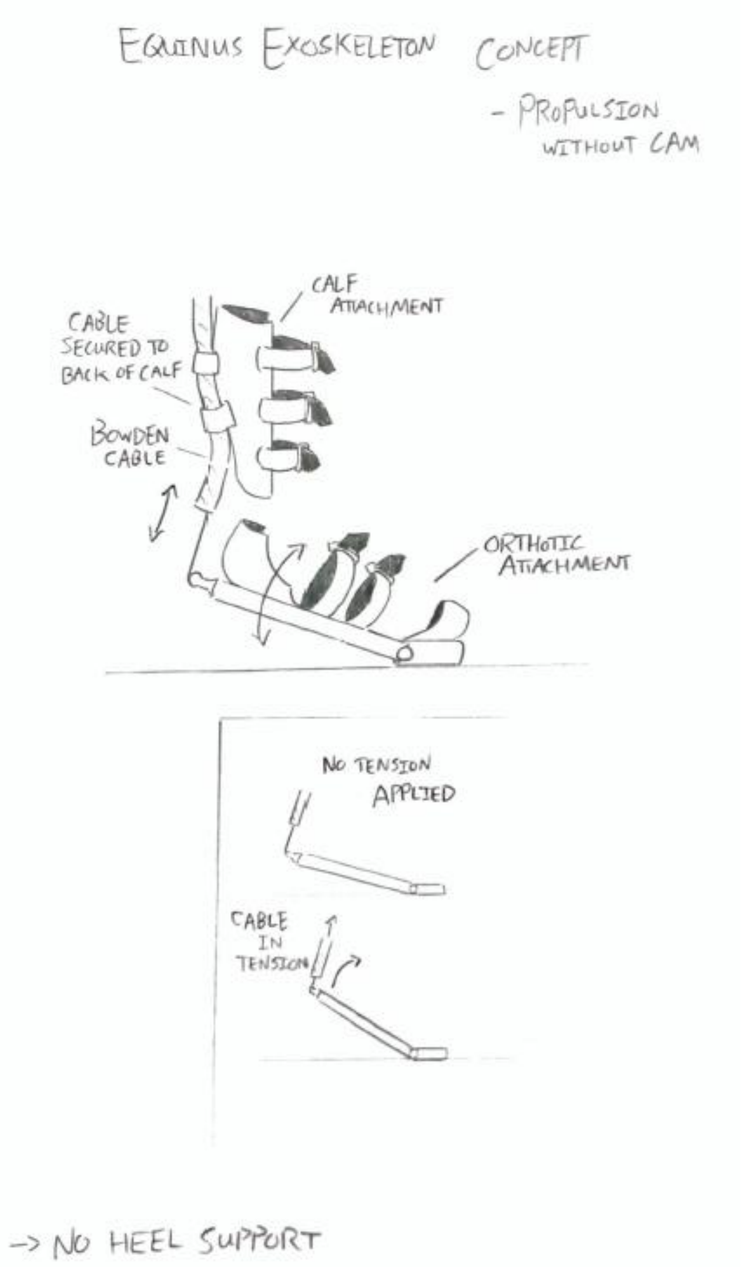


Figure 22: Design idea for exoskeleton incorporating propulsion of the foot via direct pull from the Bowden cable, and adjustable calf and foot orthotics

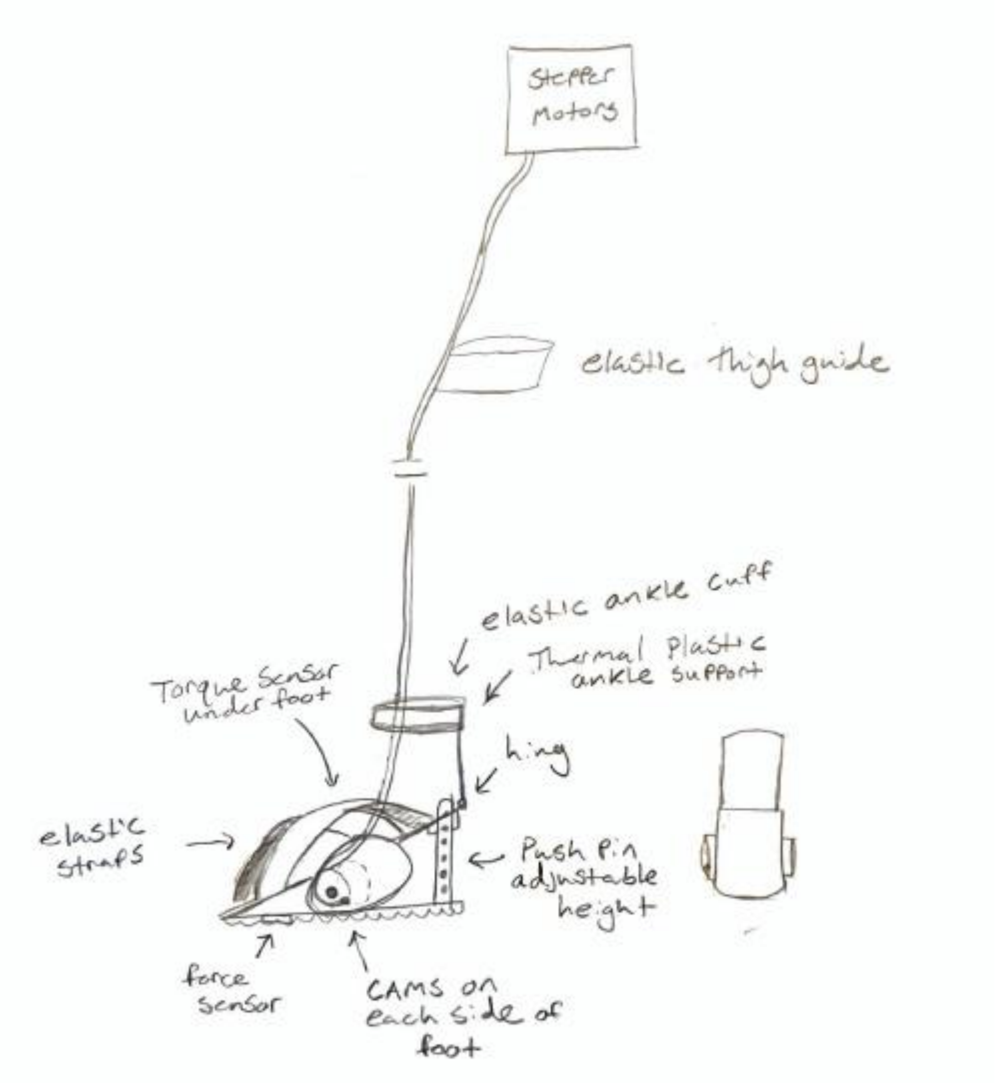


Figure 23: Design concept incorporating side-mounted cams, push pin adjustable height, and force sensors

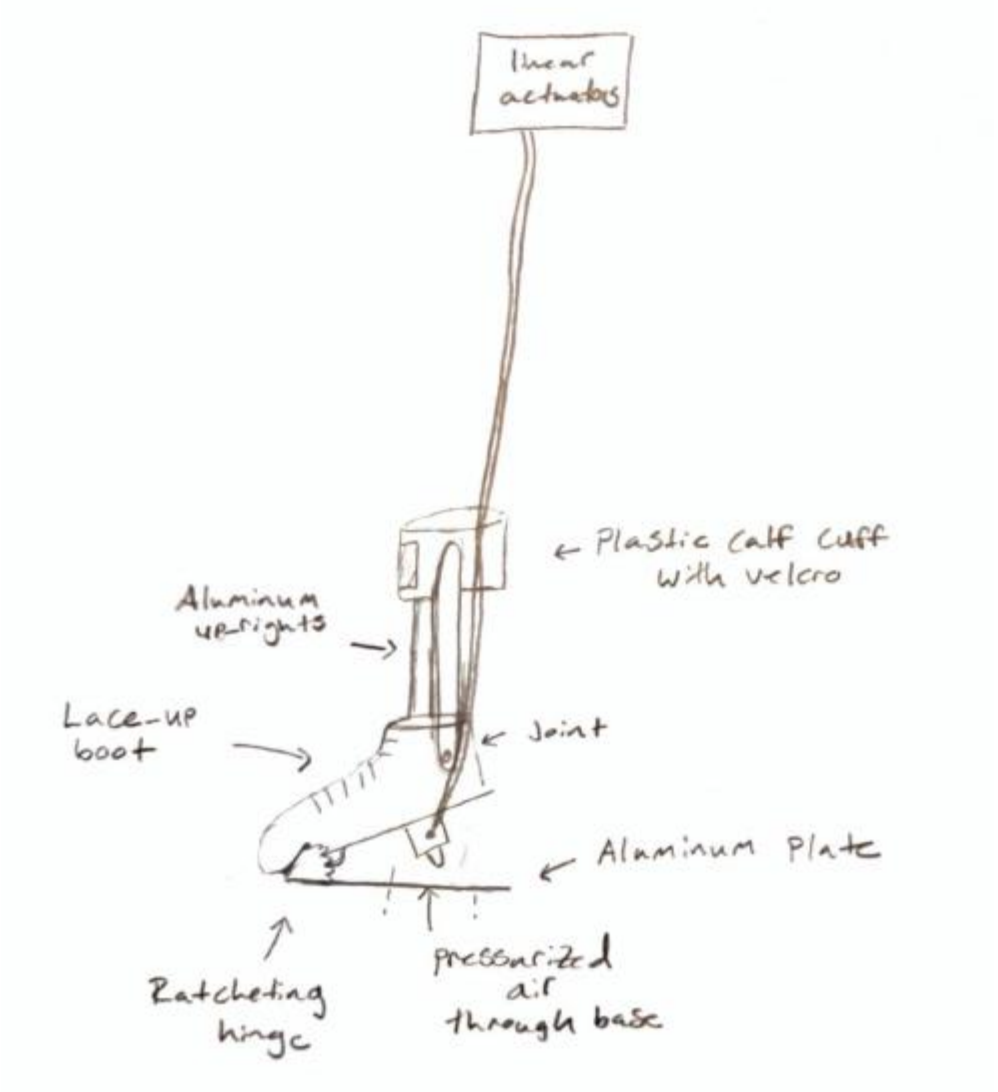


Figure 24: Design concept incorporating pressurized air propulsion, and ratcheting hinge

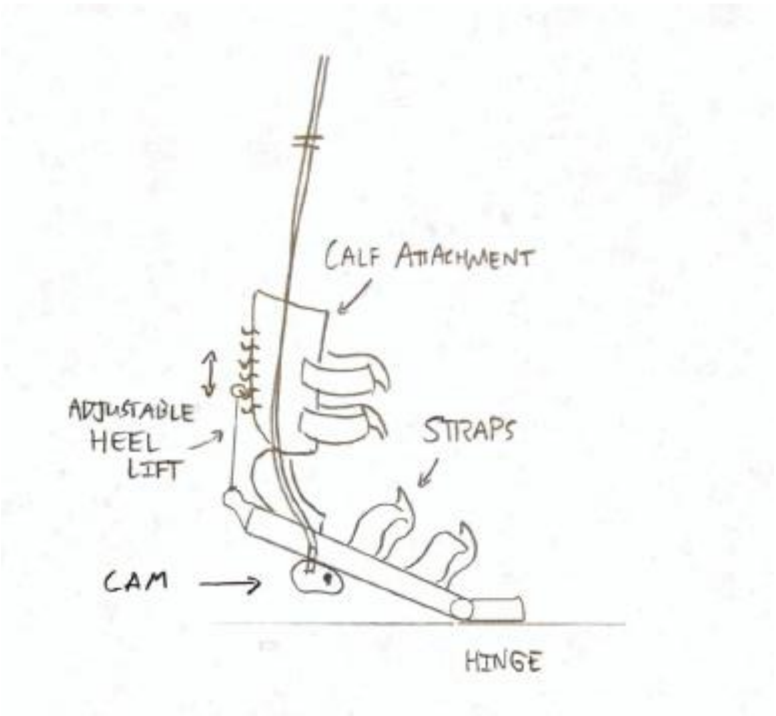


Figure 25: Design concept illustrating variable position heel lift