Soft Ankle Exosuit for Correction of Foot Drop

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ABSTRACT

Foot drop is a common condition caused by nerve damage, muscular dystrophy, as well as brain and spinal cord disorders, and is characterized by a difficulty to perform dorsiflexion: the inability to lift the front part of the foot, resulting in a dragging foot. Consequences include slow walking speed, inefficient gait, balance problems, and the inability to position the foot for heel strike. Although many people suffer from this condition, there is currently no actively powered brace on the market. This project introduces a wearable, actively powered device that can be worn beneath regular clothing. The device uses force sensitive resistors (FSR) to deduce the gait phase and an ultrasonic sensor to deduce ground conditions such as obstacles, inclines, and stairs. A lightweight and compact servo motor placed next to the knee joint actuates the ankle joint through a Bowden cable.

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

Currently, there exists millions of individuals with gait disabilities who require the use of an orthosis on a lower extremity (Russell et al., 1997). In the United States alone, over 300,000 individuals are affected by foot drop, a condition that is characterized by the difficulty or the inability of a person to lift their toes towards their shin (i.e. dorsiflex)(National Institute of Neurological Disorders and Stroke (NINDS), 2019) This type of pathology has a number of causes, including stroke, cerebral palsy, multiple sclerosis, and neurological trauma from an accident or surgical complications (Taylor et al., 1999).

One of the most common treatments used in correcting foot drop, that does not involve surgery, is the use of an ankle foot orthosis (AFO). AFOs are braces that are worn on the lower leg and foot to support the ankle and hold the foot and ankle in the proper alignment to counteract the dropping of the foot (Shiel Jr., W. C. 2018). Foot drop patients typically have the ability to plantarflex (i.e the flexing of the foot/toes downwards towards the sole) but suffer from a lack of ability to dorsiflex. The most commonly prescribed AFOs are rigid, uncomfortable, and do not allow for much dorsi- or plantar flexion. This makes it difficult for patients to ascend/descend stairs, walk over changes in elevation (e.g. a curb) or to clear certain obstacles within their walking path. Often these individuals find it necessary to change their walking patterns in order to accomodate for these brace-induced constraints. Consequently, there is an increase in stress in their other joints such as their knees, hips and back, which leads to the patients facing additional pain and discomfort

(Zancan & Arturo, 2004). There now exists a developing need to create low-costing, active AFOs that provide adequate stability for ground walking while accommodating for changes in surface elevation and obstacle clearance.

This project explores the design and development of an improved, adaptive and active, soft ankle exosuit (brace) to assist in the correction of foot drop.

In Chapter 2, we summarize the background knowledge relevant to this project. We then state our project objectives in Chapter 3 and, in Chapter 4, introduce the sensors and components used in our device. In Chapter 5, we outline the experiments conducted with our device. In Chapter 6, we review our results and key findings. Finally, we conclude the project with an overview of future work and developments for this device.

CHAPTER 2

BACKGROUND

2.1 THE GAIT CYCLE

2.1.1 OVERVIEW OF THE GAIT CYCLE

Gait can be described as a "manner of moving the body from one place to another by alternately and repetitively changing the location of the feet" (Smidt, 1990). Many types of gaits exist such as walking, running, skipping and other pathological gaits, however, the main focus of this project is on walking.

A full gait cycle (Figure 1) begins at the heel strike of one foot and continues until the heel strike of the same foot in preparation for the next step (Kawalec, 2017). Two primary phases are present within the gait cycle, the stance phase and the swing phase, which alternate for each lower limb (Ekka, 2016). The stance phase characterizes the entire time that a foot is on the ground and the swing phase, contrarily, covers the entire time that the foot is in the air.

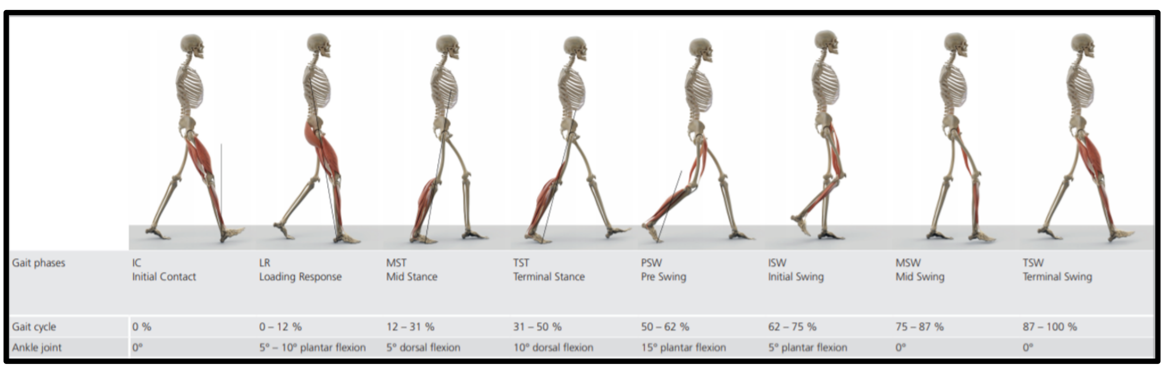

Figure 1: Complete gait cycle (Streifeneder Ortho Production, 2017)

The gait cycle can also be broken down further into eight distinct events, which delineate each step of the cycle, as shown in Figure 2.

The stance phase consists of five events:

- Initial contact (IC)
- Loading response (LR)
- Midstance (MST)
- Terminal stance (TST)
- Preswing (PSW)

The swing phase, on the other hand, consists of the other three events:

- Initial swing (ISW)
- Mid swing (MSW)
- Terminal swing (TSW)

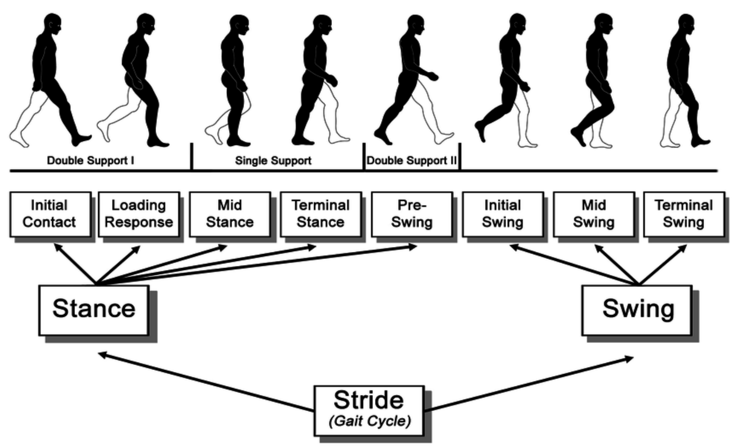

Figure 2: Functional divisions of the gait cycle according to Perry and Burnfield (2010) (Stöckel et al., 2015)

2.1.2 THE STANCE PHASE

The stance phase is the first phase of the gait cycle, and represents 60% of the total cycle. While in this phase, the foot is in contact with the ground and nearly all of the body weight is on the foot. Weight, and contact with the ground, transitions from first the heel, to the full foot, then to the forefoot in order to initiate forward motion of the body. For this process, the three important parts to recognize are the heel rocker, ankle rocker, and forefoot rocker (Figure 3). In conjunction, these rockers serve to control the forward fall of the body during normal ambulation.

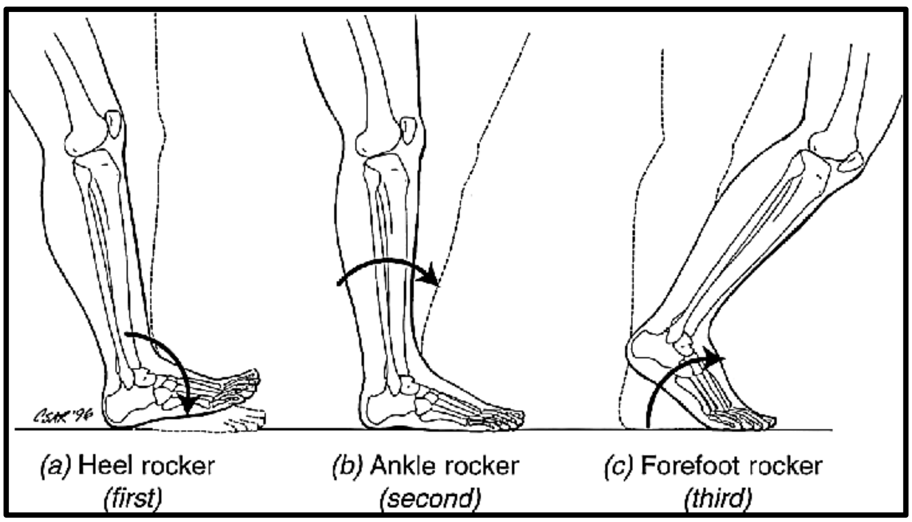

Figure 3: The three foot rockers occurring during stance phase of the gait cycle: (a) the heel (first) rocker; (b) the ankle (second) rocker; (c) the forefoot (third) rocker (Abu-Faraj, Harris, Smith, Hassani, 2015).

The stance phase begins when the heel of the foot strikes the ground. This heel strike is referred to as the initial contact (IC). During IC, the center of mass of the body is at its lowest position, the ankle is neutrally positioned, and the leg is positioned to begin stance with the heel rocker [Figure 3 (a)] (Gage, 1991; Perry, 1992a.).

The Loading Response (LR) or weight acceptance period is defined from the start of IC (0%) to about 12% of the gait cycle. During this period, the limb acts as a shock absorber and the knee consequently undergoes flexion to coincide with load acceptance and deceleration of the body as it progresses forward. The foot is in full contact with the ground and the the ankles move into a plantar flexion of roughly 5-10 degrees.

Subsequent to LR are the midstance (MST) and terminal stance (TST) phases. The period between these two consecutive points, MST through to TST, marks the single limb support period. Single limb support involves progression of the body over the foot and weight-bearing stability (Prokinetics Team, 2018). In this period, the opposing (contralateral) limb is in the swing phase (Webster, Abu-Faraj, Harris, Smith, and Hassani, 2015).

Midstance covers the first half of single limb support and from 12% to 31% of the gait cycle. During MST, the shank rotates forward over the supporting foot, creating the ankle (second) rocker motion of the cycle [Figure 3 (b)]. At the onset of single stance the ankle is slightly plantar-flexed at 5 degrees. From this position the foot gradually dorsiflexes. The basic arc is from -5 to +5, with 10 degrees of dorsiflexion being attained just as the heel rises to initiate terminal stance (Perry, 1992c). This motion creates the ankle rocker necessary for forward advancement of gait.

The second stage of single support, the terminal stance (TST), covers 31% to 50% of the gait cycle. TST begins when the heel is about to lift off the ground. The ankle is maximally dorsiflexed (10 degrees) from the start and progresses into plantar flexion. During this period, the body's center of mass (COM) leads the forefoot and accelerates as it is falling forward towards the unsupported limb. Terminal stance is the period of the forefoot rocker (third foot rocker) [Figure 3 (c)].

This rocker serves as an acceleration rocker to prepare the limb for advancement in the preswing phase (PSW).

Preswing concludes the terminal stance phase and marks the final period of double limb support. It extends from 50% to 62% of the overall gait cycle (Perry, 1992b). Preswing begins with the IC of the contralateral limb and ends with ipsilateral (stance) toe-off, just as the stance foot clears the ground (Õunpuu, 1994; Perry, 1992b; Gage, 1991). In this period, the ankle rapidly plantar flexes to a 15-20 degree position.

This period concludes stance phase and marks the beginning of swing phase.

2.1.3 THE SWING PHASE

The last phase of the gait cycle is the swing phase. It is associated with limb advancement and consists of Initial Swing, Mid Swing and Late Swing.

Initial swing represents the initial third of the swing phase from 60% to 73% of the gait cycle. It occurs from toe-off to when the swing limb foot is opposite the stance limb (Boston Orthotics and Prosthetics). In this phase, the ankle moves from 20 degrees of plantar flexion towards dorsiflexion to end at a neutral position Physiopedia, 2017). During initial swing, the flexion of the ankle helps the foot clear the ground.

Mid Swing follows the Initial Swing and accounts for 73% to 87% of the gait cycle. It is defined from the time the swing foot is opposite the stance limb to when the tibia is vertical. In this phase, the ankle is in neutral position.

Last, the terminal swing accounts for the final third of the swing phase from 78% to 100% of the gait cycle. Terminal swing is initiated with vertical tibial alignment and continues until initial contact when the foot strikes the ground (Bruckner, 1998).

2.2 FOOT DROP

2.2.1 DEFINITION OF FOOT DROP

Foot drop is characterized by the inability to raise the front portion (i.e dorsiflex) of one's foot due to weakness or paralysis of the muscles that lift the foot (NINDS, 2019) Foot drop causes two major complications. First, the patient is unable to control the falling of their foot after heel strike (Sambrook, 2018). This results in the foot slapping the ground on every step. Second, the patient is unable to lift their toes during the swing phase of the gait cycle. Consequently, in order for the person to prevent scuffing of their toes along the ground, or tripping, people with foot drop tend to bend their advancing leg higher than usual, which causes what is called a "steppage" gait (TheFreeDictionary, 2019).

Figure 4: Foot drop

2.2.2 CAUSES OF FOOT DROP

Foot drop is a common condition that afflicts many people each year. In particular, stroke survivors are a leading population of those suffering from foot drop. In the United States, there are over 800,000 stroke victims per year. Of this number, twenty percent develop foot drop as a side effect (Centers for Disease Control and Prevention, 2019). This condition develops as a result of nerve damage, which affects the ability of the brain to send neurological signals to the limb, or by weakened muscles. These muscles contribute to the rotation of the ankle and the raising of the foot. They allow the toes to swing up from the ground during the beginning of a stride and control the planting of the heel towards the end of the stride (A DIctionary of Nursing, 2019). When these muscles behave abnormally, they prevent the toes from clearing the ground during the stride, which in turn contributes to tripping and falling and subsequent injuries.

2.2.3 TREATMENTS FOR FOOT DROP

There are few options available for those with foot drop. Current, nonsurgical options include orthotics, such as ankle foot orthoses (AFOs), and functional electrical stimulation (FES).

2.2.3.i FUNCTIONAL ELECTRICAL STIMULATION (FES)

Functional electrical stimulation (FES) is a fairly new approach to treating foot drop that uses shorts bursts of electrical pulses to generate muscle contraction (Bajd, Kralj, Stefancic, & Lavrac, 1999). The application of the pulses induces the contraction of muscles by creating action potentials in motor neurons attached to a muscle. FES for foot drop involves the stimulating the peroneal nerve to produce active dorsiflexion during the swing phase of the gait (Cameron, 2010). FES is especially useful for treating foot drop when the central nervous system is damaged but the peripheral nerves, neuromuscular junction and muscles are intact.

2.2.3.ii ANKLE FOOT ORTHOSIS (AFO)

An ankle-foot orthosis, or AFO, is a support intended to control the position and motion of the ankle, compensate for weakness, or correct deformities (AliMed, 2014) As it pertains to foot drop, AFOs are usually prescribed to support the forefoot from dropping into plantar flexion during swing by locking the ankle to a fixed position (Duong, 2017).

Presently, the types of AFOs that are available for purchase are passive. These AFO devices consist of solely mechanical components, such as springs or dampers, to control the ankle joint motion during gait (Alam, Choudhury, & Bin Mamat, 2014). There are two types of passive AFOs: articulated and non-articulated.

Non-articulated passive AFOs are usually a single component, fabricated out of lightweight thermoformable or thermoplastic materials, and encompass the dorsal part of the leg and bottom of the foot (Alam, Choudhury, & Bin Mamat, 2014). An example is the posterior leaf spring AFO, which is a semi-rigid plastic AFO that assists push-off during pre-swing and prevents dropping of the foot. Posterior leaf springs are also rigid ankle AFOs which hold the ankle in a fixed position and completely restricts plantar flexion and maintain clearance between the forefoot and ground. Although non-articulated passive AFOs improve pathological gait to some extent, they still restrict some movements. This is partly due to their rigidity and bulkiness.

Passive articulated AFOs allow the ankle joint to rotate by way of hinges, flexion stops, and stiffness control elements like a spring, oil damper, one-way friction clutch, and or other mechanical means. AFOs with commercial joints and mechanical stops are capable of preventing drop-foot successfully by providing a dorsiflexion assisting force or by locking the ankle in a suitable position; however, these AFOs also inhibit other normal movement of the ankle (Alam, Choudhury, & Bin Mamat, 2014).

2.2 INSPIRATION FOR DESIGN

2.3.1 EXOSKELETONS

Exoskeletons are wearable devices that are designed to augment, or improve, user ability and performance in completing tasks. They do not completely replace a limb like prosthetics; rather they are worn outside the body. The devices can be either passive or active. Passive exoskeletons do not use power to function. Active exoskeletons, on the other hand, require a power source and may involve the use of sensors and motors to actuate the system. As such, the design of exoskeletons require a combination of robotics, mechatronics, and human physiology (Exoskeleton Report, 2015).

Exoskeletons for treatment of foot drop would be a compromise between traditional orthotics and surgery. However, the field of exoskeletons is relatively new and there are currently no such medical devices easily accessible or on the market. They are an evolving technology and are still mainly being developed in research and university settings.

Exoskeletons have been developed for use in a variety of fields. They have been designed for use in the medical field, for rehabilitation as well as mobility aids; but as mentioned, they are not widely used or available. In the manufacturing field, workers use exoskeletons to aid in performing laborious tasks. The use of exoskeletons was found to increase productivity and efficiency. Workplace injuries may also be reduced (Kara, 2018).

2.3.2 SOFT WEARABLE EXOSUITS

Compared with traditional rigid exoskeletons, exosuits are more light weight, smaller and have an increased flexibility. The combination of these factors enables the exosuit to be worn under regular clothing, avoiding special accommodation for the wearer, and additionally reduces stress on the wearer. Exosuits often aid in the walking by supporting those muscles that are weak and necessary for ambulation.

Soft exosuits are usually made up of textiles which can employ tensile forces to align joints, and can adjust systems easily. However, softer exoskeletons cannot apply the same amount of torque as a rigid exoskeletons, offering about 10% of the maximum torque.

2.3.2 EXISTING EXOSKELETONS

The ReWalk Restore Soft-Suit (Figure 5) is a cable-based system that uses a motor built into a waistband to actuate a pair of cables. These cables then lift a foot plate in the shoe which then moves the rest of the leg. built into a waistband which actuates a pair of cables to lift a footplate in the shoe consequently moves the rest of the leg. In addition, the other leg is outfitted with a range of devices that detect gait in order to better synchronize the gait cycle (Heater, 2017).

Figure 5: Rewalk Restore Soft-Suit (Heater, 2017)

The Ankle Exo (Figure 6) is a passive exoskeleton developed by researchers at North Carolina State University. It requires no power and acts as a calf muscle supplement to aid muscles through a combination of carbon fiber frames and strings. The lack of any electronics results in a lightweight device, weighing slightly more than a pound. Despite the advanced technology, the Ankle Exo is not intended for running and strenuous exercise (Herkewitz, 2015).

Figure 6: Ankle Exo (Quick, 2015)

CHAPTER 3

PROJECT OBJECTIVES

Our project focused on investigating the use and feasibility of ultrasonic sensors for exoskeleton applications. In order to do so, we designed and developed an active ankle exosuit which incorporated ultrasonic sensors as a sensing mechanism. We concentrated on creating an exosuit for users with foot drop, or an abnormal gait cycle in general.

The objectives and specifications of our project are to design and create a soft, wearable exosuit that:

1. Incorporates an ultrasonic sensor to detect obstacles at least 10 cm in front of the foot.
2. Provides the foot with at least 10 degrees of dorsiflexion during the swing phase.
3. Has a maximum weight of 1 lb. on the ankle.
4. Operates under a maximum speed of 1.1 m/s (i.e. average walking speed).
5. Allows at least a 1 in. clearance distance from foot to ground.
6. Offers ankle stability.

CHAPTER 4

METHODOLOGY

4.1 MATERIALS AND DESIGN

4.1.1 SERVO MOTOR

Servo motors are often used for robotic applications. They are usually small in size but offer a variety of torque options. Servo motors offer precise control due to its shaft, which can be positioned based on specific angle measurements that are set via an encoded signal. A servo motor contains three parts inside its casing: a DC motor, potentiometer, and a control circuit (Jameco, 2019). In order to connect the servo motor, there are three colored wires that correspond to specific inputs. The brown wire connects to ground, the red wire connects to power, and the orange wire connects to the pin number. Figure 7 is an example of a servo motor (Adafruit, 2019).

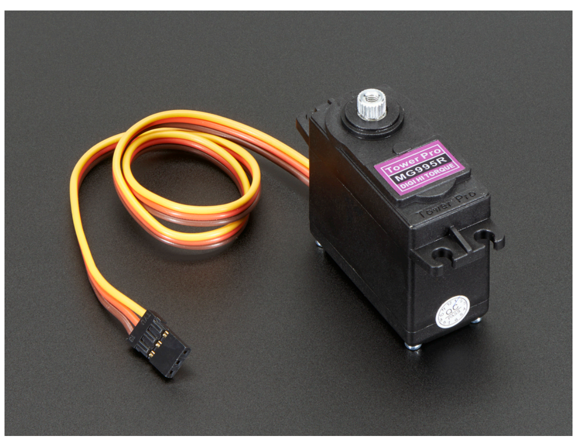

Figure 7: Tower Pro MG995R Digi Hi Torque Servo Motor (Adafruit, 2019)

In order to hold the servo securely on the skeleton leg, we created a structure, shown below in Figure 8, that attaches above the knee.

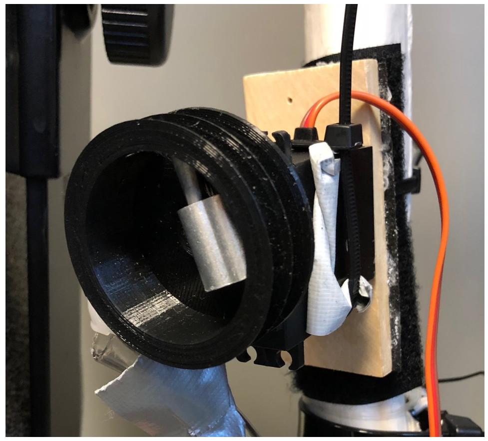

Figure 8: Servo motor attached to skeleton

4.1.2 BOWDEN CABLE

In order to raise the foot, we used Bowden cables. Bowden cables are commonly used in bicycle braking systems. They consist of an inner cable and an outer tubing, in which the inner wire can slide in and out. This movement creates a force as the wire pulls on a connected object.

For this project, we connected one end of the Bowden cable to a brace and the other end of the cable to a spool adjoined to the shaft of a servo motor. As the motor rotated, the wire wound around the spool causing it wire to effectively shorten or contract. As a result, the wire transferred the force and torque provided by the motor to raise the foot. Bowden cables were the best fit for this application because the outer tubing prevented excess movement and friction.

4.1.3 SPOOL

The spool was used to create a pulley system that would allow the Bowden cable to wrap around it and transmit the tension force required to lift the foot as the adjoining servo motor rotated. The spool component was 3D-printed and fastened to a manufactured servo motor attachment, shown in Figure X. Using the manufactured attachment ensured an exact and secure connection between the servo motor and 3D-printed pulley. As the motor pulled the cable, the wire wound onto the spool. This design was inspired by that of retractable badge clips, shown in Figure X, which operate in a similar manner.

4.2 SENSORS AND CONTROL

4.2.1 ULTRASONIC SENSOR

Ultrasonic sensors transmit and receive ultrasonic waves to determine distance. We used the HC-SR04 Ultrasonic Distance Sensor from SparkFun, pictured in Figure 9. This sensor has a distance sensing range of 2-400 cm, which was suitable for our purpose. There are four pins on the ultrasonic sensor: VCC, Trig, Echo, and GND. VCC connects to the power source. Trig transmits ultrasonic waves. Echo receives ultrasonic waves. GND connects to ground (Sparkfun, 2019b).

We placed the ultrasonic sensor on the front of the foot, pointing forward. As the user walks, the sensor registers the distance between the foot and obstacles in its path.

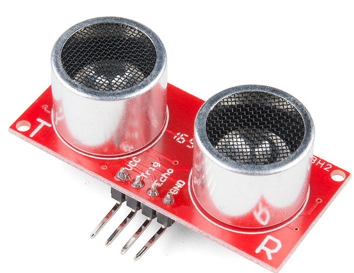

Figure 9: Sparkfun HC-SR04 Ultrasonic Distance Sensor
(Sparkfun, 2019b)

4.2.2 FORCE-SENSING RESISTORS

Force-sensing Resistors (FSRs) are sensors that can detect when pressure or force is placed on them. An FSR is composed of three layers: a semiconductor layer, spacer, and an electrode layer. As pressure is placed on the FSR, the semiconductor layer and electrode layer touch and cause resistance to decrease. The resistance level determines how much force is placed on the FSR. However, though FSRs are relatively inexpensive, these sensors are not very precise and are best for getting approximate values (Adafruit, 2012).

In this project, we used the Force-Sensing Resistor: 0.6”-Diameter Circle from Interlink Electronics, shown in Figure 10 (Pololu, 2019).

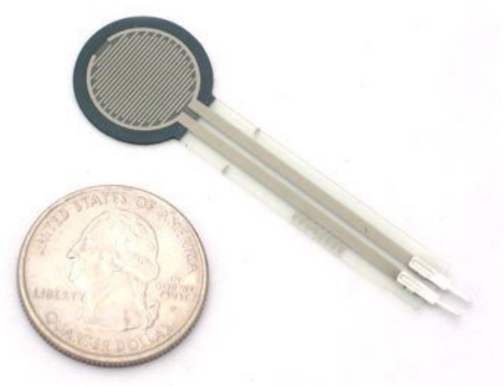

Figure 10: Force Sensing Resistor (Pololu, 2019)

4.2.3 ARDUINO UNO

The Arduino board is a basic microcontroller which allows users to upload their own code to complete a variety of tasks (Figure 11). It is the ‘brain’ behind our system and contains the code which powers our exoskeleton. We used the SparkFun RedBoard (henceforth referred to as an Arduino), which operates the same as an authentic Arduino Uno board. In order to upload and test code, we connected the board via USB to a computer. Connecting to the USB port also powered our system which allowed our servo and sensors to run.

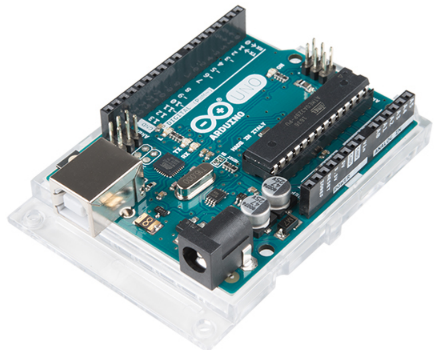

Figure 11: Arduino Uno Board (Sparkfun, 2019a)

4.3 SKELETON

We used a skeleton leg and foot as a representation of a person's leg. The skeleton foot had a reasonable amount of flexibility and ankle rotation, comparable to that of a typical foot. We strapped the knee brace and ankle brace onto the skeleton. The servo motor and connected pulley was placed over the knee. The Bowden cable extended from the motor to the ankle brace. It closely followed the contour of the leg. The end of the Bowden cable slipped through a loop on the ankle brace and was secured.

4.4 PROGRESSION OF DESIGN

4.4.1 Initial Design

In our initial design (Figure 12), we conceptualized building a hinged brace that would consist of a orthotic footplate to help support the arch and keep the foot in proper position. The footplate would run the entire length of the foot and would not be able rotate below a certain fixed position; thus, this would statically correct the dropping of the foot. Attached to the footplate would be four thin cables which extend from the toe region of the footplate to just above the shin of the leg.

Just above the the shin area of the leg would be a bearing-like semicircular ring encompassing the shin where the ends of the cables attach. The semicircular ring would consist of a stationary inner piece and a rotating outer cap. The 4 strings would attach between the inner and outer pieces of the ring. When the outer ring rotated, it would cause the strings within to also rotate, thus pulling the foot upward.

However, we encountered issues with this design in terms of implementing it in a physical form. We could not develop a way to actuate the twisting movement required for this design. In addition, this would require too many moving parts which could lead to more issues, such as increased cost, requiring more maintenance, and increase difficulty of use.

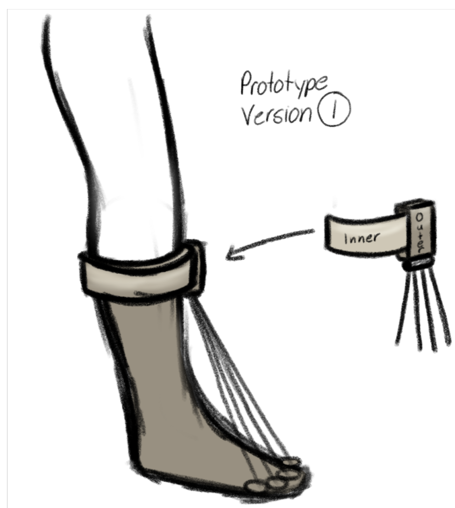

Figure 12: Prototype Version 1

4.4.2 Second Design

We amended our original design to reduce the number of the parts needed and thus cut down production cost and increase ease of use. In this second iteration (Figure 13), we replaced the four cables with two cables secured to the top part of the brace and attached to both sides of the foot. As we wanted to model the anatomy of the foot,, we wanted the cables to effectively act as the extensor hallucis longus tendon of the big toe and the extensor digitorum longus tendon of the pinky toe. Both the cables would run alongside the brace in a similar fashion to the tendons.

The difference in our design, however, was that the two cables would run along the ankle and would extend parallel to both the inner and outer sides of leg, respectively, until it reached just below the knee. This was unlike the true muscle anatomy where the tendons ran parallel to the toes and then combined as they ran towards the front center of the leg (shin).

We decided to forgo our idea of incorporating a bearing structure for the motion of the cables for a mechanism that enhances comfort and simplifies the design. We instead thought of using servos with pulleys attached to them.

Figure 13: Prototype Version 1

4.4.3 Final Design

After further brainstorming, we decided upon our third and final design (Figure 14). We employed the use of one cable instead of two to lessen the amount of moving parts for simplicity, easy maintenance, and comfort. We also encountered an issue of running two servo motors for actuation, since both servos would need to be absolutely synchronized. Any difference in different noise level between the two motors would ultimately disrupt the leg motion.

We placed the cable in the front within a tubing which ran the length of the cable from the toes to the servo. This tubing was attached to an external soft brace and did not permit much fiction. It allowed the Bowden cable to run freely through it while maintaining close proximity to the leg, enabling it to be hidden and secured to the leg down to the toes. We had the servo with a pulley attached mounted to the shin section of the brace. The Bowden cable was secured to the pulley and when the pulley rotated counterclockwise due to the motor's actuation it would lessen the length of the Bowden cable as it moved through its cylindrical encasement. This in turn would pull on toes of the foot causing it to dorsiflex. After a step is taken and weight was reapplied to the bottom of the foot, the motor would return to original position and cause the foot to be lowered. This final design replicated the motion that would be provided by the two parallel cables that were connected at the sides from the previous iteration.

Figure 14: Prototype Version 3

CHAPTER 5

EXPERIMENTS

5.1 ELECTRICAL SYSTEM

5.1.1 ARDUINO CODE

In order to process data collected from the ultrasonic sensor and FSRs, we used Arduino code. The code went through many iterations as we debugged and experimented with it. The final version is included in Appendix B.

We started with basic Arduino codes used to actuate each of the sensors and motor. As we continued experimenting, we combined the separate Arduino codes into a single code that actuated the whole system and reworked the code as necessary.

5.1.2 ELECTRICAL SYSTEM TESTING

In order to conduct initial testing, we wired our electrical components onto a breadboard and then uploaded code onto the Arduino board. The wiring schematic is included in Appendix A. We tested versions of the system, listed below. This was done to test whether each component worked separately, and whether the components all worked together as intended.

1. Servo motor with Arduino
2. Ultrasonic sensor with Arduino
3. Servo motor and ultrasonic sensor with Arduino
4. FSRs with Arduino

5. Servo motor, ultrasonic sensor, FSRs with Arduino

5.2 FULL SYSTEM

5.2.1 FSR EXPERIMENTS

After testing the electrical system, we put together the actuating components on the skeleton. We attached them onto an ankle brace and knee brace, as pictured in Figure 15. First, we tested whether the servo motor correctly pulled upward on the ankle brace, then we determined the best fit position for the motor.

In order to demonstrate the effectiveness of our device, we tested it while the FSRs were worn on a person's foot, shown in Figure 16. As the person assumed an average walking gait cycle, the Bowden cable and servo motor raised the skeleton foot accordingly.

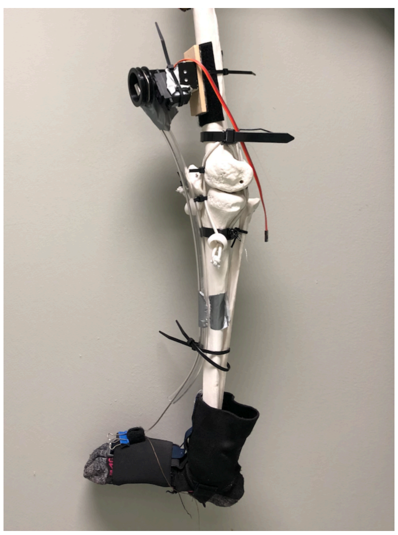

Figure 16: Skeleton with components

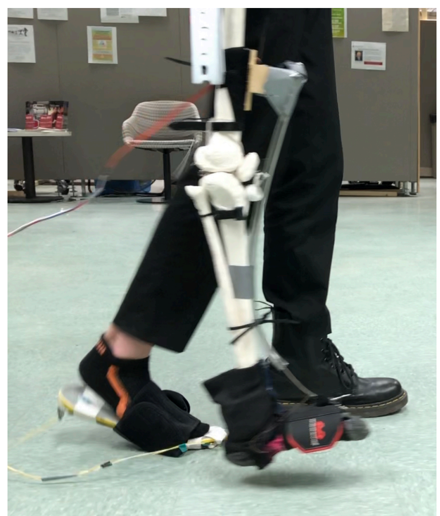

Figure 15: Testing with FSRs

The FSRs were utilized in a footswitch control method where both sensors were placed beneath the foot, one under the heel and one under the toes, to recognize the ‘initial contact’ and ‘toe-off’ phases of the gait. Based on the detected state of the foot—if it was at the start or end of the gait cycle—a control signal would actuate the servo via the Arduino coding.

As a step is taken, pictured in Figure 17:

- When the heel is down, the skeleton foot is at the neutral, 0 degree position
- When both the heel and toes are down, the skeleton foot is at the 0 degree position
- When just the toes are down, the skeleton foot is at the 0 degree position
- When the heel and toes are off the ground, the servo motor actuates and the skeleton foot is raised

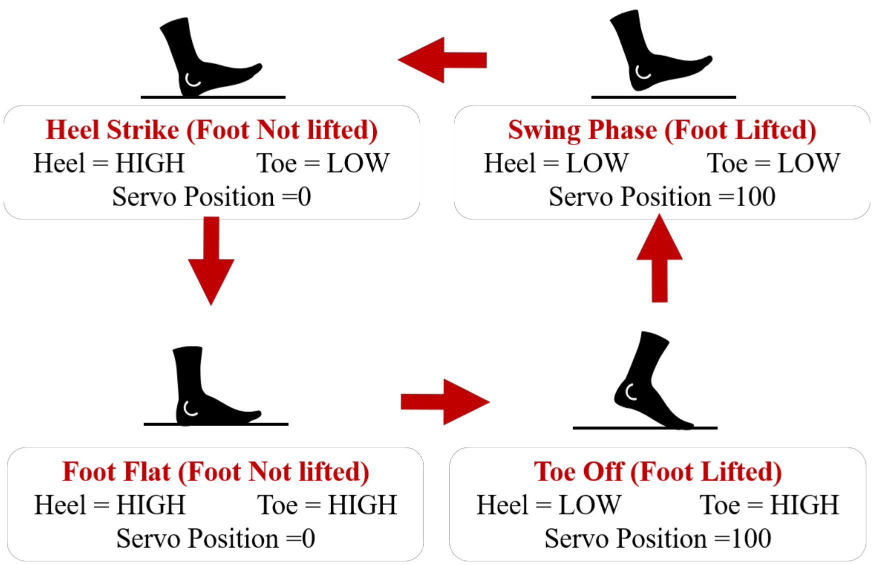

Figure 17: Servo positions as a step is taken

5.2.2 ULTRASONIC EXPERIMENTS

In the same manner as the experiments with the FSR sensors, we also tested the effectiveness of the ultrasonic sensors. The ultrasonic sensor was placed on the front of the foot facing forward. When the sensor detected an obstacle within 10 cm, the servo motor actuated and the skeleton foot raised in order to clear the obstacle.

To test the effectiveness of the ultrasonic sensor, a box was placed on the ground, in the line of detection of the sensor, to represent an obstacle. One member of our team wore an insole fitted with the ultrasonic sensor and FSRs, and approached the obstacle walking normally. When the ultrasonic sensor detected the obstacle within the determined range, the skeleton foot raised accordingly.

To test the effectiveness of the ultrasonic sensor faced at a sloped surface, we pointed the ultrasonic sensor at an angle. One member of our team again wore an insole fitted with the ultrasonic sensor and FSRs, then walked up to the obstacle. However, during this experiment, the skeleton foot did not raise accurately as when faced with a flat surface.

CHAPTER 6

KEY FINDINGS

6.1 GAIT RESULTS

We were mainly concerned with the angle of the foot during the swing phase, or 'Phase 4' as in Figure 18. For our results, we recorded a video of our FSR experiments. We then analyzed this video using a app called Hudl, which is able to measure angles. We took screenshots of specific points during the video and got the ankle angle measurements (Figure 19). These measurements were then plotted to ensure that they followed the general curve of the gait cycle (Figure 20).

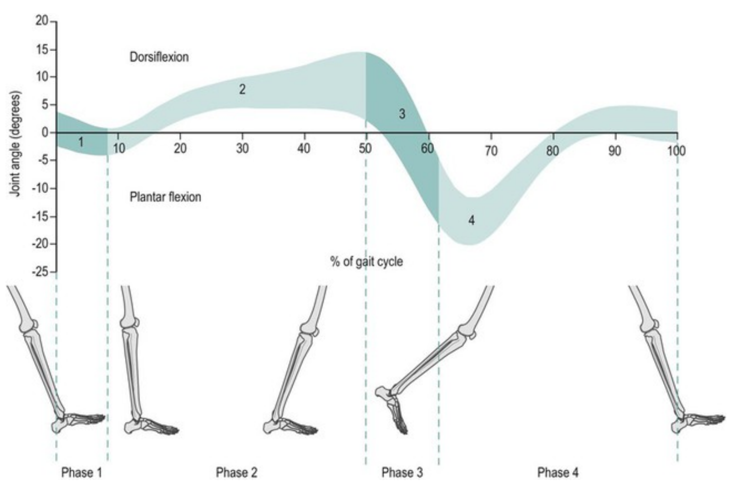

Figure 18: Ankle angles during the gait cycle (Richards, Chohan, Erande, 2017)

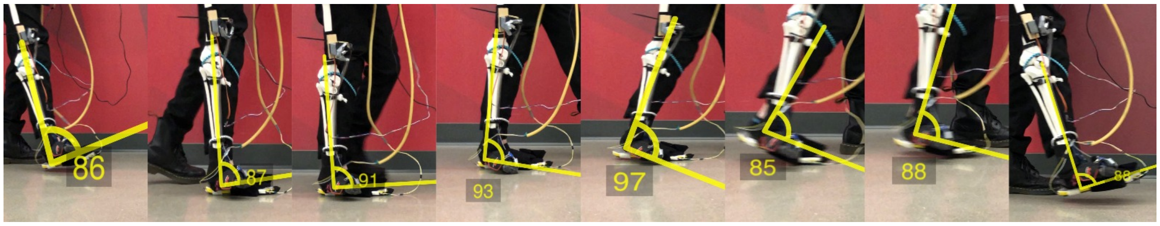

Figure 19: Angle measurements taken from the video

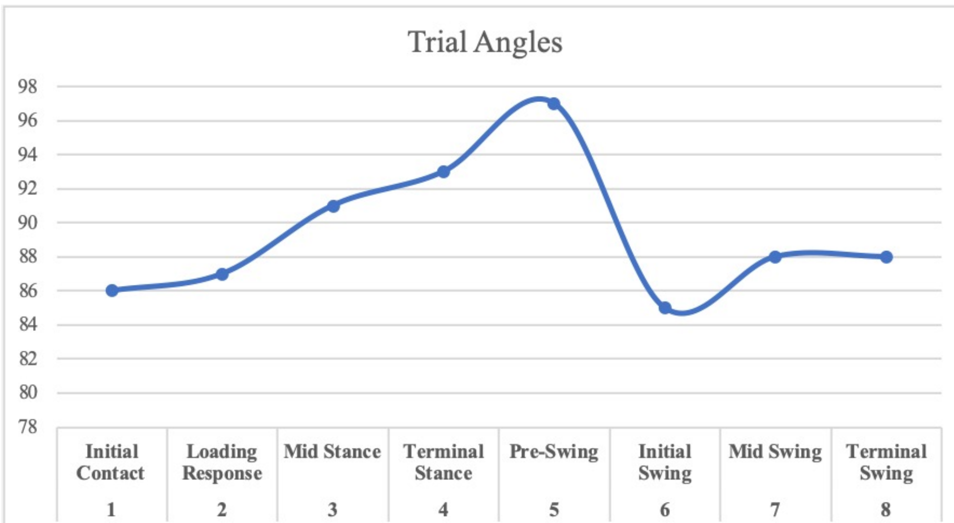

Figure 20: Ankle angles from our experiments

From the plotted data, the angle of the skeleton foot is within biological angle range during swing phase. Note that the ankle brace includes a strap that restricts the foot to a maximum angle of approximately 90 degrees.

6.2 ULTRASONIC RESULTS

As a result of our ultrasonic sensor experiments, we determined that the ultrasonic sensor was able to accurately detect an obstacle and correctly generate the actuation of the motor to lift the foot during certain situations. When we tested the ultrasonic pointed straight at a flat surface, it caused the foot to rise as intended.

However, when we tested the ultrasonic pointed at a sloped angle, it did not cause the foot to rise as determined. When pointed at an angle, the ultrasonic received noisy data and resulted in the servo motor rotating back and forth.

6.3 LIMITATIONS

We would like to note several limitations from our findings.

The ultrasonic sensor was able to detect objects fairly accurately when pointed straight at an object. However, when pointed at an angle or at a slope, the data that it received was not as accurate. This was due to the fact that a sloped surface does not have a consistent measurement of distance. This limited the placement of the ultrasonic sensor and its reliability. Also, the ultrasonic sensor occasionally sensed a stray error in data. This may be due to the accuracy of this specific sensor.

The device is not intended as a final, marketable product. It is merely for demonstration of concept and research purposes. More developments and improvements must be made on this device before it is finalized for market.

The skeleton used for testing is not a totally accurate substitute for a real human foot and leg. It was used merely to simulate a human leg and to get a general understanding of the design and concept.

6.4 APPLICATIONS

There exists a very large market for a soft ankle exosuit. Our design was specifically intended for persons that suffer from foot drop, but the device could possibly be used in other applications that revolve around the augmentation of the foot during walking. It could be used as a replacement for existing AFOs that are used for rehabilitation purposes. The ultimate benefit this design is that since it is not rigid like typical AFOs, it is more comfortable and the active aspect makes the brace both supportive and aligned to the typical walking gait.

CHAPTER 7

CONCLUSION

In our goal to develop a soft ankle exosuit for correction of foot drop, we successfully created a device that achieved all of our objectives. However, there are further steps to be taken before the exosuit design can be finalized.

Further developments to refine this device would be to conduct a more detailed study regarding the use of ultrasonic sensors in the exosuit. Research areas may include studying the accuracy of ultrasonic sensors; ultrasonic sensors used on uneven surfaces; ultrasonic sensors used in outdoor environments; ultrasonic sensors used in various weather conditions, such as rain or snow. Experiments could also be conducted to test the accuracy of different ultrasonic sensors.

Later iterations of this project would be to develop the exosuit to be worn on a human leg. This may involve the use of stronger motors and components in order to accomodate for the heavier weight and higher torque required. Other ways to improve the fit on a human leg would be the placement of the motor. Depending on the weight of the motor or other heavy components, it may be better to place them at the hip region to lessen the load on the user’s leg.

Another consideration would be the wiring. The current prototype requires a lot of wiring and long wires to connect all the electrical components together. Since the exosuit would be worn under clothing and shoes, further investigation may be conducted regarding the use of wireless sensors to reduce the amount of wire.

Lastly, introduction of an inertial measurement unit (IMU) would improve the sensing capabilities of the exosuit. IMUs are devices that combine an accelerometer and a gyroscope to measure angular velocity and acceleration. Acceleration data could be used to more accurately determine where the foot is in the gait cycle. During the swing phase, the foot first accelerates then decelerates as it nears the ground. By this thinking, and from data from previous studies, we could determine the exact moments to raise the foot based on its acceleration. Additionally, the sensor would be able to determine the type of motion of the user (eg. running, climbing, jogging) and adjust the foot actuation accordingly.

Every user is different and has different requirements, especially since each condition of foot drop is unique. One set mode of ankle rotation for one user may not be comfortable for another user. Therefore, personalization is an important aspect of any future design. An app could be developed that would allow users to change the angle of ankle rotation and customize the exosuit according to the wearer's needs.

This soft ankle exosuit would serve as a mobility aid for many users, not only those with foot drop but also those with abnormal gait cycles. Exosuits are more comfortable than rigid exoskeletons, and are able to be worn discreetly. The device would play an important role in rehabilitation and greatly increase the quality of life for patients.

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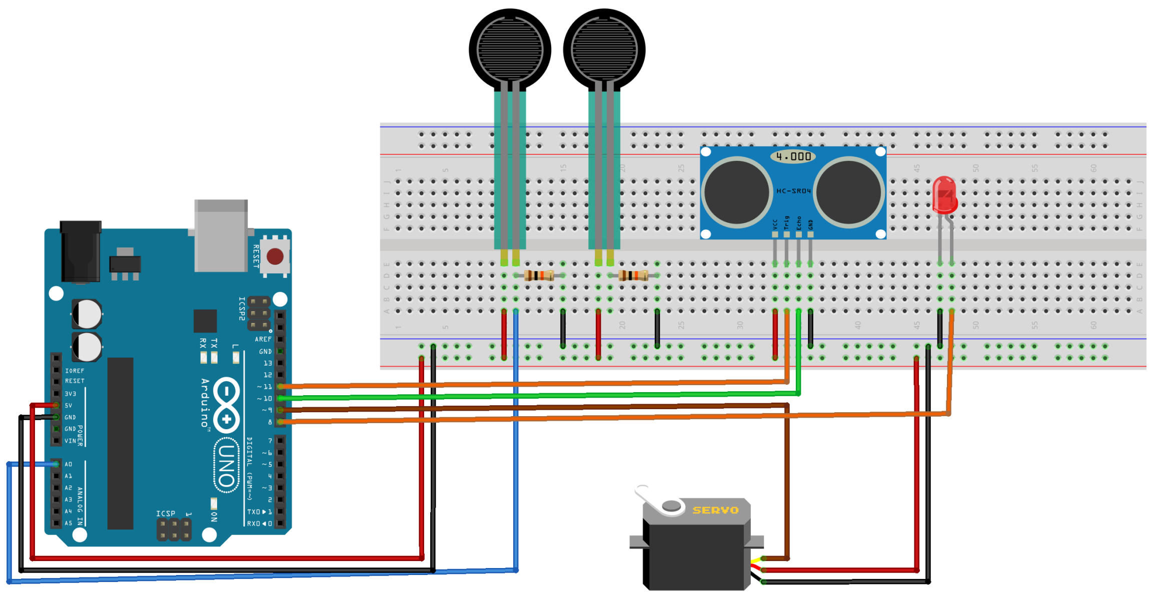
APPENDIX A

ARDUINO SCHEMATIC



APPENDIX B

ARDUINO CODE

```
#include <Servo.h>

Servo servo;

// Set pin numbers:
//FSR 1 (Toes)
int fsrAnalogPin = 4;    // FSR is connected to analog 0
int fsrReading =0;      // the analog reading from the FSR resistor divider

//FSR 2 (Heels)
int fsrAnalogPin2 = 5;    // FSR is connected to analog 1
int fsrReading2 =0;      // the analog reading from the FSR resistor divider

void setup() {
 Serial.begin(9600);

 servo.attach(9);            // the number of the servo pin

 //initializes the FSR pins as inputs:
  pinMode(fsrAnalogPin, INPUT_PULLUP);
  pinMode(fsrAnalogPin2, INPUT_PULLUP);

}
```

```
void loop()
{

  // read the state of the FSR  values:
  fsrReading = analogRead(fsrAnalogPin);
  fsrReading2 = analogRead(fsrAnalogPin2);

  // Show the state of FSRs on serial monitor
  Serial.print("Analog reading = ");
  Serial.println(fsrReading);
  Serial.print("Analog reading 2 = ");
  Serial.println(fsrReading2);

 //If statement for FSRs on the Toes and Heels
 //CASE1
    if(fsrReading >= 400) {
    servo.write(0);
    delay(100);}

 //CASE2
   else if(fsrReading2 >= 400){
    servo.write(0);
    delay(100);}

  //CASE3
     else {
    // turn LED off:
    //digitalWrite(ledPin, LOW);
    servo.write(150);
    delay(100);
  }
}
```