1.0 Masters Portfolio

Jacob Sindorf, Systems Engineering, Arizona State University

Masters in Passing, Summer 2021

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6.1.a MAE598 Final Paper, The Design of a Soft, Passive Ankle Device for Providing Assistance During Walking

6.1.b MAE598 Final Presentation Slides

6.1.c EGR 557 Final Presentation Slides

2.0 Resume

Jacob Sindorf

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Education

Arizona State University, Tempe, AZ
PhD, Systems Engineering
GPA- 4.0

The University of Arizona, Tucson, AZ
Bachelor of Biomedical Engineering, May 2020
Minor of Mechanical Engineering
GPA- 3.917

Community Service and Leadership

Banner University Medical Center Emergency Department, Research Volunteer

- Collaborative efforts with Nurses and Doctors in the Emergency Department to speak with patients about clinical trials and ongoing University of Arizona research projects
- Speaking and hospitality experience when communicating with patients about research studies, giving all patients an opportunity to participate

University of Arizona Senior Engineering Design Team Lead

- Year long engineering design project with cross discipline experience closely following the engineering process
- Lead a 5 student team and facilitated communication with Roche Tissue Diagnostics (Team Sponsor)
- Delivered complex Solidworks assembly files and presentations of a custom automatic pick and place device

Work Experience

ASU Teaching Assistant August 2020 – Present

- EGR280, statistics: Assisted students in office hours, hosted and recorded supplemental instruction sessions
- EGR201, Use Inspired Design: Drafted course material including lectures and homework and assisted in 3D printing training and use

2018 Clemson University SURE REU May – July 2018

- Professional project poster and PowerPoint presentation to Clemson Engineering and Science faculty
- Developed and designed a laser cell micro patterning control system using stepper motors, Arduinos, LEDs, joysticks, switches, and Solidwork designed laser cut acrylic pieces

BIO5 Public Affairs Assistant- University of Arizona September 2017- May 2020

- Managed and co-created professional development focused BIO5 Ambassador Internship for UA students
- Lead tours and gave presentations on BIO5 research/building to Professional and Student crowds
- Moderated professional science discussion panels

Laksari Research Lab- University of Arizona October 2018 – May 2020

- Multi-subject statistical analysis of processed MRI data in Matlab and JMP
- Statistical testing to identify significant brain region trends between healthy adults, MCI, and young adults
- Contributor on published paper, https://doi.org/10.1111/jon.12845, Journal of Neuroimaging

Personal skills

- Proficient in Solidworks, Matlab, Python

3.0 Overview

During my first year as an ASU graduate student, I found myself immersed in coursework, projects, research, and teaching. A wide range of robotics-based projects provided me with knowledge and skills that could be applied to future work and research in my professional career. Maintaining a 4.0 cumulative GPA is an accomplishment in itself, however, it reflects the quality of my education. Time outside of coursework was dedicated to research and teaching. Through research, I was able to work on projects based on neural networks through Python and Matlab. Teaching Assistantships with EGR 280, statistics, and EGR 201, use-inspired design, brought opportunities to host supplemental instruction sessions, 3D printing assistance, and even drafting classes. My most notable achievements were through three-course projects. With the changes due to COVID-19, course projects were heavily restricted to 'at home' materials, coding, and minimal in-person team meetings, presenting challenges for me and my teams to overcome. The three notable projects completed are, a soft, passive ankle device in MAE 598 Bio-Inspired Robotics, a single actuated walking robot in EGR 557 Foldable Robotics, and a Simulink design for autopilot in EGR 598 Robotic Systems II.

First, MAE 598, Bio-Inspired Robotics, provided the opportunity to work on a course project while simultaneously learning about the vast topic of bio-inspiration. Homework assignments tested our knowledge of the math and physics behind bio-inspiration from locomotion to flight. The real accomplishment was the semester-long project which allowed us to choose our own topic and perform a research project. My project was chosen based on a muscle-inspired wearable device. Throughout the semester, my team and I were responsible for background research, design, purchasing, and testing the device to deliver a final presentation and an IEEE formatted paper. This project was very influential on my graduate studies as it pertained to wearable devices. The short semester and limited funding also brought up a great opportunity for our team to work through the challenges presented and deliver a final working product. The design utilized cheap materials to create a passive, muscle-inspired orthosis, meant to assist in the human gait cycle. After research, design, and construction of the device, we also tested it on a treadmill using EMG and ankle angle to validate it. This project was chosen as it highlights a fast-paced, full research project, with a successful final device and written report.

Second, through EGR 557 Foldable Robotics, I was able to learn important engineering concepts pertaining to kinematics and dynamics simulation and their application to robotics. The course revolved around using foldable robotic techniques and creating a working final device. Each step in the class helped us evolve our initial idea into a working prototype. Halfway through the course my team and I also had to change our source of bio-inspiration, switching our entire assignment from a worm to a starfish podia-inspired project. Extensive Python programming using foldable libraries allowed us to simulate the kinematics and dynamics of a sarrus linkage, the main component of our device. That one sarrus linkage evolved to simulating an entire system to model and optimize the stiffness in a cardstock leg. Our final design used python simulated foldable manufacturing designs to craft a cardstock frame, sarrus linkages, and multiple legs of varying stiffness. A 3D printed gear hat and single DC motor pulled cables to compress the sarrus linkages at a ¼ offset so the system could walk. This project tested design, coding, optimizing, and foldable concepts to create a working robot capable of walking.

The third would be using Simulink and Matlab to work through the major concepts in simulating an autopilot system meant for a Zagi aircraft. The concepts of EGR598, Robotics Systems II, relied heavily on Matlab and even required the completion of 6 Matlab courses as well as 8 individual projects. The concepts were applied to aerodynamics but covered concepts vital to a roboticist including kinematics, reference frames, simulation, optimization, tuning, and trimming. Starting from reference frames and eventually path planning, the course quickly walked students through the concepts needed to create a working autopilot code. The Simulink block was adapted to each project and eventually, we were able to use trimmed and tuned blocks for our final Simulink implementation. Due to time constraints, we weren't able to fully create a working autopilot, however, the concepts used along the way can be used in many of my future work as a graduate student.

4.0 Accomplishments

4.1.a Design of a Soft, Passive Ankle Device for Providing Assistance During Walking

4.1.b Explanation

Bio-inspiration is a vast topic, that MAE 598 quickly covered, with topics such as locomotion, adhesion, and flight. The course allowed us to pick a course project and a team of four students. The project had to relate to a bio-inspired topic and a final presentation and IEEE formatted paper were submitted. My team's project was to use bioinspiration from human muscles to create an inexpensive soft wearable ankle device that assists in human locomotion. The device uses a vinyl reservoir and an elastic actuator to transfer the air by using the human user's weight. The elastic actuator helps pull the foot in dorsiflexion, and stepping on the air reservoir releases this tension and assists in plantar flexion. The orthotic device was created using inexpensive materials such as pool floaties and rafts to create the air reservoir, balloons, and hoses for the actuator, and flip flops to attach the device to the user. The project started with an extensive literature review, then prototyping and optimizing the design, and finally testing using EMG and ankle angle was performed to validate our orthotic. The wearable device performed well and showed promising results if it is fine-tuned and pursued in future research.

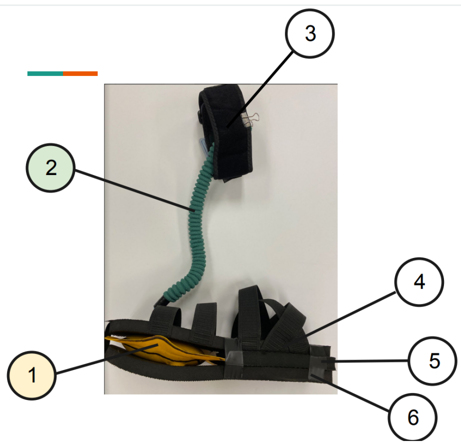
4.1.c Reflection

This project faced many challenges due to COVID-19, lack of funding, and a short time span. COVID-19 made it difficult to perform in-person team meetings and work on the project, including building and design making sharing materials and progress difficult. Inherently the project had no funding which restricts the actual device prototype to relatively inexpensive materials. The short time span was the last restriction as the project only had one semester to research, build and test. The shortened time span really helped my team and I learned the fundamentals of a research project from start to finish, as we had to expedite everything to deliver a high-quality prototype as a final deliverable. Even with these challenges, my team and I were able to problem solve and create a working prototype that provided promising results. Although we were remote, we each purchased inexpensive materials and prototyped designs, collaborating at each step to know what worked and what didn't. This assisted in our design optimization and allowed us to create a working passive wearable device for under 10$. The challenges we faced also helped us change our thinking towards cheap orthotics that would be affordable to users, which is why we focused on a completely passive device driven by the user's weight. The topic itself has few prevalent research studies about it also allowing us to create a unique device filling the need for less complex and inexpensive designs that compete with the current state-of-the-art devices. Through our literature review, we also recognized other areas that burden similar devices, including the device's activation timing, air supply, and cost. We were able to find promising results that use the human's gait cycle to activate the actuator when needed, an air reservoir to keep the device lightweight and mobile, and a passive approach to stay inexpensive and available.

4.1.d Evidence

See Appendix 6.1.a for the Final IEEE formatted paper
See Appendix 6.1.b for the final presentation slides

4.1.d.a Device Assembly



Bill of Materials	
#	**Part Name**
1	Reservoir
2	Actuator
3	Velcro Strap
4	Modified flip flop with elastic straps
5	Wedge spacer
6	Modified flip flop base

4.1.d.b Experimental Set-up

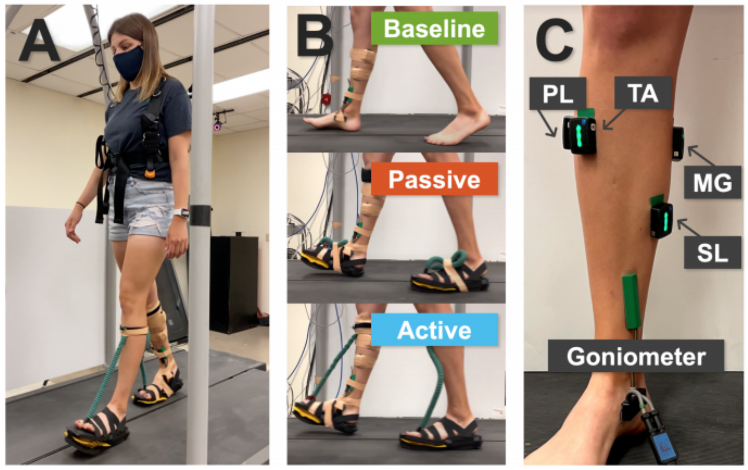
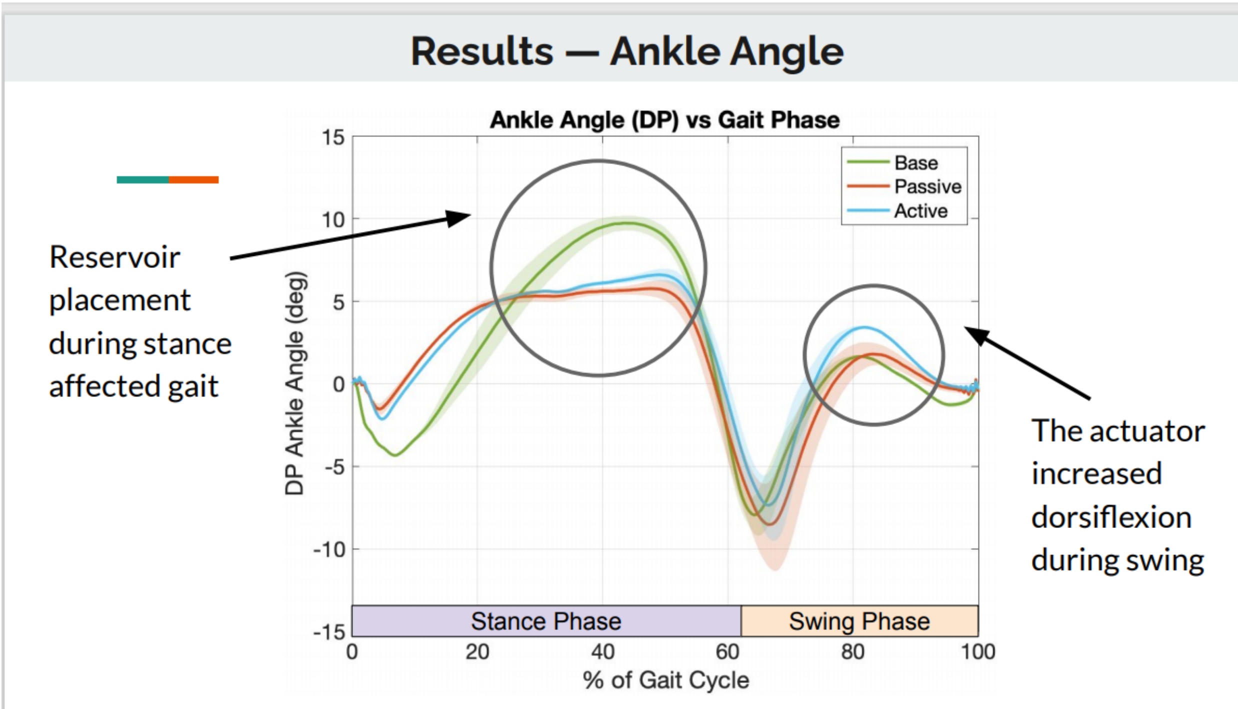
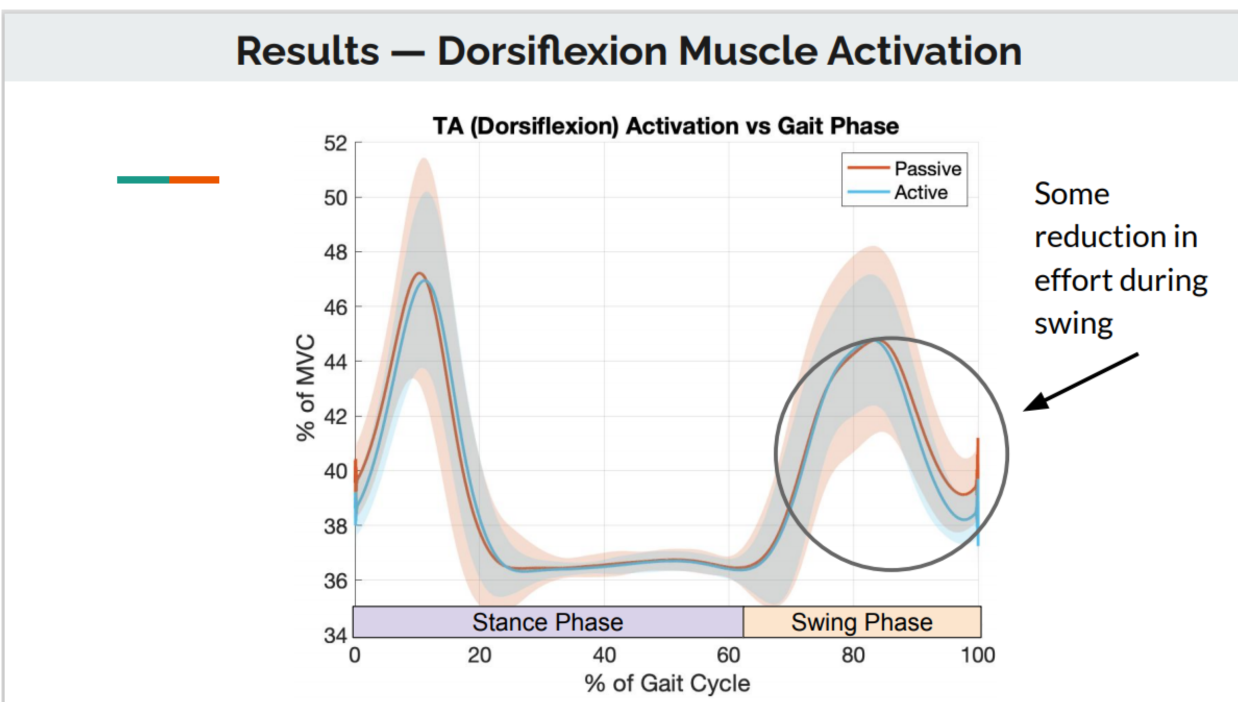


Fig. 9. The experimental set-up and conditions. **A**: A full view of the subject walking on the split-belt treadmill while wearing the device on both feet and sensors on the right leg. The subject wore a safety harness which did not bear any weight. **B**: Photos taken during the experiment in each of the experimental conditions. **C**: A close-up view of the sensors on the right leg. The four EMG sensors are indicated by the muscle that they correspond to, and the goniometer can be seen connected to the ankle.

4.1.d.c Results





4.1.e Summary

Designing and delivering a bio-inspired ankle orthotic required a literature review, multiple prototype iterations, testing, data interpretation, then formatting everything into a final report. The chosen evidence to highlight the entire project and the steps we took along the way would be the final paper (6.1.a) and the final presentation (6.1.b). Displayed in the evidence section (4.1.d) are four screenshots from the final paper and final presentation (where the entire report and presentation are in the appendix)that help highlight each of the major steps taken to complete the project. Those being the design, testing, and results of the project.

Creating the device started with the design phase. Through literature reviews, we found a need for human weight-activated orthotics using cheap materials and having lower complexity. This would make the device both easy to manufacture and easy to wear for any user. The literature mostly focused on specific use cases such as drop foot and rehabilitation, but our project also sought to address healthy individuals by reducing effort in walking. A common trend we noticed was the high complexity of pneumatically actuated systems, with many having heavy electrical components, difficult circuits, and being tied to an air compressor. With those considerations, our team also had to work with no funding for the project and covid-19 restricting group meetings. These challenges further drove our device design considerations. In 4.1.d.a, the final device assembly is pictured with each individual component. All materials were low cost and easily accessible to all team members so design iterations could be rapidly prototyped and improved. The reservoir required the most work as we had to take pool floaties and rafts to get the vinyl material, as well as the air valves. Through the design iterations, we found a streamlined manufacturing process that allowed for the reservoir to stay airtight, while having two valves, one to easily fill up the reservoir with a hand pump, and one to actuate the actuator. The actuator was designed using a fabric garden hose to restrict a balloon from expanding in one dimension. Its stiffness values and specific attachment point to the shank were calculated to verify the design. Flip flops and elastic straps were custom made to allow for comfort to the user as well.

With a device designed our team was then able to test it using EMG sensors and a goniometer as seen in 4.1.d.b. The testing system was verified with one subject, then data was collected on a different subject through three main trials. Those three trials were baseline, with no shoes, passive, with the device being worn without the actuator attached, and active, where the device and actuator are attached. Data for the EMG sensors and ankle angle was collected to verify the device. After post-processing in a custom Matlab script, result graphs were obtained, with two shown in 4.1.d.c. The most significant results were the changes in ankle angle in dorsiflexion as well as the muscle activation in dorsiflexion. The ankle angle during gait helps point to further device improvements by changing the reservoir placement. It also helped indicate that prior to experimentation, the user should be allowed to accumulate to the device to help normalize walking in it. Muscle activation in dorsiflexion helps show that during the active trials, the device assists the user, so further testing on stiffer materials could increase this change more. Given the time and covid restrictions, the project still saw success and allowed for my team and me to complete an entire research project in a semester. The device showed initial promising results and can be further improved in potential future research.

4.2.a Single Actuated Podia Inspired Foldable Cardstock Robot

4.2.b Explanation

Through foldable robotics, my team and I were able to create a working cardstock robot capable of locomotion. Our goal was to answer the following question:

"How can foldable techniques translate a small number of actuators into unique locomotion?"

To start the project, we had to start with a source of bioinspiration and use the specifications to design and simulate kinematics and dynamics. With sufficient kinematics and dynamics to back the design, the final prototype was created and tested to optimize a leg stiffness value. The project began with a worm inspiration but was changed halfway through the semester to a starfish podia. Bioinspiration was not the main goal, however, it was used to find real values to use in the simulations, such as force, weight, lengths, and more. Kinematic and Dynamic simulations were performed in python using a foldable robotics toolkit and pynamics. The project focussed on a sarrus linkage, which was simulated initially to find the kinematics, where a jacobian was calculated. Stemming from the sarrus linkage came a full system design simulated in python where dynamics were calculated. A simple frame and moving points to mimic sarrus linkages were used so we could focus on optimizing a single leg meant to drive the robot. The final design included a frame with two rigid legs and a central leg driven by two sarrus linkages attached to a gear hat and a single dc motor. By offsetting the gears by ¼ phase, it created a loop allowing the robot to walk. This was proved in python simulations prior to building. After creating a detailed manufacturing plan the final design was built where different legs of different stiffness values (layers of cardboard) were used. The distance traveled per leg could then be compared to the simulated python results, where both showed a middle stiffness value to be ideal, rather than the most rigid or most deformable.

4.2.c Reflection

As the semester faced the challenges of covid-19, the course was changed to focus heavily on python simulation. Then with python simulation, a design could be validated and created into a final device to be tested. The project started with a literature review, then progressively built on itself until the final device was physically built and tested. Python programming heavily influenced decisions, but also created a significant learning curve. Everything had to be mapped into python, altered, and simulated to prove both the dynamics and kinematics would work on our idea. Everything simulated in python was initially based on the extensive literature review and bioinspiration in order to get real-world values to test. Through python, a foldable 5 layer and single layer design if the device was also created that could be followed to create the final design. In the end, the robot was created out of 3D printed parts, string, cardstock, and a battery, all at-home materials. We successfully answered our initial question as we created a walking robot with a single motor, using foldable robotics techniques, and had it walk with a single cardstock leg.

4.2.d Evidence

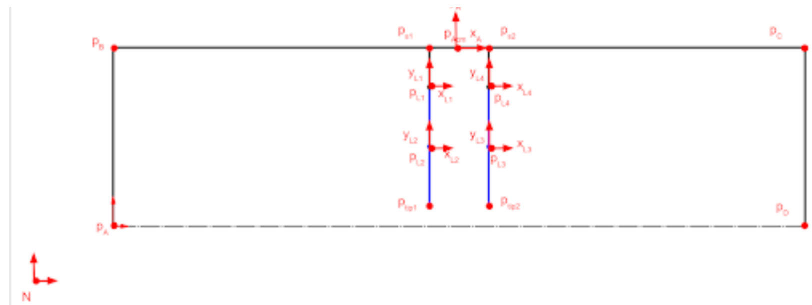
The entire project is well documented on a github website: https://l-terrestris.github.io/

Here, the bioinspiration, kinematics, dynamics, and optimization can all be seen in detail. This includes all code and all work done towards the final device. Three presentations are also on the website, where presentation 3 covers the final device and how it was optimized. Screenshots are provided:

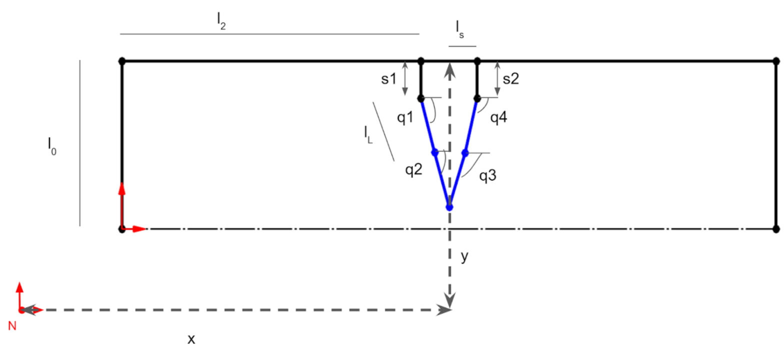
See appendix 6.1.c for the final presentation

4.2.d.a Kinematics

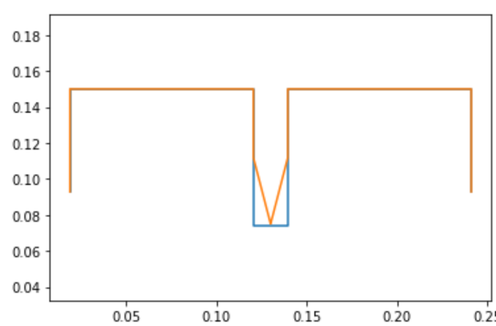
Points, and global and local reference frames



Lengths and variables

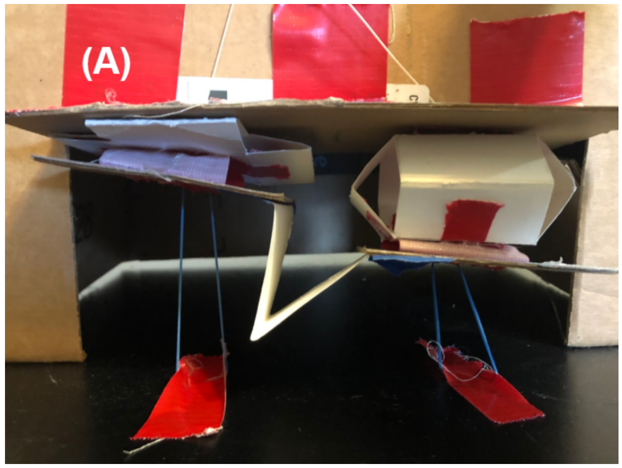


Final kinematic diagram

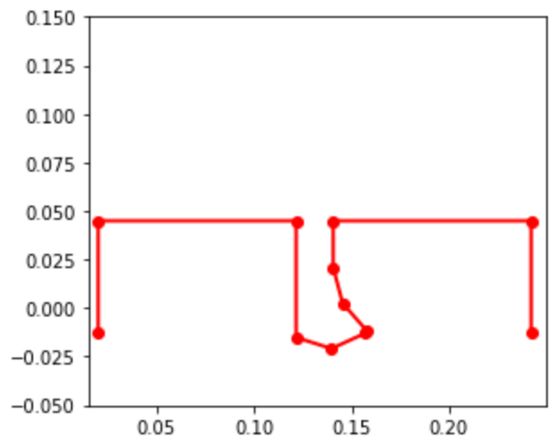


4.2.d.b Dynamics

Initial grounded prototype

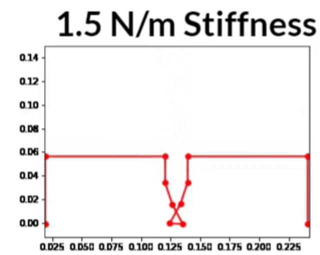


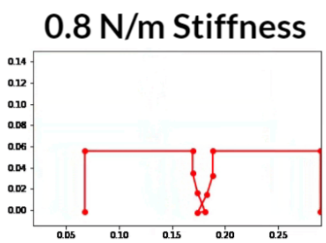
Final Dynamics simulation

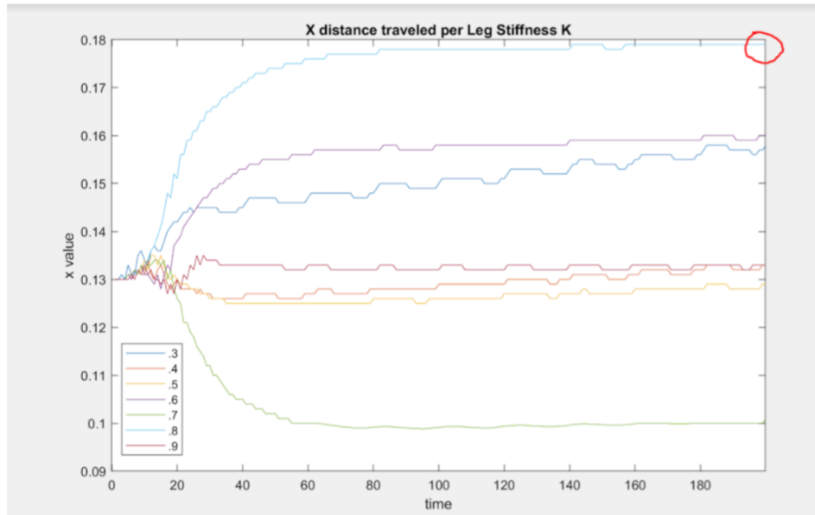


4.2.d.c Optimization

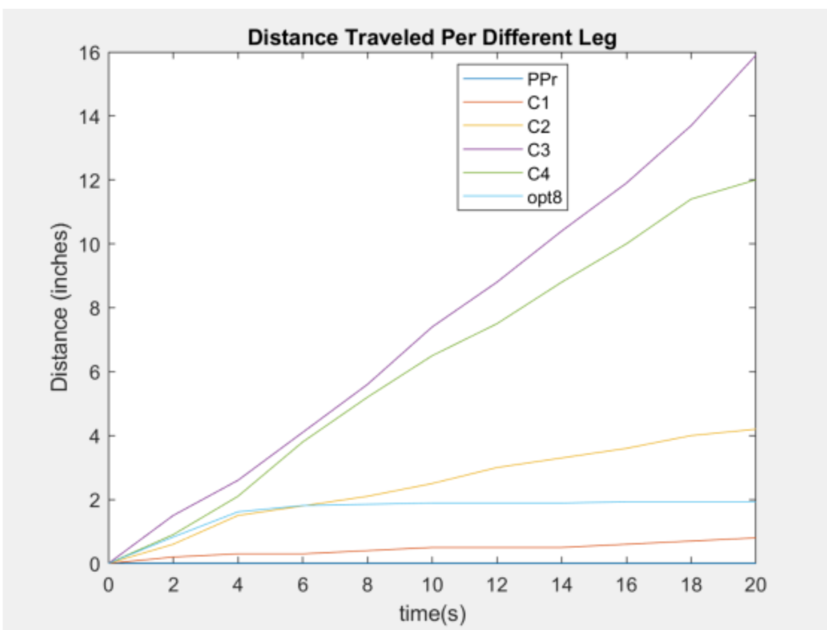
Stiffness simulation and optimization



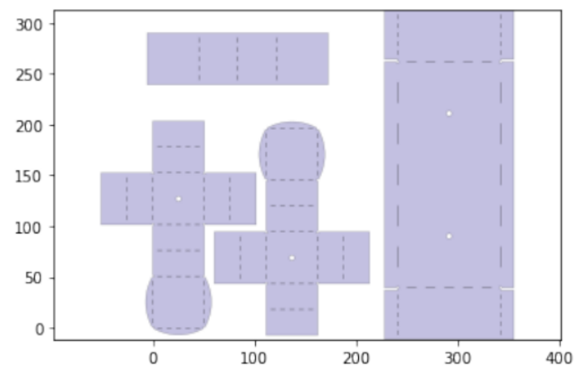




Device leg stiffness travel distance



4.2.d.d Device Design



System B: Cardstock Leg Robot	
#	Name
A	Single Actuator Gear Hat
1	Flag
2	Cardstock frame
3	String cable
4	Leg (various materials used)
5	3D printed spring
6	Cardstock Sarrus Linkage

4.2.e Summary

Starting with the kinematics of the device, our design was simplified to a frame and a v-shaped leg. Two sarrus linkages were simplified as moving points. In order to simulate it in python and pynamics, the global and local reference frames had to be defined as well as specific points in space (as seen in 4.2.d.a). In order to use pynamics correctly, the degrees of freedom had to be found then constraints equal to the degrees of freedom were created. Calculating the error of an initial guess based on the constraints formed the final kinematic diagram.

Dynamics could then be calculated using the solved kinematic diagram. Adding velocities, inertias, and forces to the device linkages and points allowed pynamics to create a simulation. That simulation takes sin waves as inputs for the sarrus linkages, and stiffness for the leg values to observe locomotion. The final simulation can be seen in 4.2.d.b, as well as a grounded proof of concept of the device.

Optimizing leg stiffness in python was the next step and required using the dynamics code and changing the q values. We could then observe how far the system traveled graphing the results of different stiffness values. The optimal python value was found to be in the middle of the range of values. After building and testing the final device, the python optimal value was compared to the actual values of varying leg stiffness.

The final device can be seen in 4.2.d.d, where it takes into account the python simulations run to create the final device. Prior to building, a python code was created to plot a 1 layer cut-out design for the cardstock components as seen in 4.2.d.d. A 5 layer design was also created but was unused. Using a single DC motor and a gear hat, we were able to offset the sarrus linkages contraction and extension by ¼ phase, the same as the dynamics simulation using sin waves. This created a loop to allow for locomotion. All components listed in the evidence section emphasize the steps taken to create a final, optimal foldable robot. It was created with a single actuator and was based on extensive python programming and simulations.

4.3.a Matlab and Simulink Autopilot Simulation

4.3.b Explanation

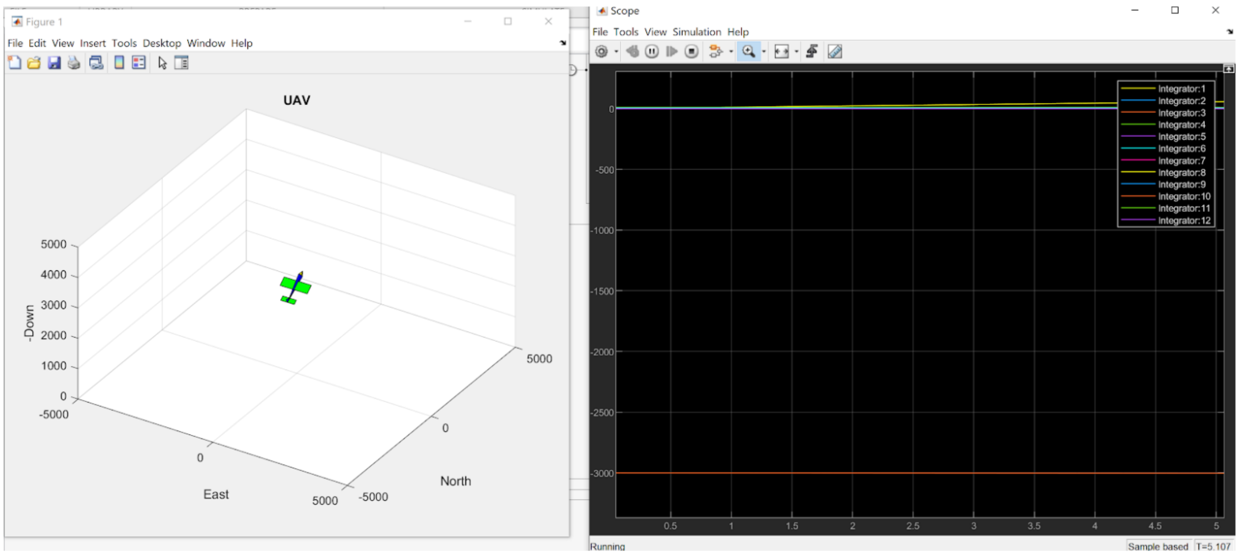
EGR598 Robotics System II had students follow the textbook Small Unmanned Aircraft by Beard and Mclain, to utilize robotics topics to create an autopilot system in Matlab. The course required a strong background in Matlab and Simulink and even had students complete 6 Matlab self-paced courses. Course scope began with a review of robotics systems I and the reference frames and how they can be applied to an aircraft and ended with path planning algorithms and concepts. Although the course focused on a Zagi aircraft, the concepts described can be applied to many future robotics projects. Overall, the course had 9 projects that each tested a new step in the autopilot system in Simulink. Most projects were a continuation of the previous project and involved adding or optimizing components.

4.3.c Reflection

Significance from the course is from the individual projects and the takeaways from every lesson taught. On the surface, the course taught about a Zagi aircraft and how to write an autopilot system for it. Most students in the course had no background in aerodynamics or aircraft, however, it was the robotics application that was emphasized at every step. Starting at reference frames, the course reviewed the topics of robotics I and expanded on it with reference frames of the aircraft. Complex robotics topics such as the Simulink control blocks and path planning were also discussed. Everything came together into a Simulink script capable of having a Zagi aircraft achieve level flight given forces and angles. The simulation also allowed the user to change values such as the roll, pitch, and yaw, while seeing the different forces applied and how the simulated aircraft moved. Scope blocks could be added to see positions, forces, accelerations, and more giving us a Simulink-controlled aircraft. Future work on the projects would be to fully implement the autopilot by following the rest of the content in the book and working out the projects provided.

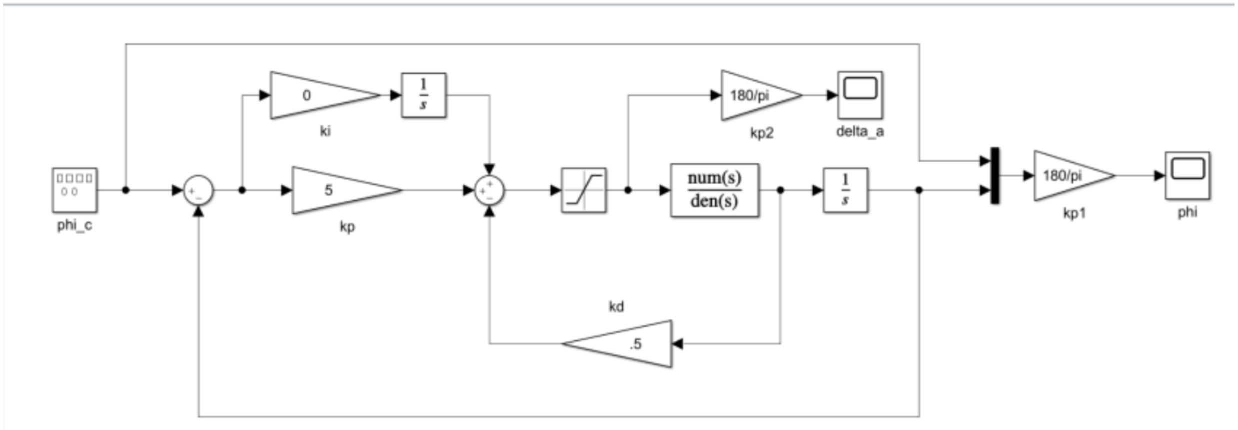
4.3.d Evidence

4.3.d.a Simulation and Trim

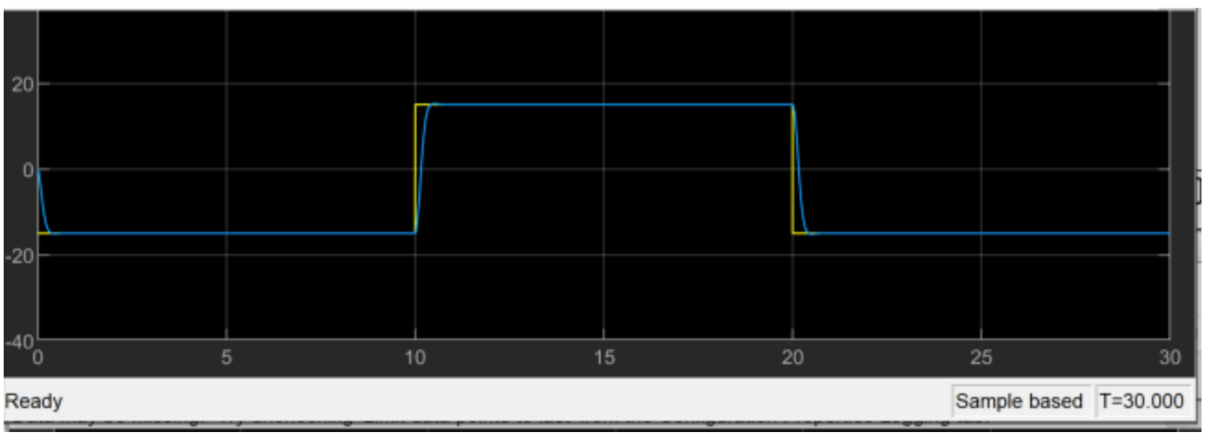


4.3.d.b Gain Tuning I

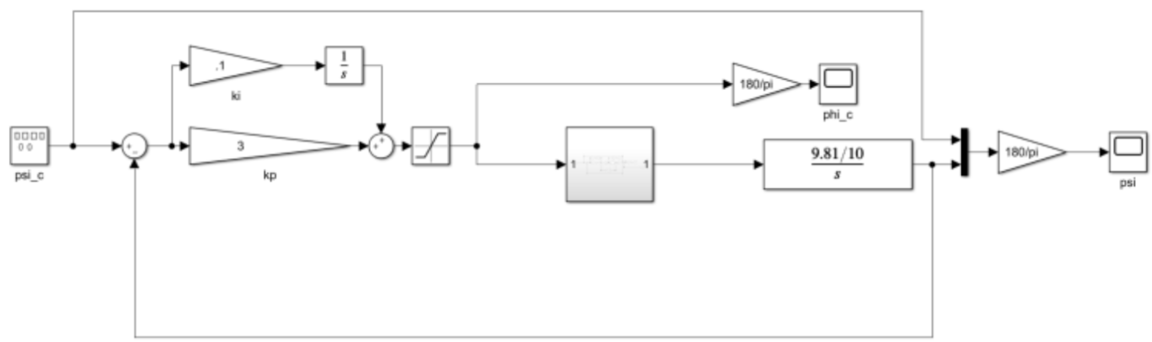
Simulink + gain values



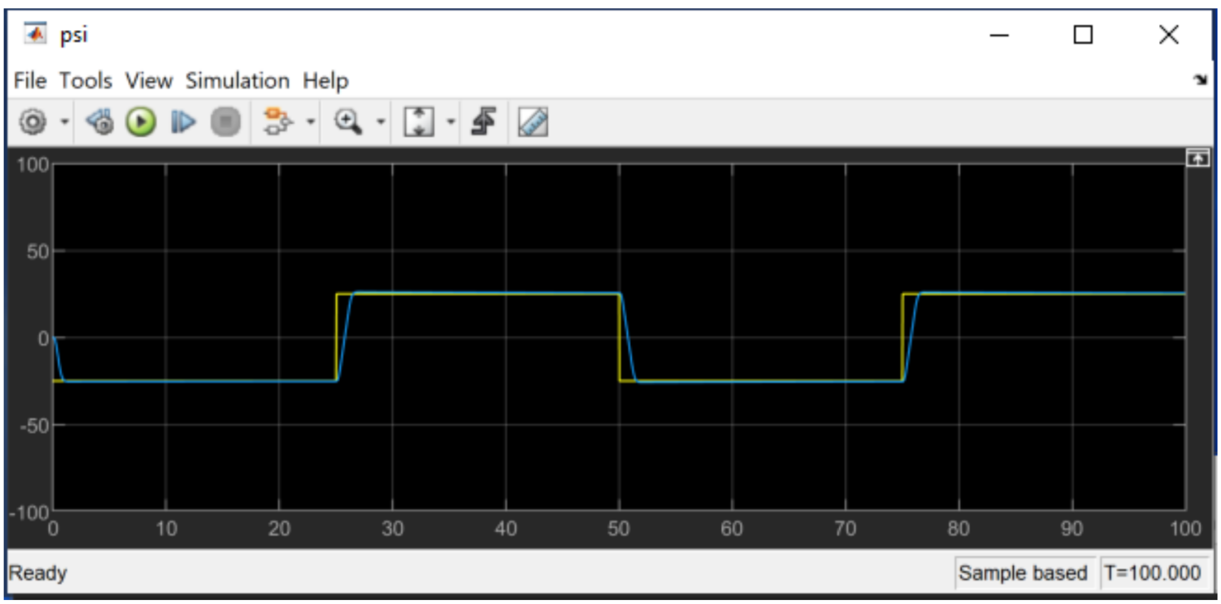
Phi graph (response) and delta a graph



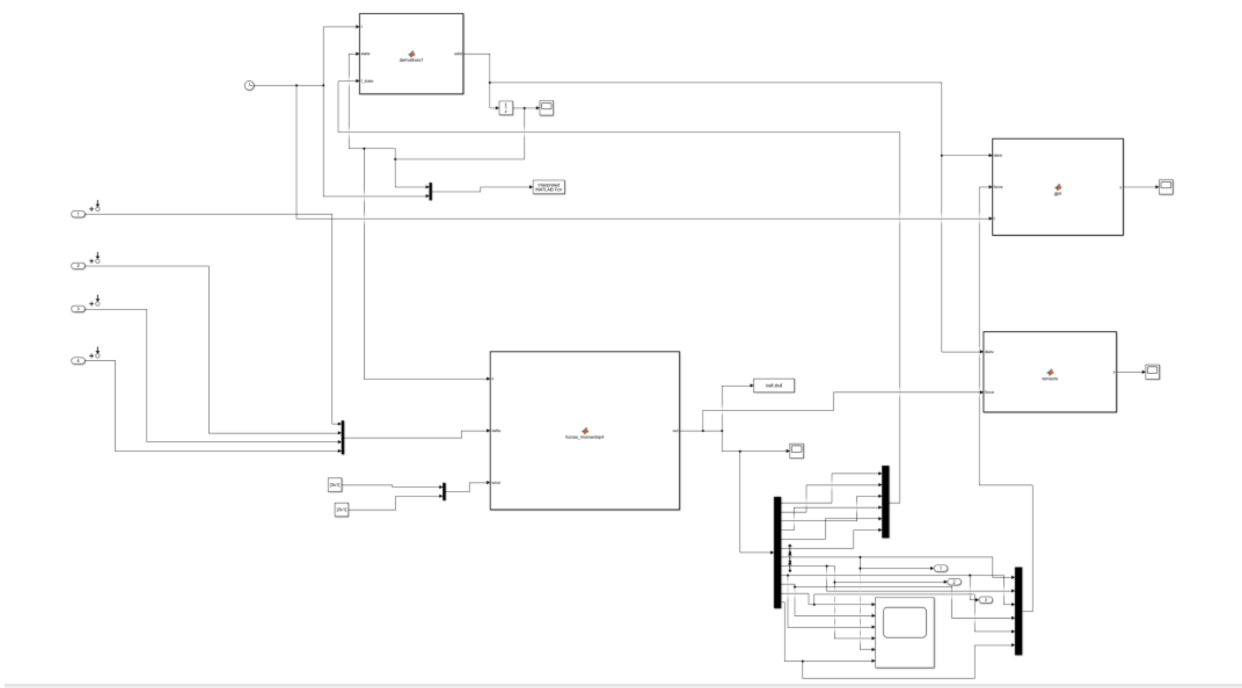
4.3.d.c Gain Tuning II



Psi and sji_c graphs from simulink



4.3.d.d Final Simulink Design



4.3.e Summary

Starting with the simulation, a sample aircraft is mapped and colored so it is easily seen as an airplane flying in some space. The aircraft, or UAV, can travel in the north, east, and down directions and is directly controlled through Simulink. Inputs such as speed, angles, wind velocities, forces, and a handful of constants are used to allow the aircraft to fly. The simulation takes 4 inputs and has 12 main states that have the derivative taken of them. Forces can then be calculated given the inputs, states, and wind.

As seen in 4.3.d.a, the aircraft was given a specific velocity, turn radius, and path angle. With the given values, the Matlab trim application in Simulink was used to allow for steady flight. This simulation includes things such as wind so the aircraft must be made to fly steady at a given height (straight red line in the graph). Trimming in the lateral and longitudinal directions as well as linearizing for state space and transfer functions can all be done through built-in Matlab functions. They allow us to get accurate results to utilize in the Simulink blocks.

With the tuned results, we were able to calculate gain values to tune our autopilot simulation. The gains specifically tune the PID loops for lateral and longitudinal control, with 7 loops in total requiring tuned gain values. 4.3.d.b and 4.3.d.c depict two of the Simulink blocks used to tune the gain values and the resultant graph displaying how accurate the results were. 4.3.d.b is the roll loop block that had its gain values found, then it was made into a small block and used in the Simulink block seen in 4.3.d.c to tune and find the next gain values. The loops were described in the textbook, but required students to create them in Simulink and then use previous trim results to tune gain values and produce accurate graphs. The blue line depicted is the tuned graph where yellow is the ideal. The goal is to utilize the previous results to produce a near-matching graph meaning we have successfully found the proper gain values. Most of the Simulink blocks required 3 gain values.

The final project was to add two new functions to the autopilot simulation. After successfully tuning gain values in the PID loops, we could move onto adding sensors (gyroscope, accelerometer, pressure) and GPS. The sensors use random numbers to mimic noise and can output results when the aircraft is flying in level flight. 4.3.d.d displays the final Simulink script for the autopilot system that was altered and added too as the semester progressed. 12 states () for direction, velocities, and angles can be fed into the derivatives block to get accelerations and velocities. Force function provided forces to the system. There are 4 inputs to the entire system as well (). Values for the aircraft could be tweaked to allow for turning, accelerating, and more which gives a future direction for the autopilot system. The next steps would have us implementing path planning into the system and using a small controller to physically fly the aircraft in the simulation.

5.0 Reflections

Graduate school has provided me with the opportunity to expand my knowledge as an engineer and as a student. In the current world situation, diving headfirst into a fast-paced Ph.D. program has been far from easy. As a new student at ASU, I lost all of my networks as an undergrad forcing me to work towards solving complicated issues without collaboration. Facing the challenge head-on I immersed myself into school and worked towards expanding my experience to face future challenges in engineering and in life. I had felt alone at first, as with covid, it made it difficult to interact with classmates and ask for help, or in general, ask about ASU. It wasn't until Dr. Rodgers emphasized the spirit of being a Ph.D. when he stated it is a process of "becoming an independent scholar." This statement resonated with me, as it brought perspective to the 'semester at home', helping me find value in the hard work I accomplished alone. To me the statement means bettering oneself and working hard to become a leader in engineering.

The three chosen projects not only encompass a wide variety of topics but encapsulate the importance of collaboration as an independent scholar. Collaboration is the heart of engineering and it relies heavily on the strength of each individual member. Through the projects, I learned many valuable skills and was provided the opportunity to network once again. As achievements, the projects all were in the spring semester and were all completed within that one semester.

Bioinspiration allowed for a bioinspired project. This brought me and 3 others together to work towards creating a fully functioning device in the span of a short semester. The project followed all the steps of a traditional research project, as we had to brainstorm a problem, perform a literature review, design, build and test. The project itself required trial and error to perfect the manufacturing of the device but most importantly, it taught how to run research trials. The system was tested with EMG sensors and a goniometer while using a force-sensing treadmill. All three modes of measurement had to be collected, filtered and interpreted to prove the device's success.

Foldable Robotics brought together me and 3 others to learn the fundamentals of foldable robotics through the simulation and design of a robot. Kinematics, dynamics, python, manufacturing, and more all had a role in the project, putting to the test all of the robotics and math concepts I had learned in other courses. Long python scripts helped back up the device design, and final testing emphasized the cardstock robot's success as it 'walked' across the floor.

Lastly, Robotics II let me delve deeper into Matlab and Simulink. Taking the concepts of an autopilot system and applying them to robotics gave a challenging approach to problem-solving. It also allowed for individual matlab courses to be applied to the math and physics topics of robotics.

Along with the three accomplishments I also accomplished a lot in research, teaching assistantships, and in class. Everything in the past year builds on the foundation of my academic career and sets me up for success in my future as an independent scholar.

6.0 Appendix

6.1.a MAE598 Final Paper, The Design of a Soft, Passive Ankle Device for Providing Assistance During Walking

The Design of a Soft, Passive Ankle Device for Providing Assistance During Walking

Team 4: James Arnold, Rebecca Red Horse, Priscilla Lamas, and Jacob Sindorf

Abstract— **This paper introduces a novel wearable ankle device that provides assistance to a human user while walking. The device has two main components: a pneumatic artificial muscle (PAM) that provides assistive torque in the sagittal plane, and an air reservoir under the foot that, when stepped on, causes the PAM to actuate. Therefore, this device is passive and does not require any air compressor or power source to actuate, and the actuation timing is determined by the placement of the reservoir under the foot. A prototype of this device was modeled, fabricated, and then tested in an experiment that aimed to determine if the device could provide assistance while walking. The preliminary study on one subject demonstrated strong potential for the device, since it was shown that the actuator successfully provided dorsiflexion assistance. There was also an indication of a slight reduction in muscle effort required for dorsiflexion. The results also indicated design changes, such as the reservoir placement and design, for future iterations of this device. Overall, the device demonstrated potential for being a lightweight and low-cost device that could be more accessible than current state-of-the-art robotic devices, but more functional than commonly used ankle foot orthoses.**

I. Introduction

In robotics, the term "soft" typically refers to highly compliant materials, closely resembling those found in living organisms. The field of soft wearable robotics is a new and rapidly growing area of research. This field offers the opportunity to wear robots like garments or accessories to assist the movement of specific parts of the body. The use of soft materials provides an advantage with human motion by minimizing restrictions to the wearer and eliminating the need to carefully align a rigid robot with biological joints, making soft materials important to the development of robotic systems that are more comfortable and lower cost alternatives compared to their rigid counterparts [1].

The nature of these materials allows these soft robots to be mechanically biocompatible and capable of lifelike functionalities. From biologically-inspired field robots for exploration to soft, lightweight cooperative robots that safely interact with people, the applications are countless. Increasingly common applications include those involved with lower limb assistance.

II. Background

Moving the human foot requires flexing the muscles in the calf, ankle, and the foot itself. These common actions are crucial for tasks like walking, but can be difficult for people who develop muscle weakness or those with chronic ankle instability. To aid in recovery for those with disabilities, wearable robotics are becoming a viable option to provide assistance to people while walking [2]. Such robotic devices have also found non-rehabilitative applications, such as in industrial and military settings to augment the strength and/or endurance of healthy individuals [3]. Many of these wearable robotic devices are focused on providing assistance to the ankle joint, since this joint directly interfaces with the environment and significant muscle effort is exerted to control the ankle while walking.

Before considering state-of-the-art wearable robots for walking, it is important to recognize that most people who require assistance for walking are not currently using wearable robots due to their high cost and limited commercial availability. Most people requiring assistance for walking are patients experiencing abnormal gait patterns that can arise from a multitude of ankle injuries commonly derived from neuromuscular disorders, sports injuries, and ageing. For patients with such issues, the ankle's range of motion is heavily influenced, restricting patients' dorsiflexion and plantarflexion when walking. An example that is caused by neuromuscular disorders or injury is drop foot. Weakening in the anterior muscles in the shank causes difficulty in dorsiflexion in patients, hindering their ability to walk unassisted [4]. Attending physical therapy or utilizing an assistive device are the main treatments for drop foot and similar disorders. Physical therapy provides an effective treatment, but restricts a patient to attend in-person while also being cumbersome financially for many. The other solution would be assistive devices: passive and active ankle orthoses.

The main passive devices for walking assistance are ankle-foot orthoses (AFOs). They restrict the ankle to a neutral position of about 90° to correct the ankle position and limit the ankle's range of motion. AFO's are rigid wearables that usually require physical therapy with its use. Overuse of an AFO causes dependence in day-to-day life. Such AFOs have also been shown to cause atrophy and muscle weakening [1,5].

Modern devices have been developed in recent years to support lower limb motion as they work to emulate muscles in parallel with the human user. These devices often use a form of pneumatic actuator (e.g., McKibben muscles or flexible pneumatic muscles) since they are typically lightweight, easy to fabricate, and are self-limiting, or have a maximum contraction, making them similar to human skeletal muscles.

Many current active solutions combine rigid AFO frames with an pneumatic artificial muscle (PAM). Such devices have been shown to assist in plantarflexion. Although these devices have been shown to reduce metabolic cost, they may not be practical in day to day life. One such device is not intended for use outside of research and another is heavy, but both are restricted by their air compressors [6, 7].

A less rigid approach uses three air muscles to "mimic" human muscles. It is capable of multiple motion assistance including dorsiflexion and eversion, and has a feedforward feedback system, inertial measurement units (IMUs), sensors, that all assist in accurate device usage. However, these components add weight and restrictions as they have to be housed and supported. Although the system can be battery powered, it is restricted to an air compressor [4] as the more rigid devices are.

To avoid these bulky and heavy exoskeletons, an approach using light, soft, and shapely wearable devices is introduced. One such design is a soft, sock-like AFO exosuit with fabric-based, thermally-bonded nylon actuators that is meant to be worn over the user's shoes. The system uses a portable pump and battery to actuate the exosuit, and it is shown to assist with dorsiflexion and aid in natural gait restoration [8].

More complex, state-of-the-art solutions include a full lower body, pneumatically-actuated system with its components stored in a backpack: using sensors and air pressure, specific actuators expand or compress to assist lower body movement [9]. Additionally, a commercially available product called the *Restore Exosuit* by Rewalk Robotics uses motors and cable tension instead of pneumatic actuators, but achieves similar walking assistance [10]. It is capable of three unique modes: assist to provide active assistance, slack to effectively allow normal walking with no interference, and brace, to provide constant stiff cables to act as an AFO. These state-of-the-art solutions tend to be expensive, not practical, and are oftentimes restricted by air compressors.

To balance the trade-off between inexpensive AFOs (which do not provide active assistance) and expensive state-of-the-art robotic devices (which are currently cost prohibitive for widespread use), we propose a soft wearable ankle device that is as inexpensive as simple AFOs, but still provides the dynamic assistance that parallels walking gait that is seen in the more active and expensive solutions. This paper presents the preliminary study of the first prototype of such a device that can provide walking assistance.

III. Methods

A. Device Concept

Our device is designed as a closed pneumatic system that is actuated using the human user's weight during the stance phase of walking. By placing a reservoir of air under the user's foot, we can convert the energy of the user pushing their foot downwards on the ground into pneumatic energy that can be used by a PAM. Therefore, the reservoir serves as both the device's power source and sole sensor for determining the gait phase. By placing the reservoir at different locations under the foot, we can tune at what phase of the gait cycle we want the PAM to actuate. The PAM in our device is connected between the user's toes and their shank just below the knee so that actuating the PAM generates torque about the ankle joint.

The PAM used by our device is a low-cost actuator that consists of a latex twisting balloon (like those used to make balloon animals) and the fabric outer lining of an expandable garden hose. When the balloon is put inside the fabric lining and constrained so that ends of the balloon must move with the ends of the fabric lining, the balloon can be filled with air so that the actuator expands in length. The fabric lining surrounding the balloon constrains the expansion of the balloon to cause the PAM to expand in a single degree-of-freedom (DOF). Therefore, the PAM used in this paper is an extensional device, unlike common PAMs (such as the McKibben muscle) which is a contractile device. Another important feature of our PAM is that it will quickly contract if air is not being forced into it. Therefore, only while the reservoir of our device is being stepped on will the PAM extend in length.

While the specifics of the reservoir and actuator design will be described in the next subsection, it is helpful to first have a high-level understanding of the device's design and how it interfaces with the human user during the walking gait. The central goal of the device is to reduce the human user's effort while walking by using the PAM to actuate in parallel with the human user's muscles. More specifically, our device is focused on the muscles used to control the human ankle in the sagittal plane, corresponding to the dorsiflexion (pointing toes upwards) and plantarflexion (pointing toes downwards) movements. While muscles other than those specific to controlling ankle motion in the sagittal plane are important for human locomotion, the ankle muscles controlling motion in the sagittal plane play a critical role in propulsion [11].

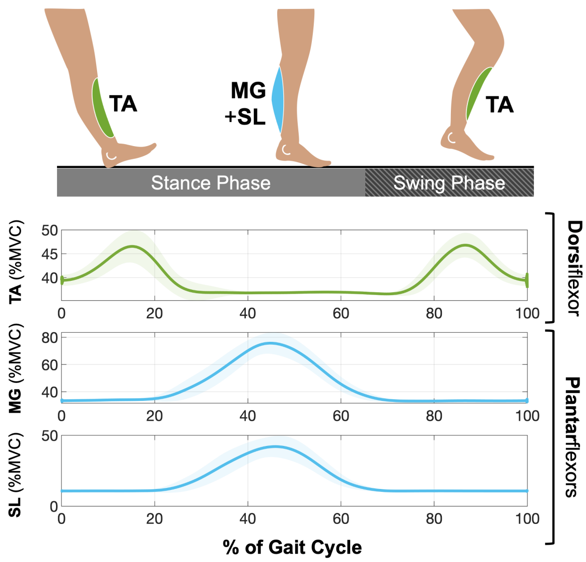


Fig. 1. A visual representation of the human muscles of interest which control motion in the sagittal plane throughout the human walking gait cycle. The three plots show the average, filtered EMG response as a percent of MVC for a single human subject walking barefoot on a treadmill.

The strongest muscles controlling movement of the ankle in the sagittal plane are the tibialis anterior (TA) which allows the ankle to move in the dorsiflexion direction and the soleus (SL) and medial gastrocnemius (MG) which allow the ankle to move in the plantarflexion direction. Our assistive device aims to actuate at the correct times in the gait cycle to provide assistance in these directions of motion. Therefore, the information of when these muscles are contracting, and therefore injecting energy into the system during walking, is critical to the design of the device which aims to use its actuator in parallel with the human muscles.

Previous research has demonstrated that providing assistance at the wrong times will cause the user to expend additional effort compensating for what the body feels is a disturbance [12], so actuating the device at the correct times during the gait cycle is important. The aforementioned muscles and plots of their respective muscle activations throughout the gait cycle can be seen in Fig. 1. Coupling this information with the previous description of the PAM connected between the toes and shank of the human user, the actuator should be inflated during the later half of the stance phase so that it promotes plantarflexion at the appropriate time. Furthermore, when the actuator is not inflated, its length and placement can be selected so that the actuator pulls the ankle upwards in dorsiflexion during the swing phase and at the beginning of the stance phase. To achieve this timing of the actuator, the reservoir can be placed at the ball of the foot to effectively "sense" when the user is in the later half of the stance phase. A diagram of the device's concept is shown in Fig. 2.

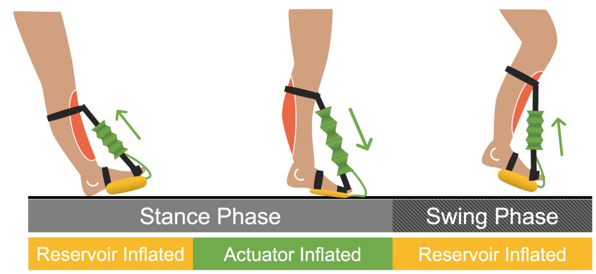


Fig. 2. Visual representation of the concept of the device. The reservoir is indicated in yellow, the actuator (PAM) in green, and the human muscle in red. Arrows are used to indicate the direction in which the actuator is pulling/pushing the toes.

B. *Modeling and Fabrication*

For the concept described above to work in practice, there are a number of important design questions that we considered. First, the length of the actuator needed to be determined so that it could pull the ankle up in dorsiflexion when deflated and push the ankle downwards in plantarflexion when inflated. Second, the design of an air filled reservoir to actuate the actuator needed to be determined.

First, the methodology for selecting the actuator length will be described. The stretchable, latex balloon within the actuator allows the actuator to generate a significant contractile/pulling force when the actuator is pulled from its equilibrium position. When the balloon is filled with air and the actuator extends, the equilibrium position (determined by the length of the actuator) and pulling force change. Therefore, the PAM can be modeled as a variable stiffness actuator in that the stiffness magnitude and stiffness equilibrium position change as a function of the air inside of the actuator. Since our device is designed so that the actuator quickly transitions between the inflated and deflated states, we will model the length and stiffness at these two states of the actuator only.

The length of the actuator was determined by the natural range of motion of the human ankle in the sagittal plane. Considering the shank and foot to be 90 degrees from one another in the neutral position, the ankles range of motion has a maximum dorsiflexion of 20° upwards, and a maximum plantarflexion of 50° downwards [13]. The ankle, shank, and actuator form a triangle with known foot and shank lengths, as well as a known angle between them. From the shank to the foot, maximum dorsiflexion would have a 70° angle, and maximum plantarflexion would have a 140° angle. Using the law of cosines, the ideal minimum and maximum lengths of the actuator can be determined based on the actuator's attachment point on the leg and the foot length. Equation (1) determines the ideal minimum length of the actuator, l_{min}, which corresponds to the unstretched neutral length, and (2) calculates the ideal maximum actuator length, l_{max}, when filled with air and stretched.

$$l_{min} = \sqrt{h^2 + l_f - 2h(l_f)cos(70°)}$$

$$l_{max} = \sqrt{h^2 + l_f - 2h(l_f)cos(140°)}$$

where h is the actuator's attachment point and lf is the foot length. With the minimum length found in (1), and the maximum length found in (2), an actuator of the ideal length could be fabricated for any size human user. Since these are ideal values, it may not be feasible to design an actuator that perfectly transitions between l_{min} and l_{max} when it is filled with air, but these equations describe the geometric relationship between the size of the user and the ideal length of the actuator which can be used to inform the fabrication of the actuator.

Next, the stiffness of the actuator can be characterized experimentally. At both l_{min} (when the actuator is deflated) and at l_{max} (when the actuator is inflated), the actuator will have different stiffness properties caused by the change in tension of the latex balloon when it is unfilled versus filled with air.

An experiment was performed to model the stiffness of the actuator. A simple linear stiffness model, Hooke's Law, (3) was used to determine the spring constant of the actuator while filled and unfilled with air [14].

$$F = - kx \qquad (3)$$

where x represents the spring's displacement and k is the spring constant. This equation can be converted into the equilibrium expression specific to the experiment (4):

$$W = kx \qquad (4)$$

where W is the weight of the applied mass at the end of the actuator. The spring constant can be determined by plotting the applied weight and the spring's displacement measurements against each other with the spring constant, k, being the slope of the plot. Fig. 3 shows the setup for measuring the spring's displacement when a range of weights is applied. Weight was applied to the actuator in 100 gram increments, then the change in length was measured in inches and compared to the initial actuator length.

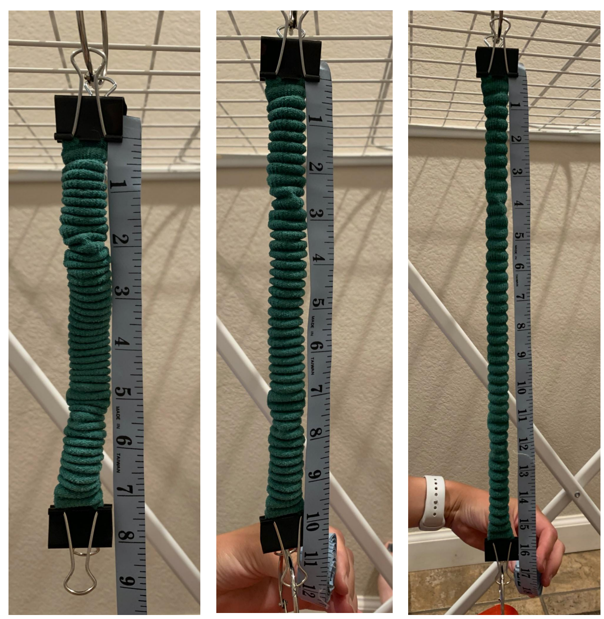


Fig. 3. Experimental setup to model the stiffness properties of the actuator. Three different conditions are shown demonstrating the change in the length of the actuator.

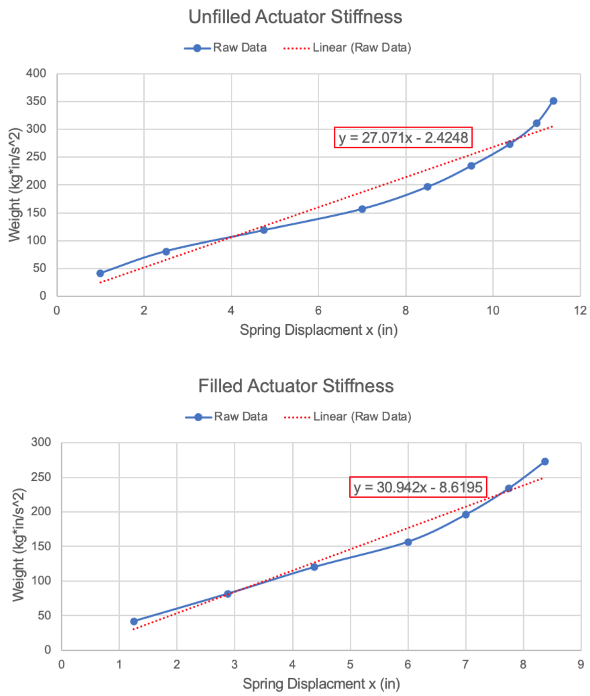


Fig. 4. Plots showing the experimentally collected data used to calculate the stiffness of the actuator when filled and unfilled with air. Blue points are the raw data collected in the experiments, and the red line shows the linear fit.

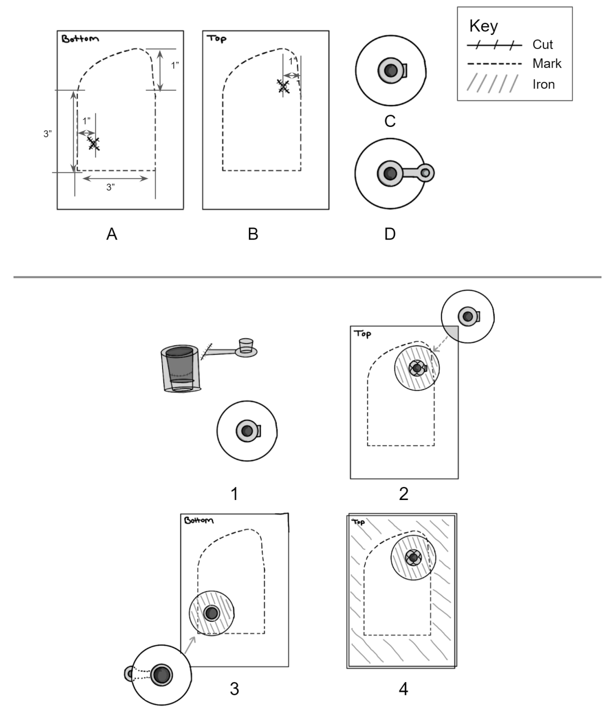


Fig. 5. Reservoir parts for assembly and manufacturing steps. Two vinyl marked cut outs, A and B, and two inflatable valves, C and D, are needed to manufacture the reservoir. The four manufacturing steps are listed and shown (1-4). The dimensions shown in the figure are specific to the size of the subject's foot.

Plots of the weight and spring displacement are displayed in Fig 4 where a linear equation has been fit to the data. The slope of this line is an estimate of the spring constant, k, of the actuator. The k value of the actuator when unfilled with air was ~27 N/m and the k value of the actuator when filled with air was about ~31 N/m. These values show the expected results that the actuator stiffens as it is filled with air, but is still considerably stiff in its deflated state.

With the actuator parameters described and modeled, the next step was to consider the design of the reservoir. The amount of air required to fill the actuator was found experimentally by fully inflating the actuator and collecting the air into a measuring cup underwater. The final reservoir design, as seen in Fig 5, was crafted with rectangular vinyl cut outs, taken from inexpensive rafts, and circular valves cut from cheap inflatables.

To manufacture the reservoir, two square vinyl cut outs (A and B) were marked with the appropriate actuator size, and an x shaped slit is cut through it to easily adhere the valves (C and D) to it. To combine parts A-D, four simplified manufacturing steps are shown in Fig 5. Step 1 is to cut the plug arm from valve C as well as cutting out the inner plastic piece to allow for continuous air flow (note, valve D is unaltered). Step 2 is to push the top of valve C through the bottom of B using the x shaped slit, and then to iron the materials together. Step 3 takes valve D and puts it through the x-shaped slit on top of B so the valve faces downward. It is then ironed together. Step 4 then irons A and B together forming a reservoir with a valve coming out the bottom to add air in, and a valve coming out the top to actuate the actuator. Following these steps ensure that the reservoir stays airtight, can withstand the weight of the user, and contains intuitive valve placement to fit the final device design.

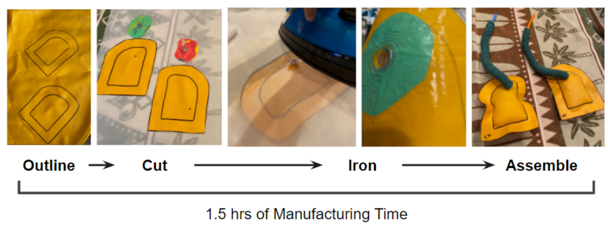
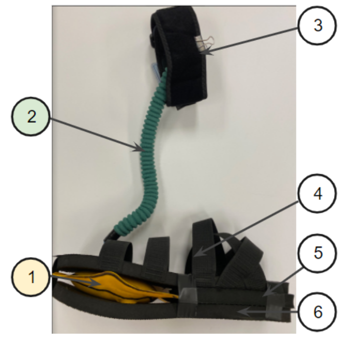


Fig. 6. Depiction of reservoir manufacturing process. The images shown are from the refined manufacturing process, with outlining, cutting, ironing and assembling two working reservoirs taking around 1.5 hours.



Bill of Materials	
#	**Part Name**
1	Reservoir
2	Actuator
3	Velcro Strap
4	Modified flip flop with elastic straps
5	Wedge spacer
6	Modified flip flop base

Fig. 7. Full device assembly with bill of materials. Six major components of the device are listed. The reservoir, the actuator, a velcro strap to secure the actuator to the leg, a flip flop to attach the device to the foot, a cut flip flop to help space out the reservoir, and a flip flop to act as the device's sole.

Photographs of the reservoir manufacturing process can be seen in Fig. 6, showing the main steps and time it takes to manufacture two working reservoirs. With around 1.5 hours of time to create them, it allows for rapid prototyping for future iterations of the device.

With the reservoir and actuator constructed, the system was designed using altered flip flops, elastic straps, and a velcro strap. As seen in Fig 7, the device consists of 6 main components. *Part 1* and *Part 2*, the reservoir and actuator respectively, have been previously described. They act as a closed loop system that transfers air at specific points in the gait cycle to provide the necessary dorsiflexion and plantarflexion assistance. *Part 3*, the velcro strap, is a common tennis elbow orthotic used to attach the actuator to the shank just below the knee. *Part 4* is a custom modified flip flop with the strap removed from the sole. Elastic straps were added instead to anchor the foot to the sole and prevent the heel from lifting during walking. *Part 5* is a flip flop sole cut to act as a wedge spacer so the reservoir does not hinder walking, encouraging reservoir compression towards the end of the stance phase. Lastly, *Part 6* is a flip flop sole to create a steady base to walk on, protecting the reservoir, and the user from harmful inversion and eversion of the foot.

Important device features are highlighted in Fig 8, labeled A-C. *Feature A* is a square cut out of the base flip flop to allow for the bottom reservoir valve to be easily accessible. A small hand pump could then be used to inflate the reservoir if needed. The valve then sits flush with the bottom of the flip flop base ensuring it does not inhibit walking. *Feature B* is an elastic strap to curve the base flip flop upwards to prevent it from dragging or tripping the user. Lastly, *Feature C* takes the top reservoir valve through the hole left behind from the flip flop strap to actuate the actuator. A small piece of tubing to connect the valve and the actuator acts as the flip flop strap and rests comfortably between the user's toes.

Both a left and a right shoe were created to run experiments and test how effective the device is in providing assistance during walking.

C. Experimental Protocol

We performed a preliminary study that aimed to determine whether or not the device could reduce the effort of the human user while walking, and to quantify the effect of the device on the user's gait. Since the device could only be worn comfortably by a single person available to participate in our study, one subject's data from the experimental protocol is presented in this paper.

One, healthy female subject (age: 24) was selected as the preliminary subject for this study. The device used in the experiment was designed to fit this subject. From (1) and (2) and measurements of the subject's leg and foot length, an actuator of uninflated length (l_{min}) was selected to be 0.23m. The volume of air was found to be ~100mL for the given actuator length. Therefore the reservoir was designed to hold at least 100mL of air when fully inflated. The width and length of the reservoir, shown on A and B, in Fig. 5 are meant to fit under the subject's foot (US women's size 9 shoe), and hold approximately 100 mL of air to actuate the actuator.

The study required the subject to walk on a split-belt treadmill (Bertec Treadmill, Columbus, OH, USA) (Fig. 9A) in three different experimental conditions: baseline, passive, and active (Fig. 9B). The baseline condition was before the device was put on the subject. The passive behavior was when the device was placed on the subject but without the actuator connected below the knee. This condition meant that while the air in the reservoir was still able to move into the actuator, the device was not providing any torque about the ankle. Finally, the active condition was when the device was placed on the subject with the actuator connected and provided assistive torque about the ankle joint. As the subject walked in the active condition, the actuator would pull the foot upwards in dorsiflexion when it was not inflated, then as the reservoir was stepped down on at the end of the stance phase, the actuator filled with air and allowed the foot to plantarflect without having to overcome the stiffness of the actuator in its deflated state.

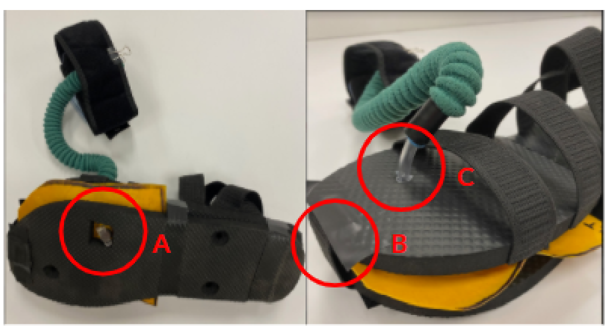


Fig. 8. Important device features. Features A-C display necessary device design points through easy access to the reservoir valve (A), an elastic strap to prevent tripping (B), and the actuator attachment to reservoir (C).

During all three experimental conditions, ankle angle data in the sagittal plane was collected by an electro-goniometer (Biometrics Ltd., Newport, UK). The goniometer was placed along the bottom of the ankle and captured data for dorsiflexion and plantarflexion. Electromyography (EMG) data was collected by surface EMG sensors (Delsys Inc., Natick, MA, USA) (Fig. 9C). The EMG sensors were placed on four muscles important for ankle motion: the tibialis anterior (TA), soleus (SL), medial gastrocnemius (MG), and peroneus longus (PL). As mentioned previously, the TA allows for ankle movement in the dorsiflexion direction, the SL and MG are for the plantarflexion direction, and the PL is for the eversion direction. While assisting motion in the frontal plane (eversion and inversion directions) is not a goal of our device, the PL EMG data was useful for understanding how the design of the device affects user's stability in the frontal plane. The PL data is not presented in this paper since it did not show any significant differences between the three experimental conditions.

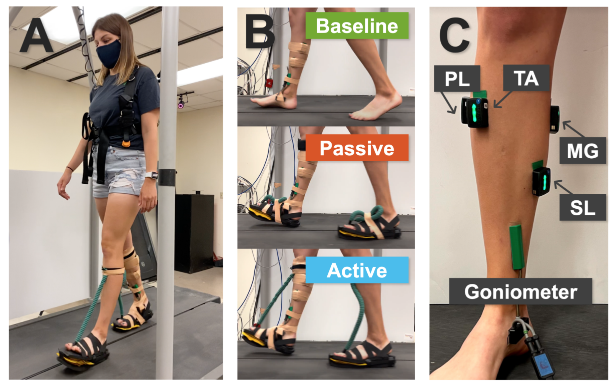


Fig. 9. The experimental set-up and conditions. **A**: A full view of the subject walking on the split-belt treadmill while wearing the device on both feet and sensors on the right leg. The subject wore a safety harness which did not bear any weight. **B**: Photos taken during the experiment in each of the experimental conditions. **C**: A close-up view of the sensors on the right leg. The four EMG sensors are indicated by the muscle that they correspond to, and the goniometer can be seen connected to the ankle.

Prior to the experiment, the subject was required to perform a maximum voluntary contraction (MVC) test whose data was used to scale the collected EMG data. The MVC test was performed based on typical muscle testing guidelines [15, 16]. With this collection of data, we were able to find the maximum activation specific to the subject so we could calculate the results in terms of a percent muscle activation compared to the maximum the subject was able to perform. Ankle position data was also collected with the ankle at known angles in the sagittal plane, which was used to convert the raw goniometer voltage signal to position data.

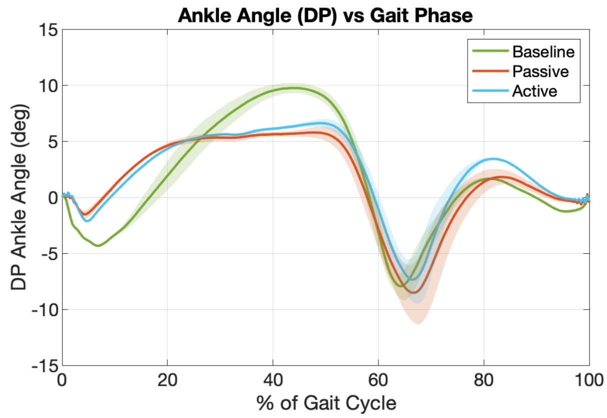


Fig. 10. The filtered angle position data in degrees over the gait cycle, with 0% corresponding to the heel strike. The darker, solid lines represent the mean of the sensor data for each stride and the lighter color around the line is the mean ±1 standard deviation (STD).

D. Data Analysis

The data collected from the experiment needed to be processed in order to make any conclusions about how the device impacted the subject's gait. Since only a single subject's data was collected for this preliminary study, the results were analyzed by looking directly at plots of the subject's ankle position (collected by the goniometer) and muscle activation (collected by the EMG sensors) for the three experimental conditions. From these plots, we could understand how the device impacted the subject's position and muscle activation responses throughout the gait cycle.

Before the plots could be generated, an important consideration was how to filter and scale the data collected from the goniometer and EMG sensors. The filters for both the goniometer and EMG sensor data were selected based on previous work on designing active AFOs for providing assistance while walking [17]. The goniometer data was filtered using a 2nd order Butterworth low pass filter with a cutoff frequency of 10 Hz and fit to calibration data. The EMG data was demeaned, rectified, and filtered using a 2nd order Butterworth low pass filter with a cutoff frequency of 5 Hz, and scaled by MVC. By scaling by MVC, the voltage information collected from the EMG sensors could be considered as a percentage of the subject's highest possible effort for each muscle.

The force data collected from the split-belt treadmill was used to identify the heel strike of each stride for the right leg. With this information, the plots of the average ankle position and muscle activation could be created by overlapping the data corresponding to each stride of the gait cycle. These plots are in the following section, and are used to understand the effect of our device on the subject's gait.

IV. Results and Discussion

The effect of the device on the subject's gait will be considered from the average position results for the subject, shown in Fig. 10. The baseline results show the expected curve for the subject's ankle angle over time. When this curve is compared with both the passive and active conditions, it is clear that there are some differences in the subject's ankle angle throughout the gait cycle. However, some of the effects can be attributed to the design of the reservoir and shoe components of the device, while other effects can be attributed to the actuator/PAM.

First considering the position results during the stance phase (between 0 and 60% of the gait cycle) there is a strong indication that the design of the reservoir and surrounding shoe caused a difference in how the subject's ankle was able to move. Compared with the baseline condition, both the passive and active conditions show similar results during the stance phase, with the subject moving their ankle less in both the dorsiflexion and plantarflexion directions. This result can be attributed to the wedge shape of the shoe which likely caused the subject to rely on the shape of the shoe rather than the bending of their ankle to transition between heel strike and toe off. The addition of a shoe to a person's foot will inevitably change their ankle movement, but this result gives some indication that a goal of future designs should be to make the shoe and reservoir thinner and flatter.

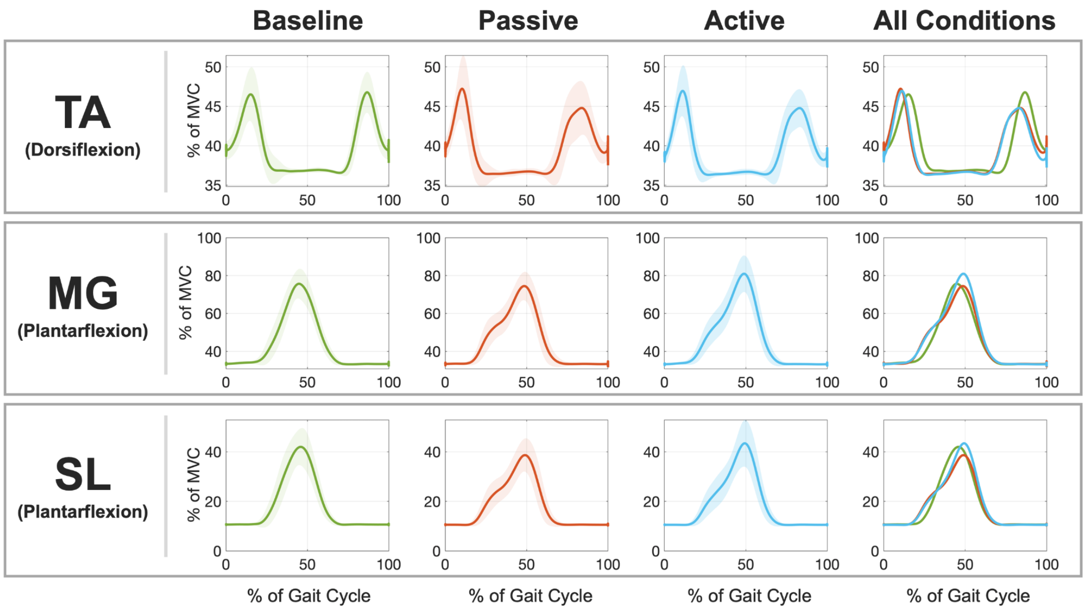


Fig. 11. The filtered EMG data in % MVC over the gait cycle, with 0% corresponding to the heel strike. The darker, solid lines represent the mean of the sensor data for each stride and the lighter color around the line is the mean ±1 standard deviation (STD).

Next, the position results during the swing phase (between 60 and 100% of the gait cycle) indicate that the subject's ankle movement during swing was affected by the actuator. While the baseline and passive results follow similar curves during the swing phase, the active condition results demonstrate that the actuator did provide torque about the ankle joint in the positive direction during the swing phase. For applications like helping those with foot drop, this result is promising as it demonstrates that the stiffness of the actuator is substantial enough to pull the toes up in dorsiflexion during the swing phase.

Now, the muscle activation results collected by the EMG data will be discussed. The plot in Fig. 11 shows these results separately and overlapped for each condition and muscle of interest. Due to the inherent noisiness of EMG data and high variability, it is difficult to make any strong, quantitatively-backed conclusions, but there are some important differences seen from the muscle activation results that will inform future designs.

First, the muscle activation results for the TA muscle indicate an effect of the shoe design on when the subject was activating their TA muscle and a possible reduction of effort caused by the actuator. Comparing the baseline results with those of the passive and active conditions, there is a noticeable time shifting of when the TA muscle is activating that was likely caused by the shoe design. Most likely, the thickness of the shoe changed the time when the subject's foot was in the air versus on the ground, therefore shifting the times when the subject would dorsiflect. The other result of the reduction in effort caused by the actuator can be seen near the end of the swing phase where the active condition curve is lower than the curves of the other conditions. While this reduction in effort is low, this information, coupled with the position results previously discussed, is a positive result showing that the device allowed for an increase in dorsiflexion motion but at a reduced effort. It is also possible that if the subject were given more time to acclimate to the device during before the active condition experiment, there would be a greater reduction in TA effort and a smaller increase in motion in the dorsiflexion direction.

Finally, the muscle activation results for both the MG and SL muscles indicate that there may be a slight increase in effort caused by the actuator. As mentioned previously, the goal of our device is to provide dorsiflexion assistance during the swing phase, but then to allow the user to plantarflect properly during the end of the stance phase when the actuator fills with air and becomes longer. The slight increase in muscle activation seen in the active condition results indicates that the current placement of the reservoir under the foot is not ideal. More specifically, it appears that while the actuator was long enough when inflated to allow for uninhibited plantarflexion motion, the actuator may not have been inflating soon enough in the gait cycle, and therefore the subject had to overcome the stiffness of the deflated actuator for a short period of time, causing an increase in muscle activation.

Taken together, the results demonstrate the device being effective in providing dorsiflexion assistance during the swing phase, but also indicate some changes to the design to make the system more transparent during the stance phase and actuate at the correct time. These preliminary results indicate that designing a thinner, flatter shoe with the reservoir further back on the foot would be a good candidate for the next design iteration of our device.

Some comparisons can be made between these results and the results of other devices that have been designed for helping people walk. Previous research has shown that non-robotic AFOs (like those for foot-drop) can often provide assistance for one direction of motion, but at the expense of requiring an increase in effort in the opposite direction [18]. By improving the reservoir placement of our device, we could alleviate this trade-off by changing the actuator's length and stiffness during the correct time of the stance phase.

Like state-of-the-art, robotics solutions for helping people walk [4, 8-9], our device was able to use a PAM in parallel with the human muscles to actuate at certain times by identifying different gait events. However, our device did not require any expensive sensors, power sources, or heavy equipment for the user to carry, so our device is much more lightweight, practical, and accessible than current state-of-the-art robotic devices.

V. Conclusion and Future Direction

Our inexpensive and accessible design of a pneumatic system that is actuated by the user's weight worked to assist the user's dorsiflexion while walking. The device parallels the robotic and dynamic devices seen on the market and in recent research, but at a lower cost to users. This design can be applicable to a wide range of markets whether it is utilized by people who hope to reduce the efforts needed while walking, people who need extra assistance with dorsiflexion because of an injury, or even space exploration applications. The design presents a solid baseline with many different applications within different industries.

The testing and results highlighted some design flaws that should be improved upon for future design iterations. The footbed did not provide proper support throughout the gait cycle as the elastic straps stretched and allowed the wearer's foot to slide. The strap material and layout can be adjusted to reduce slipping and improve the effectiveness of the system in future iterations.

The preliminary results also gave insight into some adjustments that should be made for the reservoir design and placement. Creating a thinner, flatter reservoir that is placed further back under the foot could aid in reducing walking efforts throughout the whole gait cycle compared to the current design that is optimized to reduce dorsiflexion efforts. It would also be beneficial to create a device that can fit a wider range of foot sizes in the future opposed to the current design which was optimized for a single foot size. The current design and any future iterations should be tested and directly compared against other devices on the market.

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6.1.b MAE598 Final Presentation Slides

Design of a Soft, Passive Wearable Ankle Device

Team 4

James Arnold, Rebecca Red Horse, Priscilla Lamas, and Jacob Sindorf

Introduction

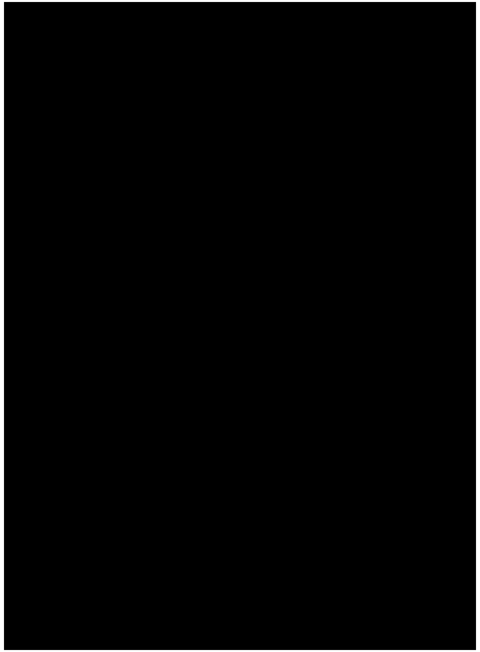
- How can we design a **low cost, soft, wearable ankle device** that is actuated passively by the human user’s weight to **reduce human effort required while walking**?


Introduction — Bio-inspiration

- Human skeletal muscle
    - Pneumatic actuators can achieve similar output

Human Muscle

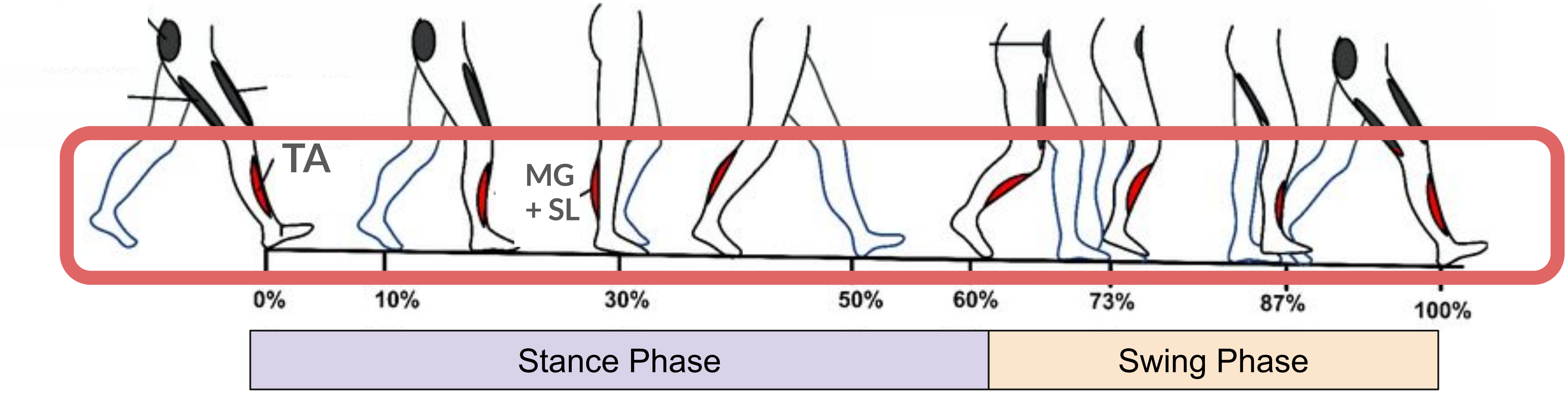
McKibben Air Muscle



Our Pneumatic Actuator

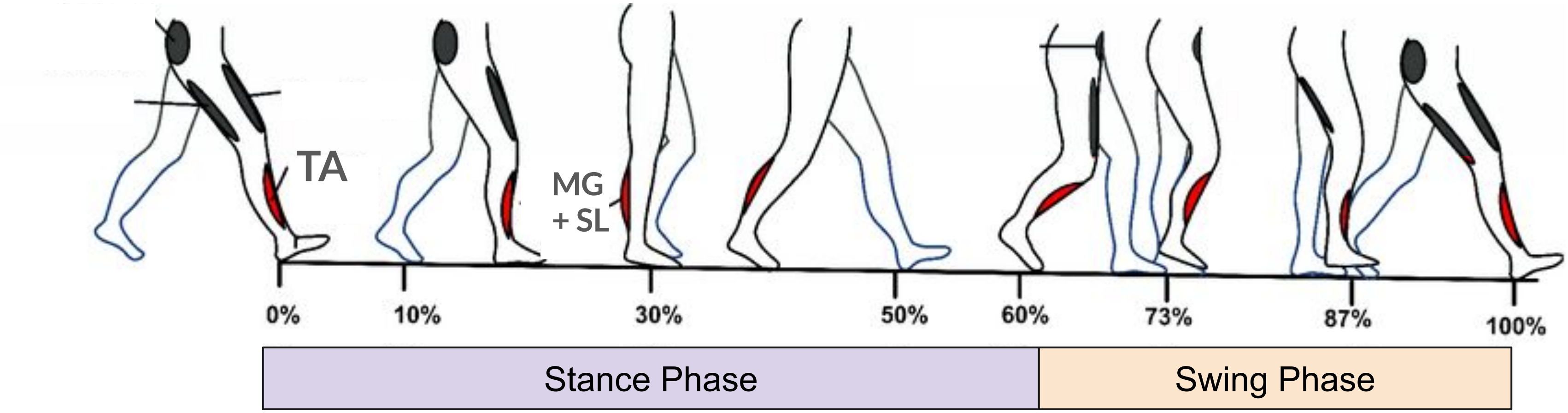
Introduction — Human Muscles during Gait

- When is a human putting in muscle effort into while walking?



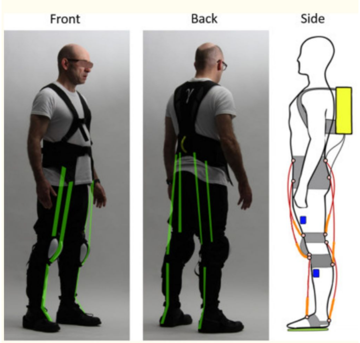
Introduction — Human Muscles during Gait

- When is a human putting in muscle effort into while walking?

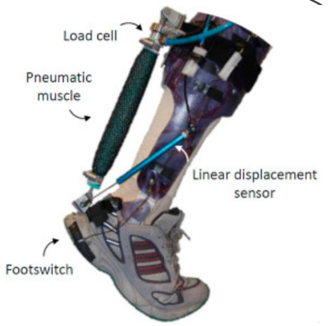


Introduction — Devices Assisting in Walking

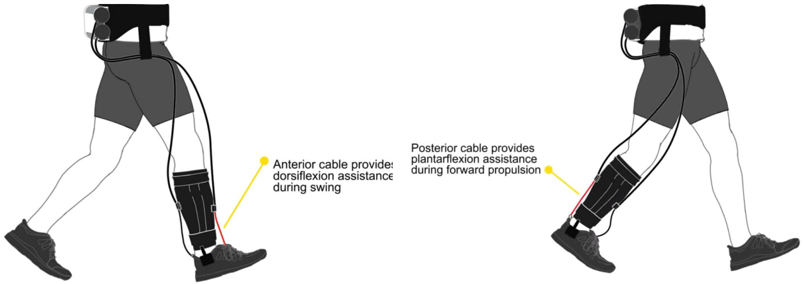
Robotic Devices (State of the Art)



Lower Limb
Exoskeleton [1]



Plantar-flexion
Assistive Exosuit [2]



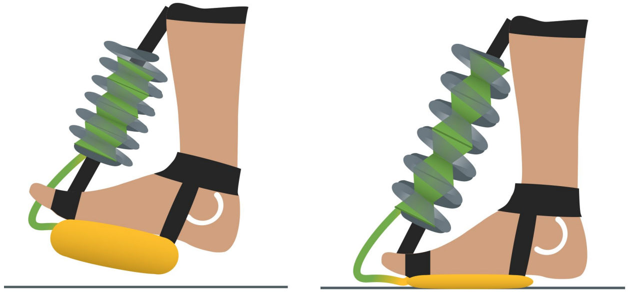
ReWalk Robotics- ReStore Exosuit [3]

Non-Robotic Devices

Foot Drop AFOs

Our Device

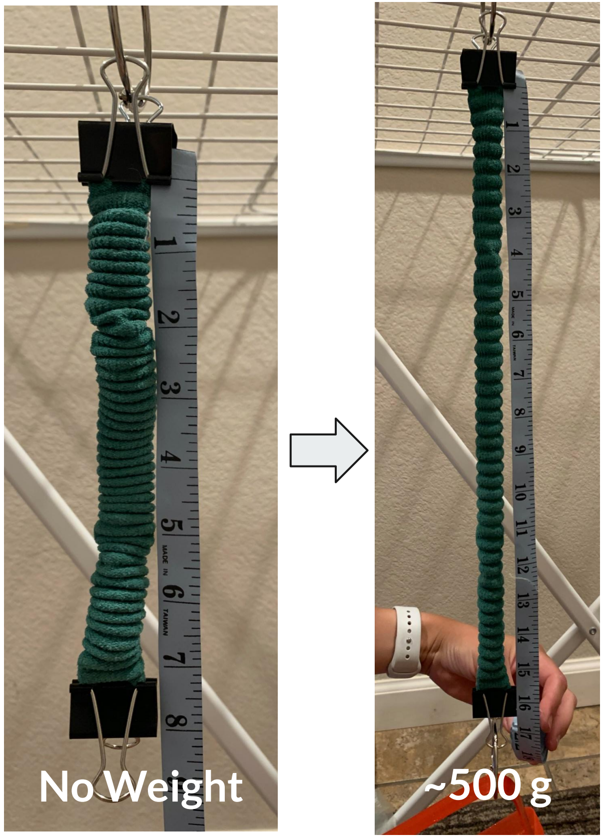
- Instead of electronics/sensors, we propose to use a **closed pneumatic system** to identify gait events and turn on and off our **pneumatic muscle**
  - Apply robotics research on pneumatic muscles to a low cost device



Methods — Actuator Modeling

- Model our pneumatic muscle to make design decisions

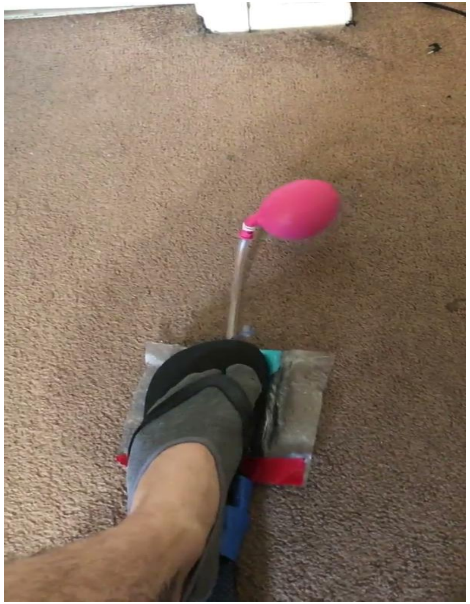
Volume Measurements



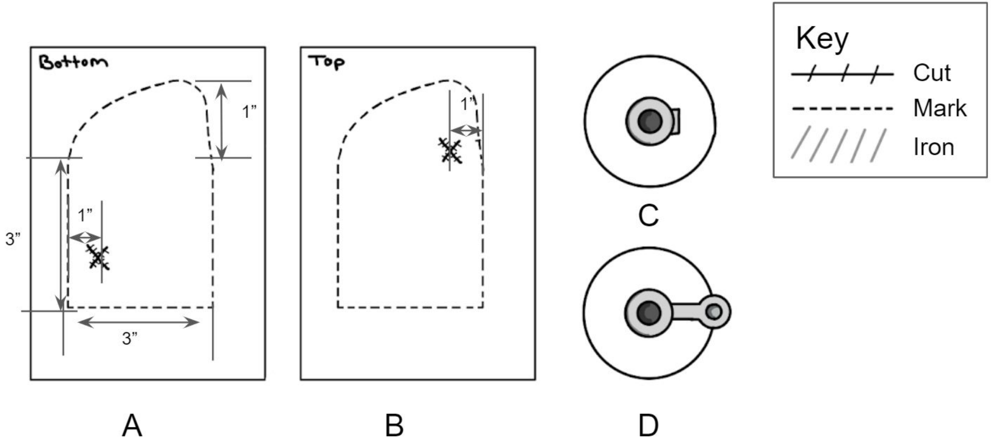
Stiffness Characterization

Methods — Reservoir Design Iterations

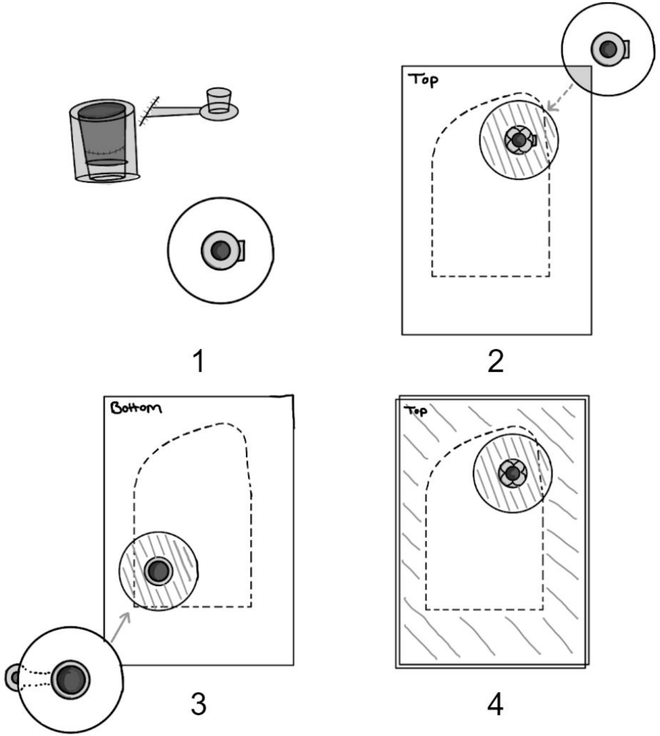
- Used volume measurements required for actuator to **choose reservoir size**
- Reservoir placement based on muscle activation



Methods — Reservoir Design Final

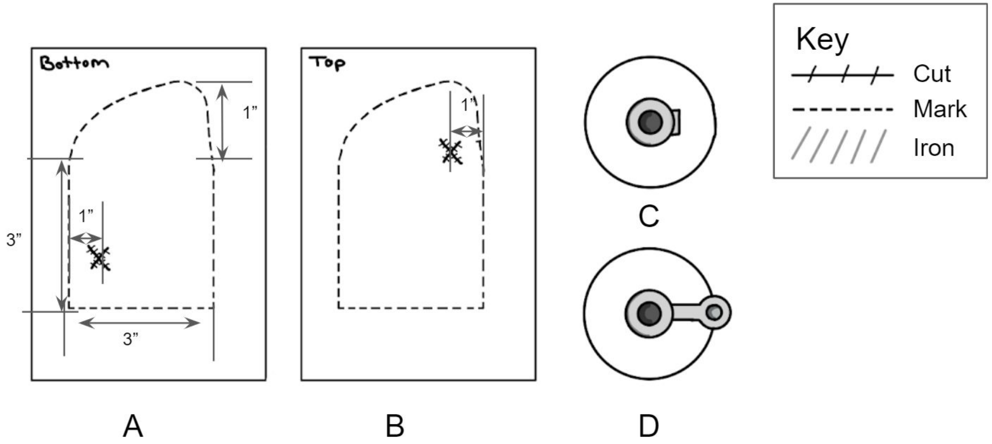


Parts of the Assembly

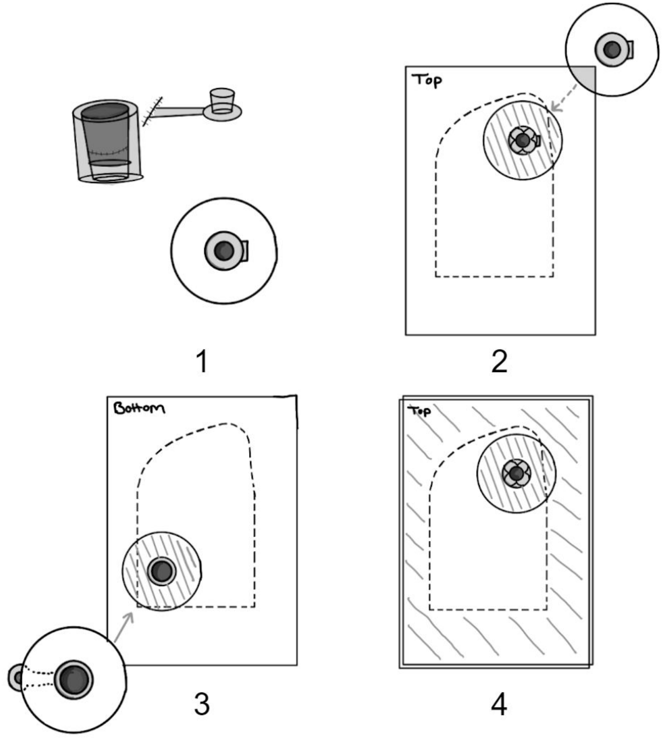


Manufacturing Steps

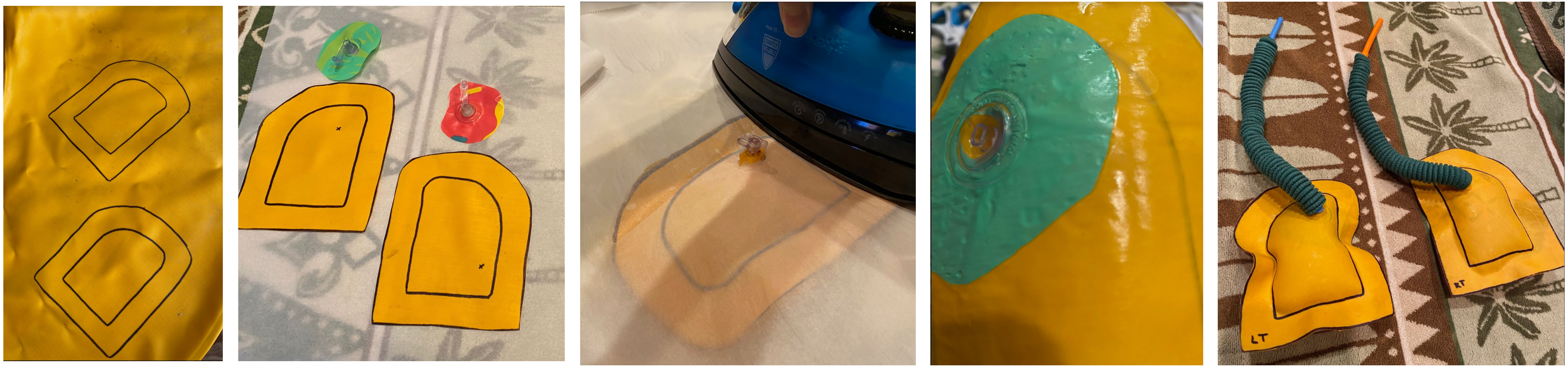
Parts of the Assembly



Manufacturing Steps

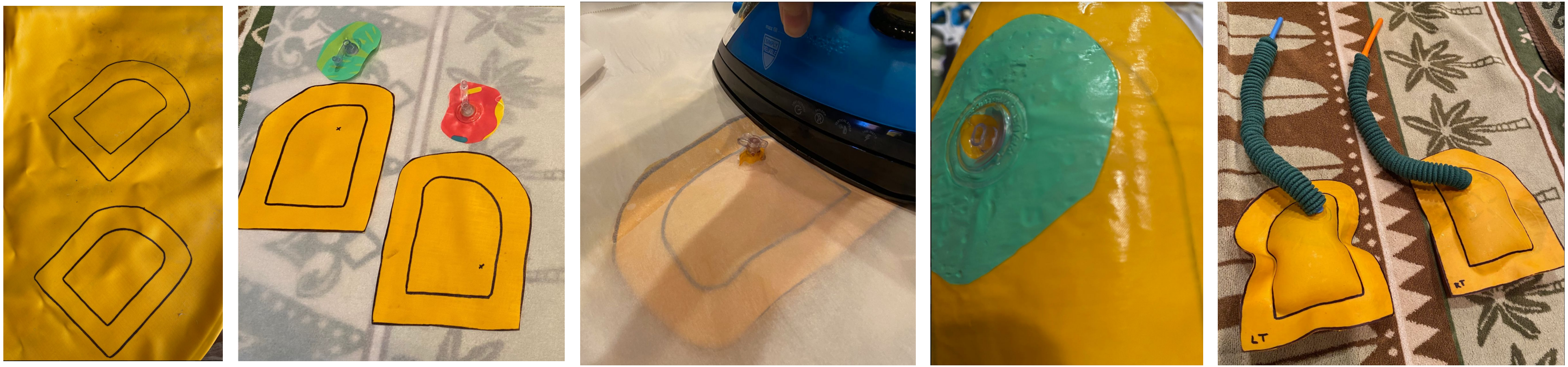


Methods — Reservoir Design Final



Outline → **Cut** → **Iron** → **Assemble**

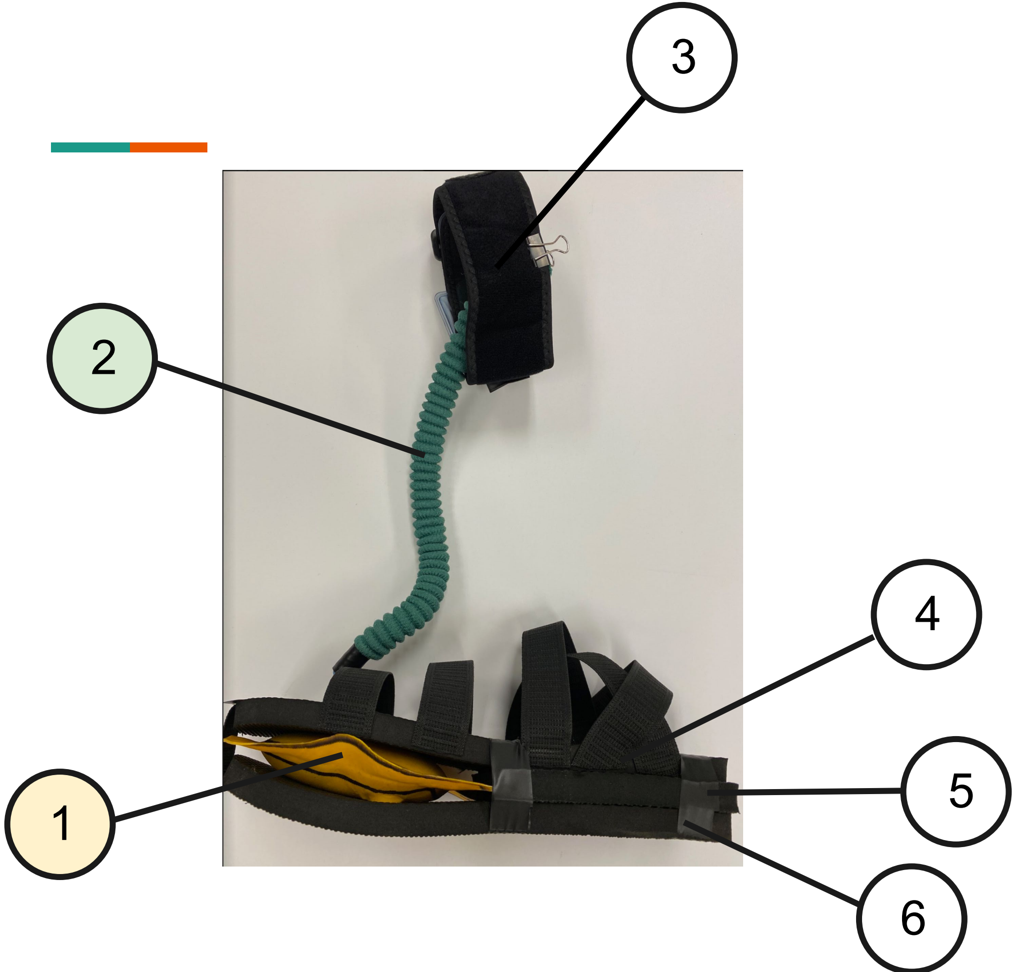
1.5 hrs of Manufacturing Time



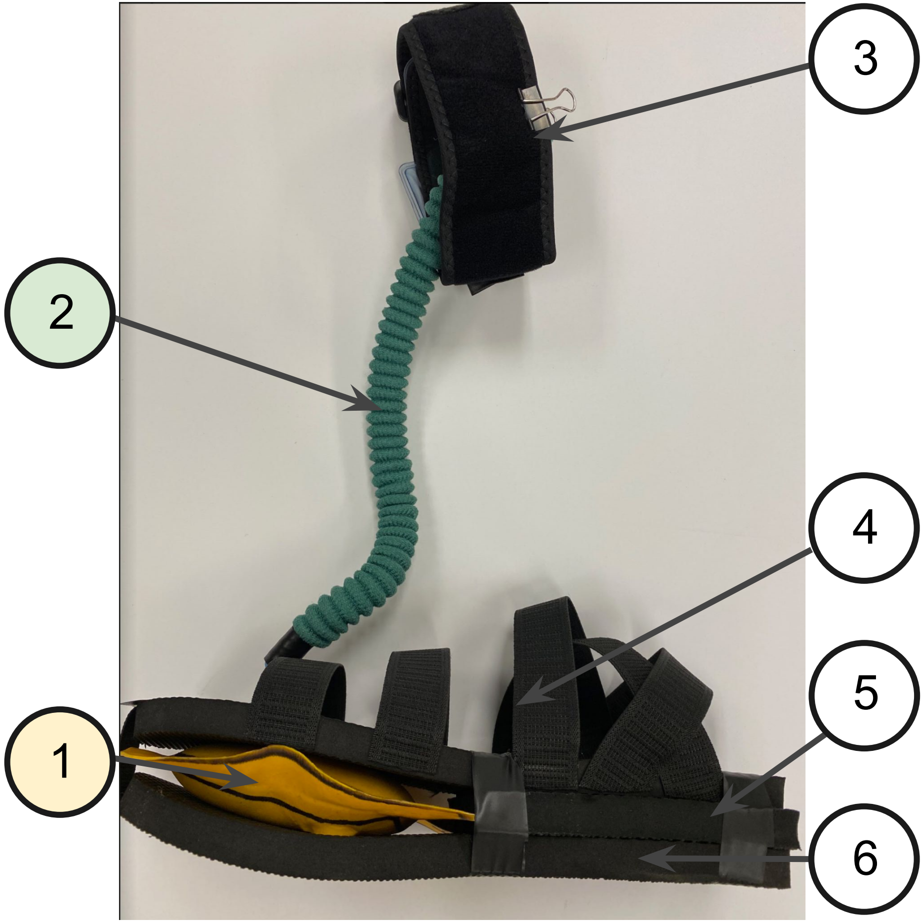
Outline → **Cut** → **Iron** → **Assemble**

1.5 hrs of Manufacturing Time

Methods — Full Assembly



Bill of Materials	
#	**Part Name**
1	Reservoir
2	Actuator
3	Velcro Strap
4	Modified flip flop with elastic straps
5	Wedge spacer
6	Modified flip flop base

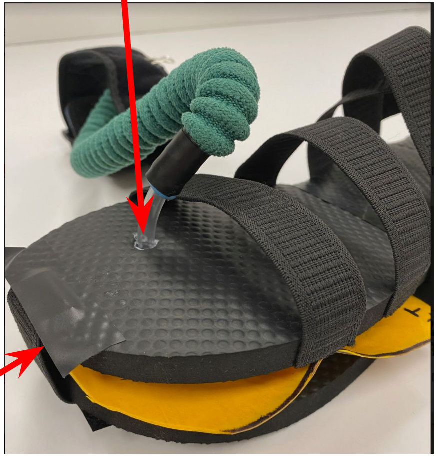


Bill of Materials	
#	**Part Name**
1	Reservoir
2	Actuator
3	Velcro Strap
4	Modified flip flop with elastic straps
5	Wedge spacer
6	Modified flip flop base

Methods - Features

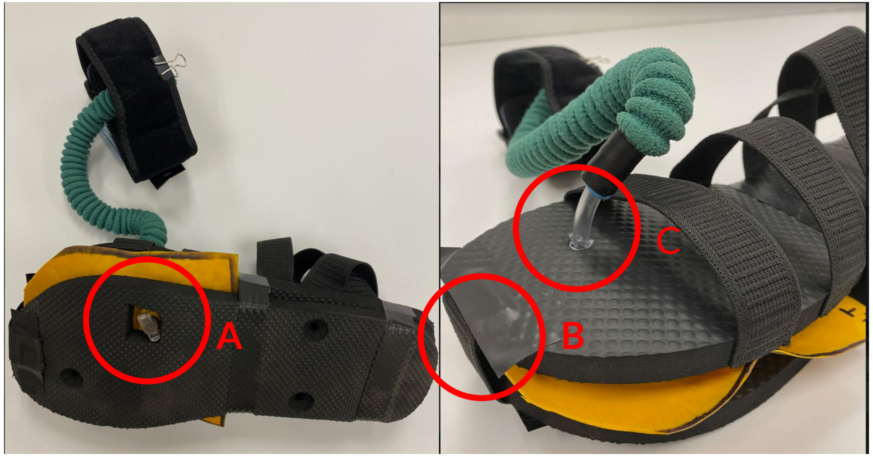
Cut out to fill reservoir with air (flush with flip flop)

Actuator attachment to reservoir mimics flip flop



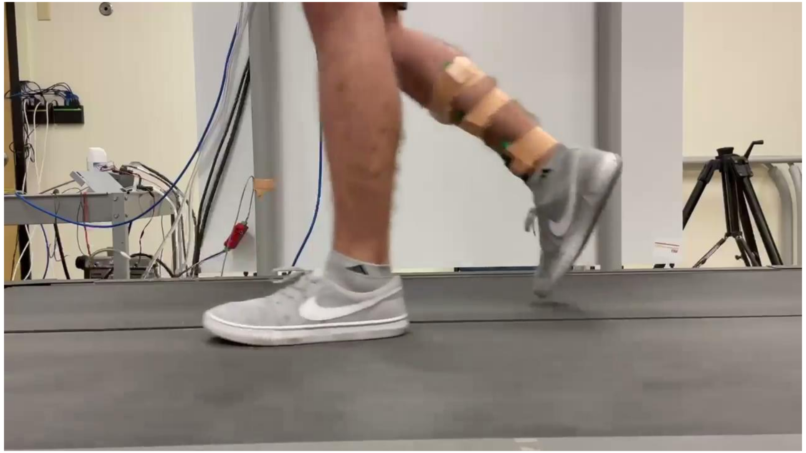
Elastic limit strap (to prevent tripping)

Methods - Features



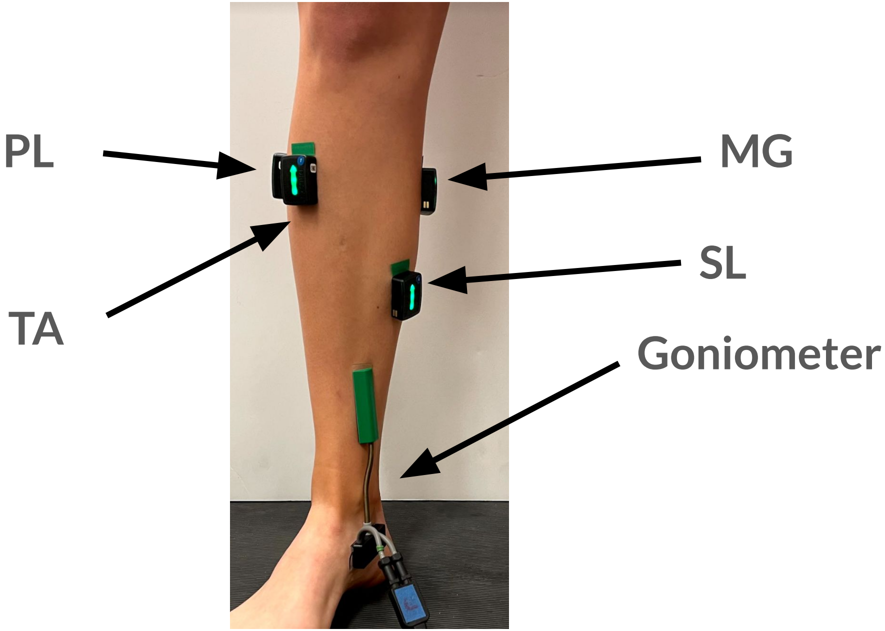
Experimental Design — Preliminary

- Setting up experiment
- Restrictions
- Device is not one size fits all



Methods — Experimental Protocol

- Collected MVC measurements and calibrated goniometer

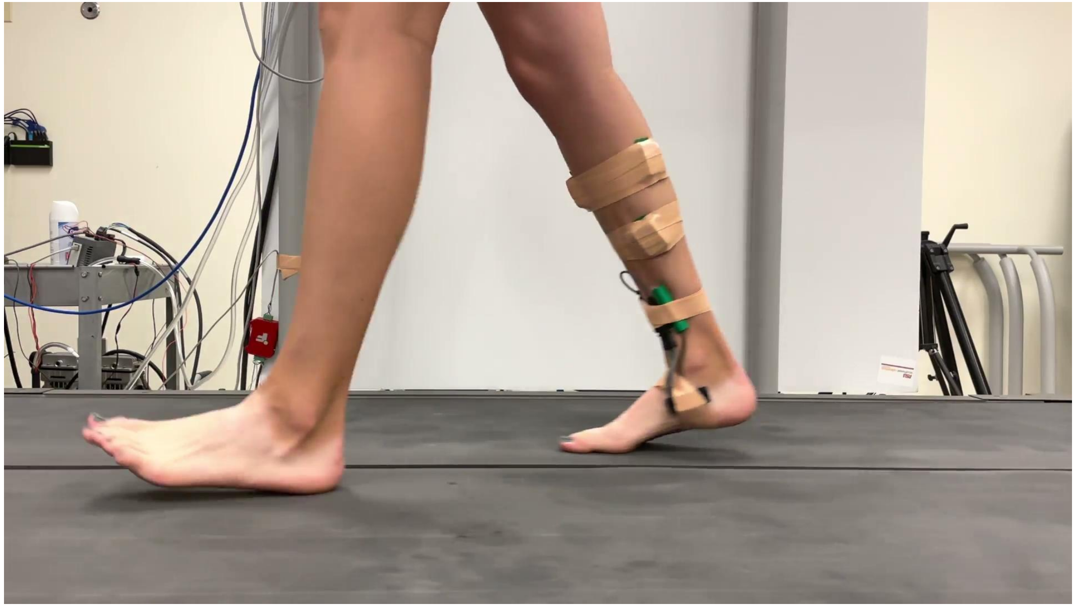


Three Experimental Conditions

(3 min each)

Results — Demo

Baseline *Walking barefoot*



Results — Demo

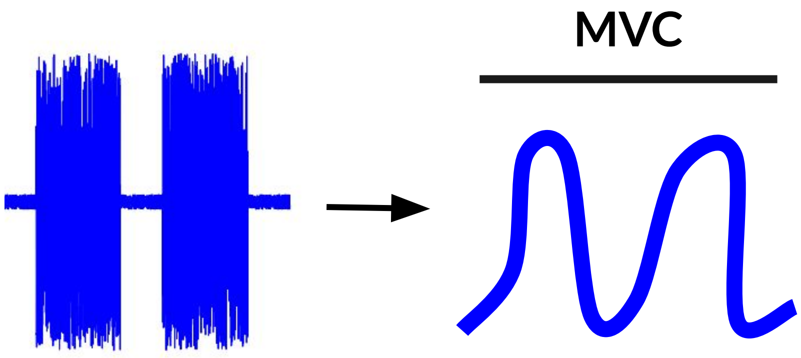
Passive *Actuator disconnected*

Results — Demo

Active *Actuator connected*

Results — Data Processing

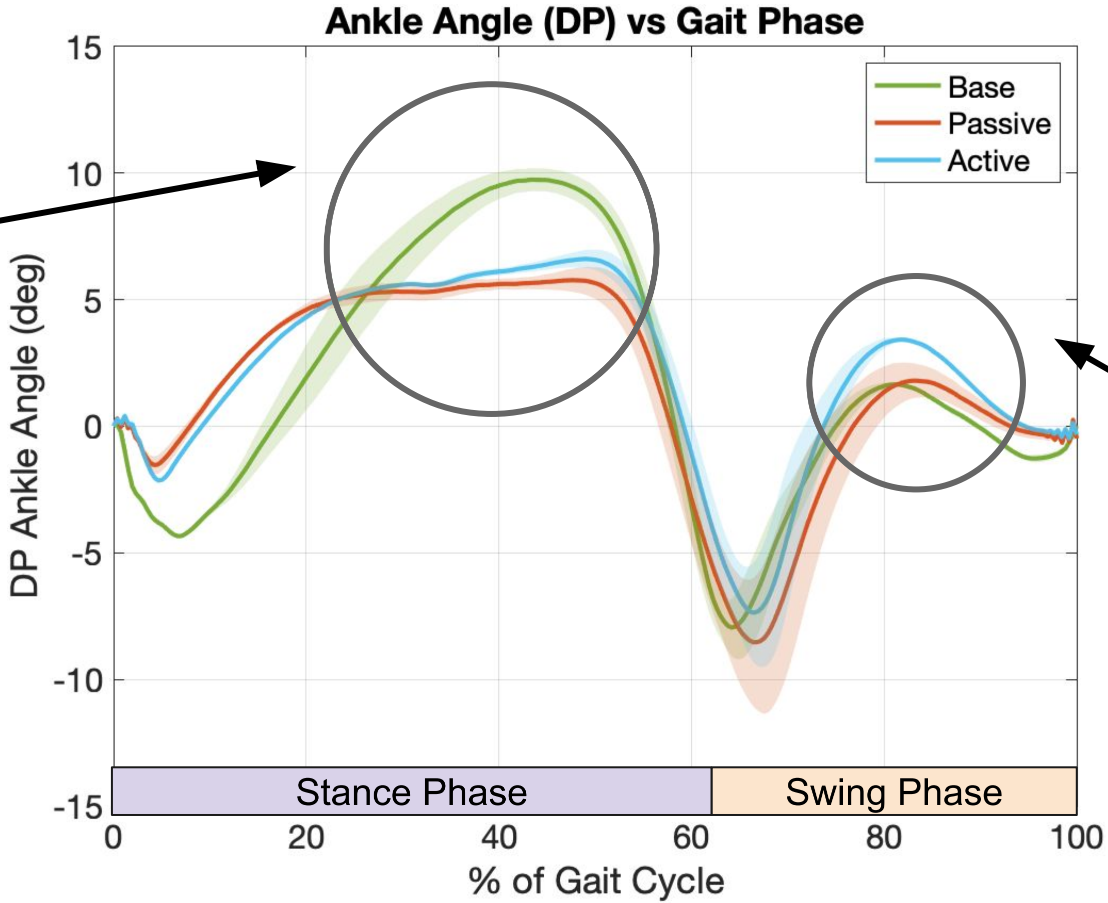
- EMG and goniometer data filtered/scaled using filtering techniques found in previous gait studies [4]
- Analysis code identifies heel strike from force plate data
    - Each step can be overlapped to find mean response



Visualizing EMG Filtering

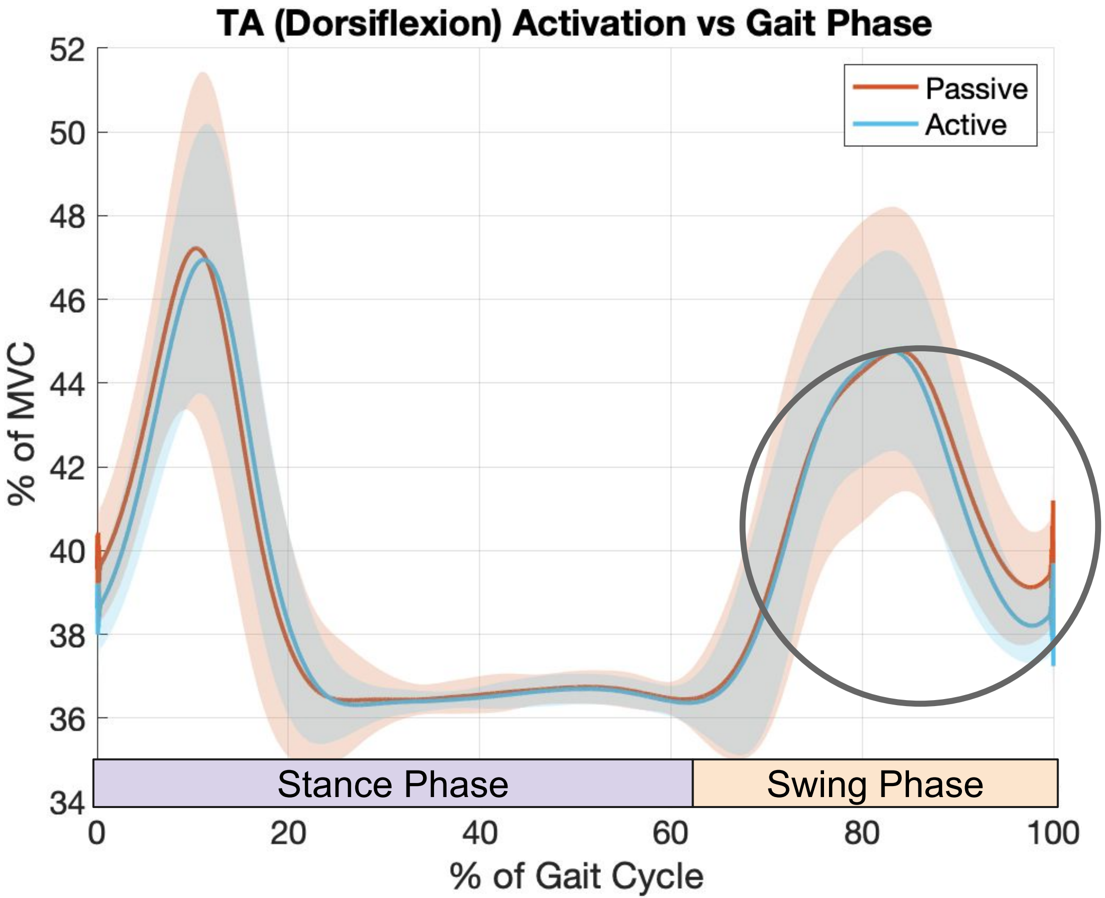
Results — Ankle Angle

Reservoir placement during stance affected gait



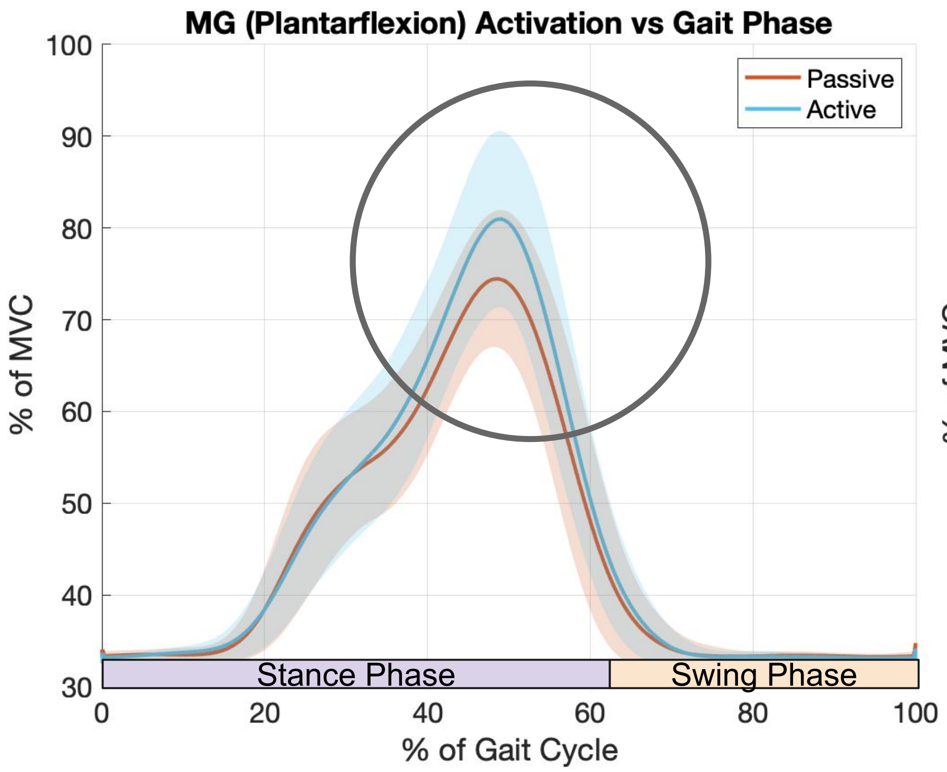
The actuator increased dorsiflexion during swing

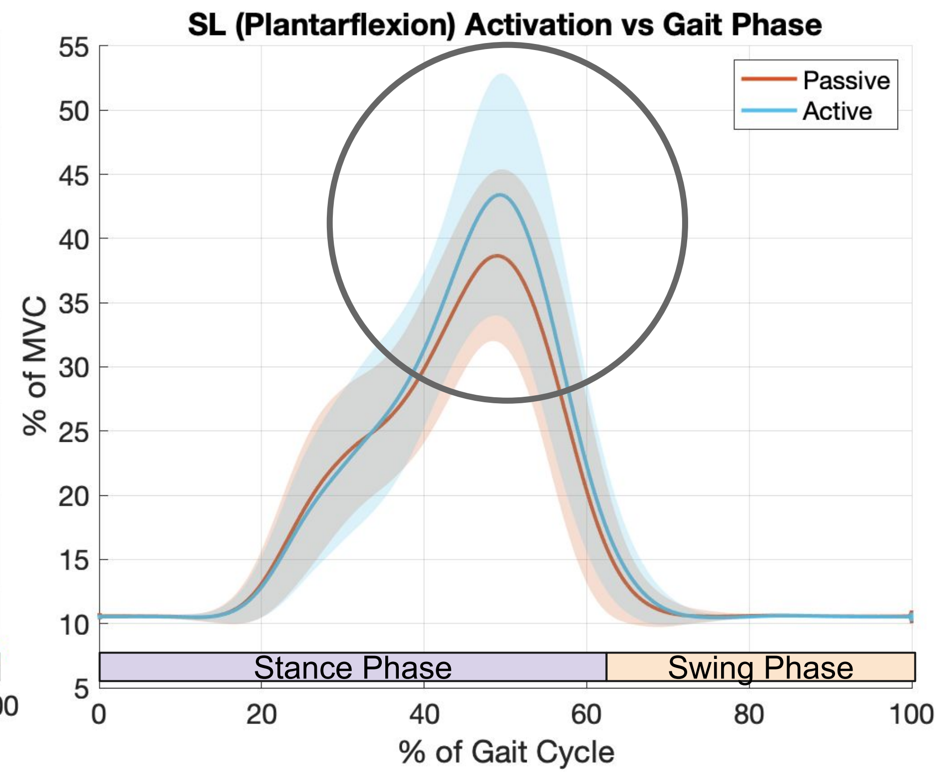
Results — Dorsiflexion Muscle Activation



Some reduction in effort during swing

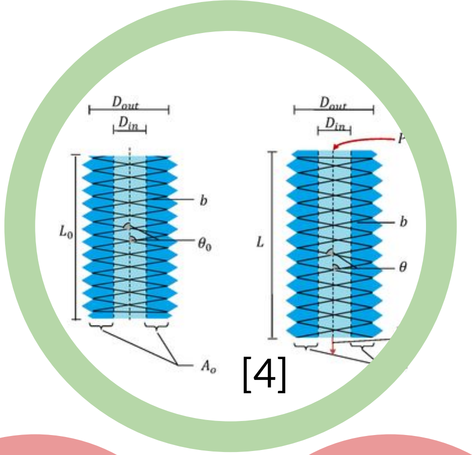
Results — Plantarflexion Muscle Activation





Discussion — Comparing Our Results

- Effect of common AFOs: “several persons tried to plantarflex their ankles during toe-off, although they were restricted in this direction by the AFO” [5]
- We created a low cost **pneumatic artificial muscle** device without subjects carrying air compressors/motors in a **backpack** or **tethered system**

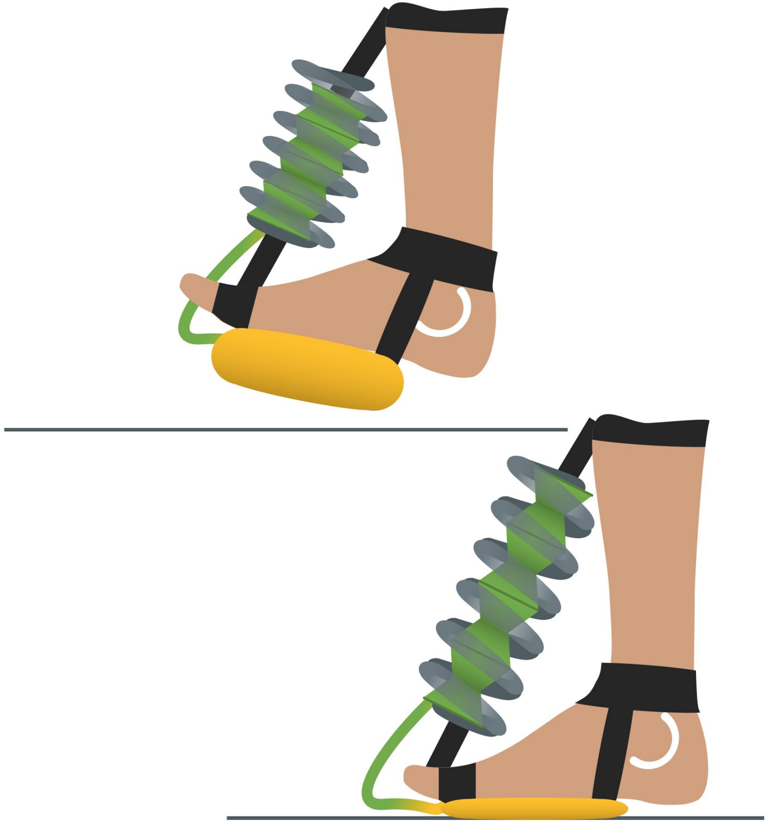


Future Work

- Improve design
  - Shoe design, reservoir placement
  - Material selection
- Gather data from more subjects
  - This was difficult since we made one sized shoe
- Directly compare to other affordable braces on the market

Conclusion

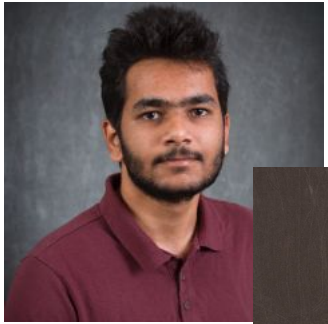
- Viable design to assist dorsiflexion
  - Real-world application
- Create inexpensive and accessible prototype
- This concept could be expanded upon to create untethered, soft wearable robots



Acknowledgments

Thank you to...

- Omik for helping us run the experiments and teaching us how to perform analysis
- Dr. Lee for letting us use the lab equipment
- Dr. Marvi for his guidance on our project



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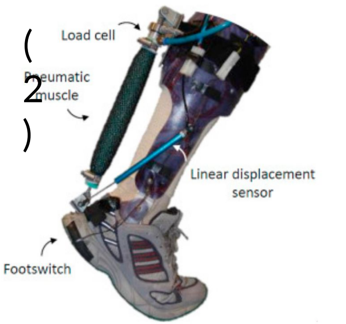
Questions?

Introduction - State of the Art

- Similar designs
- State of the art devices (quick review)

(2)



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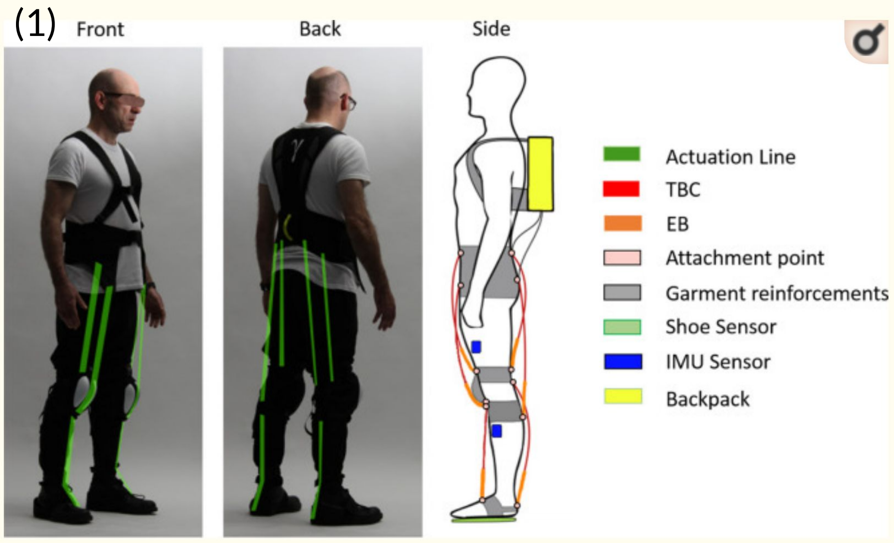
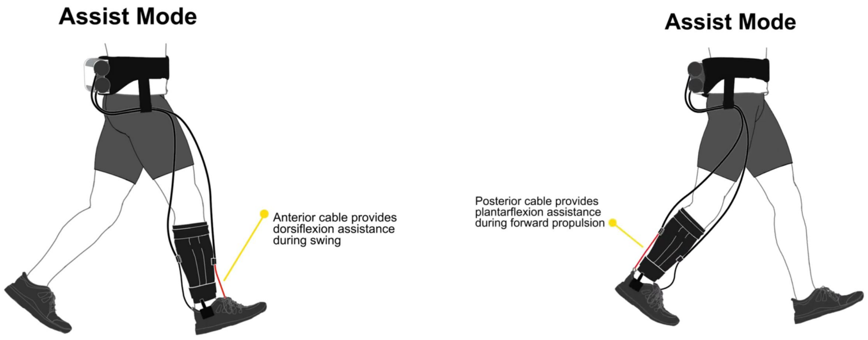


(2)

ReWalk Robotics:
ReStore Exosuit



Final Presentations:

The final presentations will be online only and will be held on 4/19/21 (12-1:15 pm), 4/21/21 (12-1:15 pm), and 4/28/21 (12:10-2 pm). We will follow the same order of teams that we used for midterm presentations. Each team will have 15 minutes to present the project with additional 5 minutes for questions. A live demo of the final physical prototype/program is highly recommended. If a live demo is not possible (with justified reasons), there should be videos showing the performance of the robot.

The recommended topics to be discussed during the final presentations are as follows:

- **Introduction:**
    - The bio-inspiration process (state the problem and why it is important, model organism, inspirations taken towards design and control of the robot)
    - Quick review of the state of the art
- **Methods:**
    - Discuss the design and fabrication of the prototype/code development
    - Discuss the testing procedure
    - Discuss any modeling performed
- **Results and Discussion:**
    - Show a live demo (or videos of the robot)
    - Present results (experimental/simulations)
    - Discuss the results and compare to the literature, do the results make sense? lessons learned, challenges
- **Conclusions and Future Directions:** Summarize your work and discuss potential future improvements

6.1.c EGR 557 Final Presentation Slides

Team 5- Final Presentation

Members:

Gilgal Ansah
Javon Grimes
Jonathan Nguyen
Jacob Sindorf

Refined Research Question:

"How can foldable techniques translate a small number of actuators into unique locomotion?"

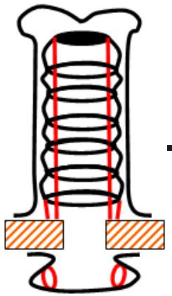


Figure 1: Tube foot (podia) bioinspiration [1]

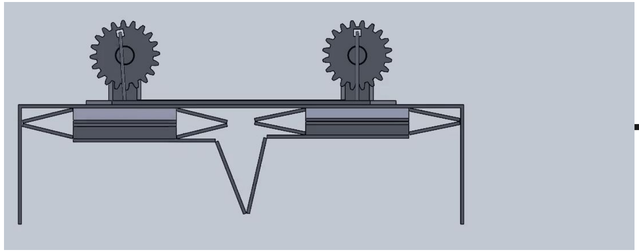


Figure 2: Conceptual device drawing

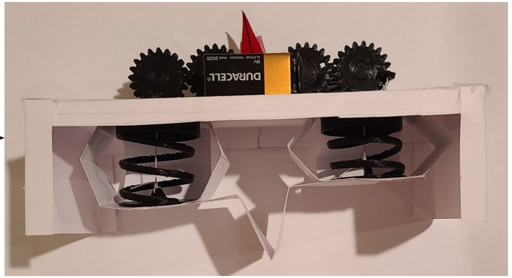


Figure 3: Final Device Design

Manufacturing

1 Sheet VS 5 Sheet

Pros
- More easily cut out of single large sheet
- Simpler hinges
- Easier to create digitally

Cons
- Flimsier depending on materials
- Requires added spring
- Perforated hinges more subject to degradation
- Less versatility

Figure 4: 1 Layer Design

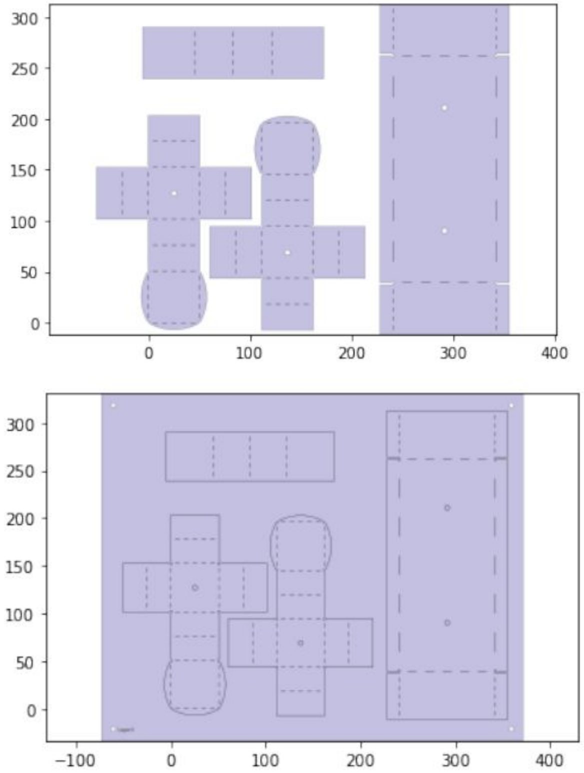
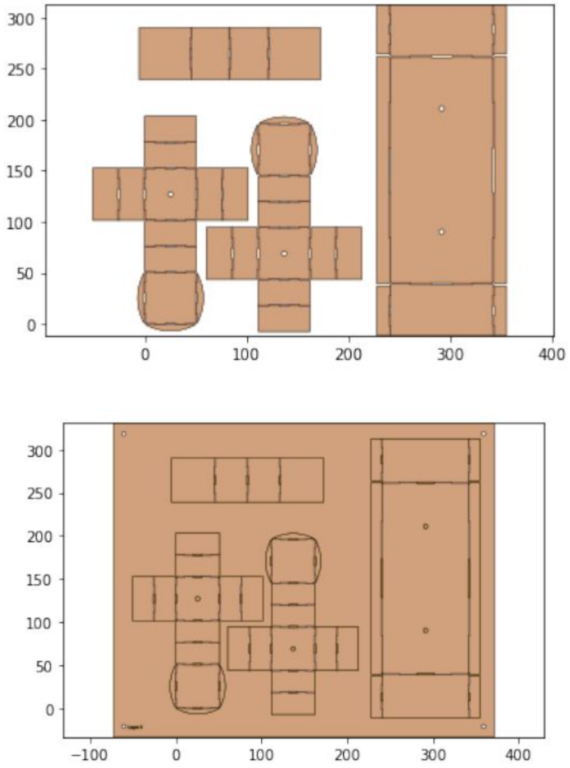


Figure 5: 5 Layer Design



Manufacturing- Use in Design

Figure 6: Single layer leg

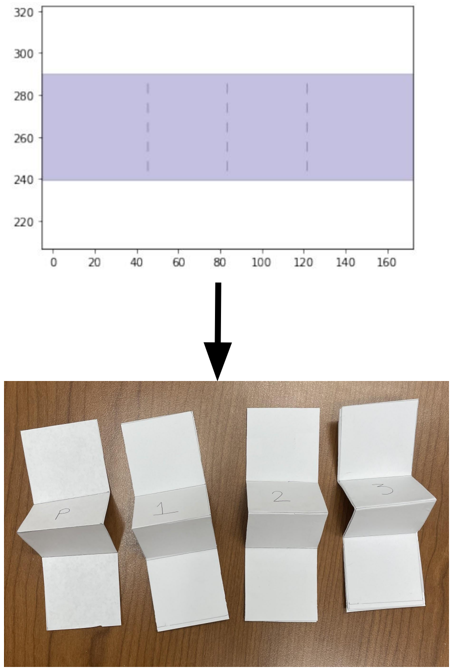


Figure 6: Single layer sarrus linkage

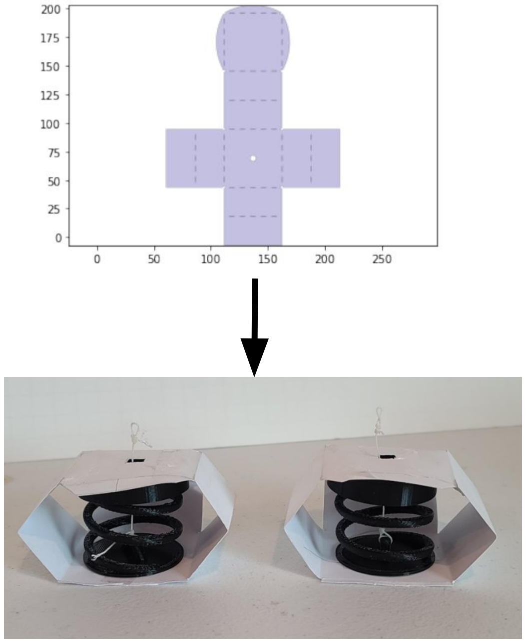
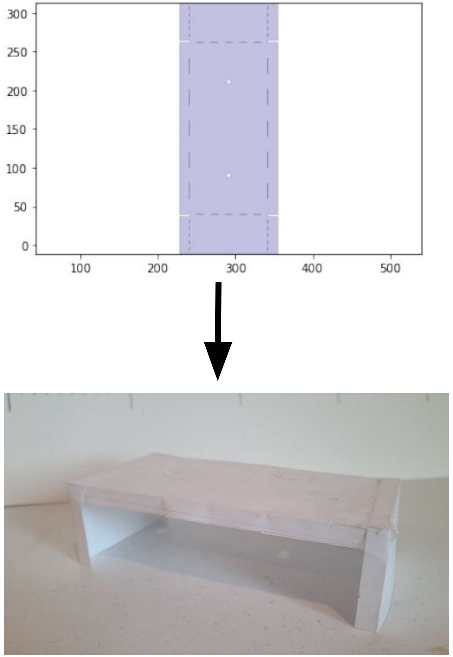


Figure 6: Single layer outer frame



- 1 Layer design used in actual device
- Pieces cut with scissors from cardstock sheets
- Scoring not necessary → cardstock is easily folded

Optimization

Dynamic model

- Updated with position/time plots
- Measures effectiveness of movement
- Constraints
  - Stability of movement
  - Amount of movement
- .3 and .6 had best results with .9 dropping in distance
  - Test values of .3 to .9 to find optimal value

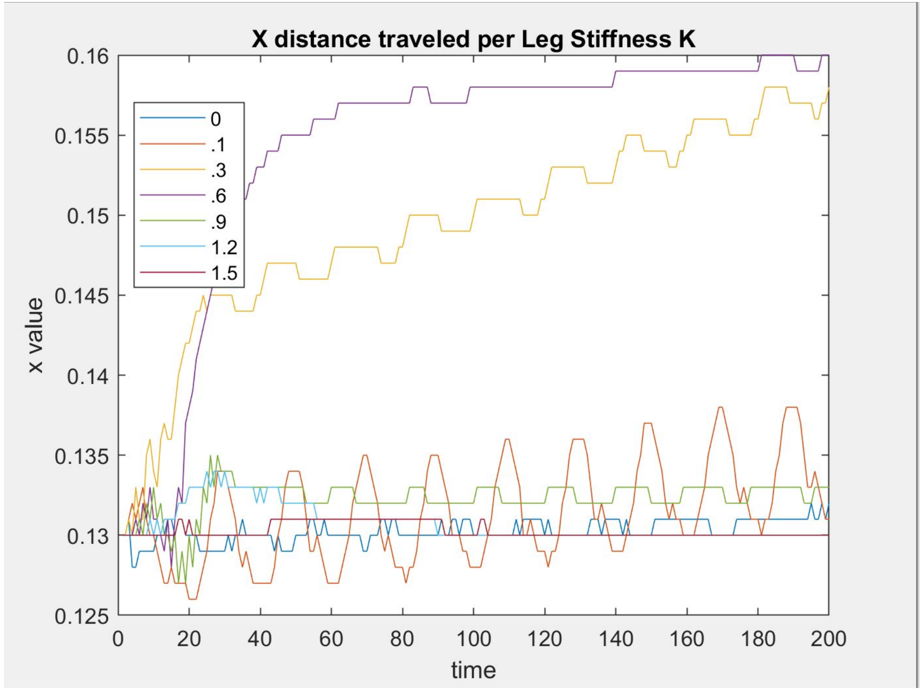


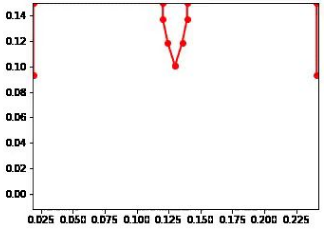
Figure 9: Varied stiffness values and their overall distance traveled

Optimization

Design Optimization

- Found .8 to be the most optimal stiffness
- Comparing .8 and 1.5 shows the device traveling in x
- Middle value is most optimal (not the most flexible or most rigid)

1.5 N/m Stiffness



0.8 N/m Stiffness

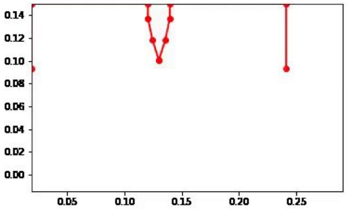


Figure 10: 1.5 (worst) stiffness vs 0.8 (best) stiffness

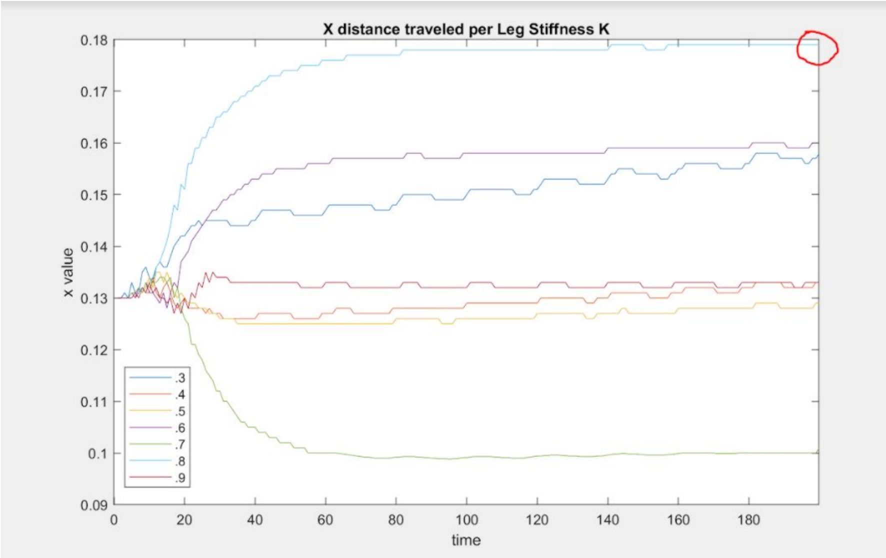
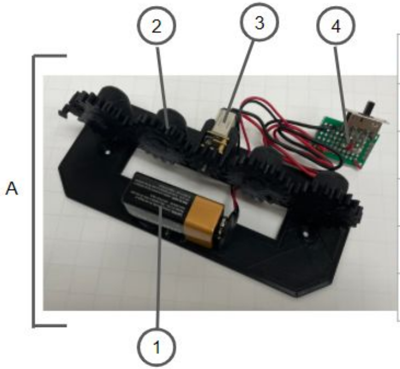


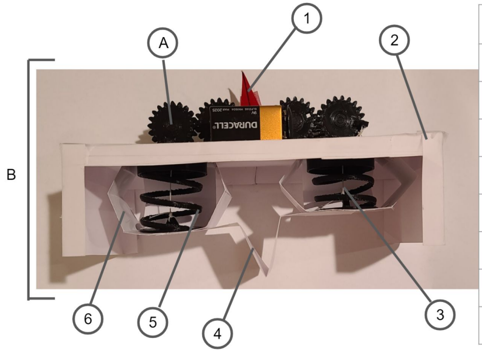
Figure 11: Optimal stiffness value range (.3 to .9) and their distance achieved

Experimental Validation - System Assembly



System A: Single Actuator Gear Hat	
#	Name
1	9V battery
2	3D printed gear hat
3	12V DC gear motor
4	Circuit + switch

Figure 12: Gear hat assembly



System B: Cardstock Leg Robot	
#	Name
A	Single Actuator Gear Hat
1	Flag
2	Cardstock frame
3	String cable
4	Leg (various materials used)
5	3D printed spring
6	Cardstock Sarrus Linkage

Figure 14:Device assembly

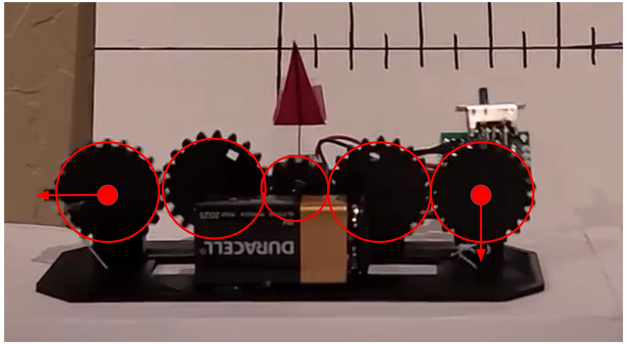


Figure 13: Gear design and ¼ offset

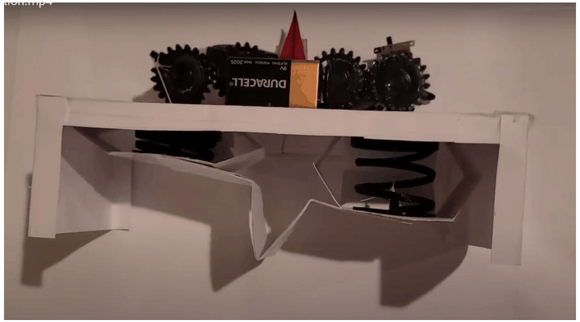
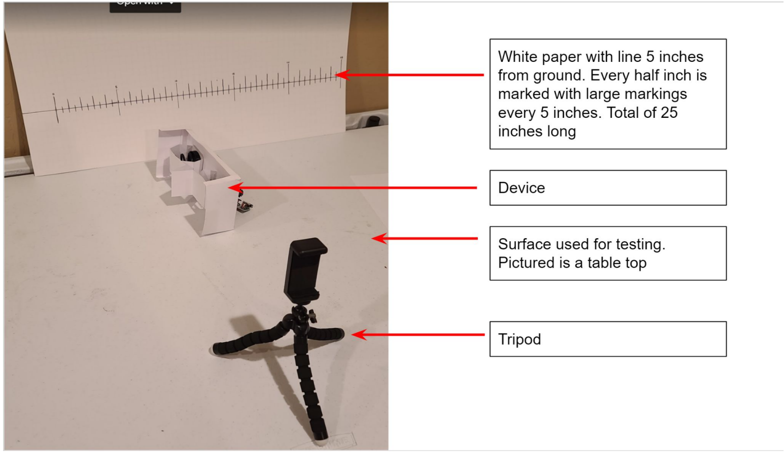
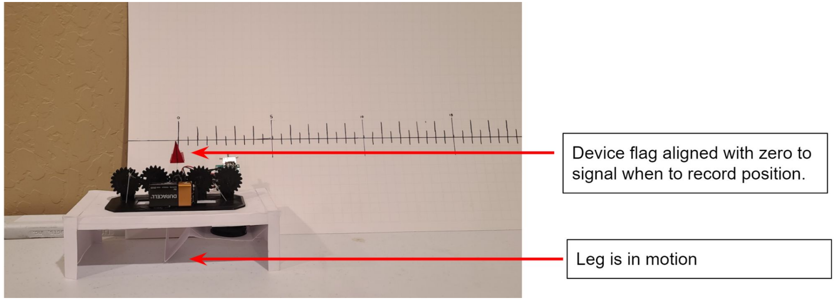


Figure 15: System motion example

Experimental Validation - Experimental Setup

Figure 16: Experiment Setup





- 5 tests of 5 different leg stiffnesses
  - Printer paper, 1-4 layer cardstock
- 20 seconds run time
  - Position value recorded every 2 seconds
- System started before zero point, experiment started once flag crossed zero

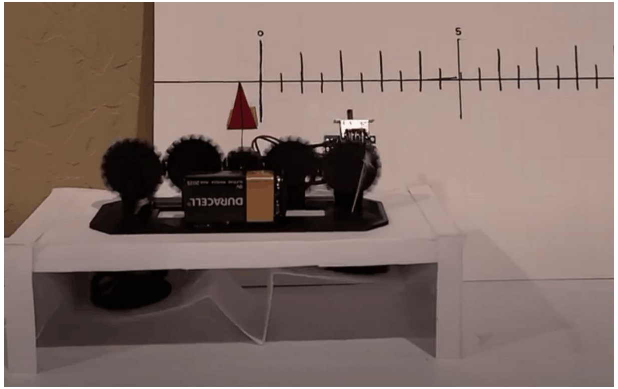


Figure 17: Video of experiment for 3 layer cardstock leg

Experimental Validation - Results

- Most movement with 3-layer leg
- Too flimsy → can't lift bot
- Too stiff → tip of leg slides/doesn't catch
- Legs catch on carpet, preventing movement

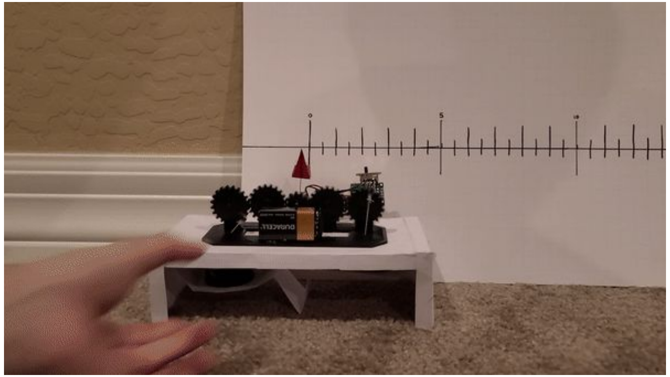


Figure 18: Inconclusive carpet tests

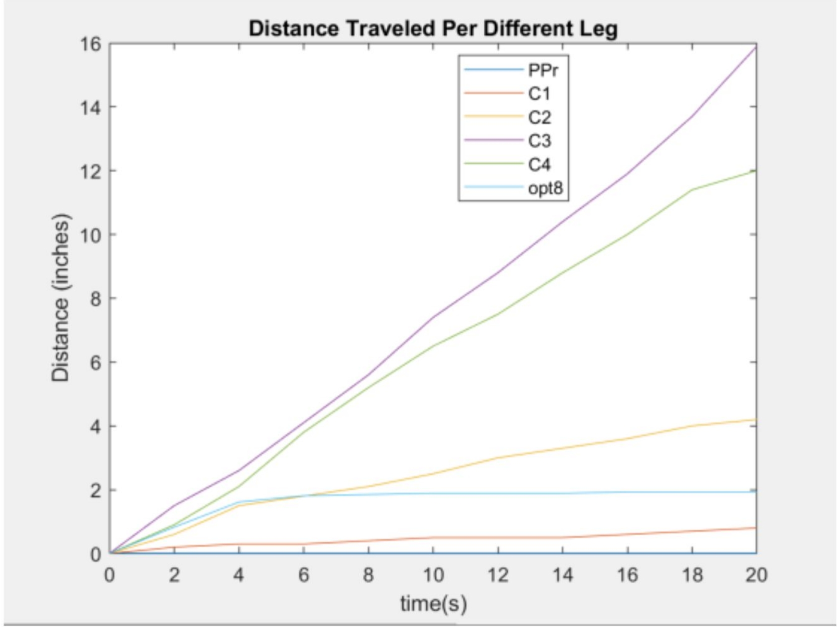


Figure 19: Different legs and optimization (opt8) results compared

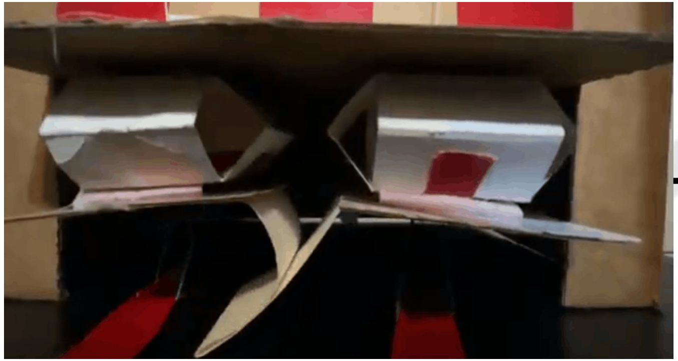
Conclusions

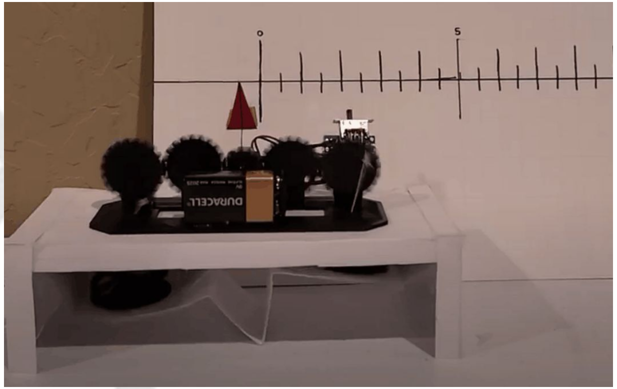
Impact

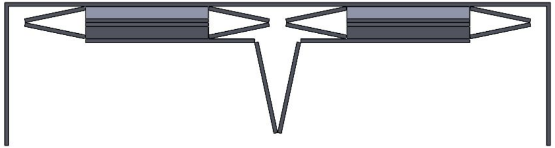
- Roboticists
  - Under-actuated + Low-cost materials + Foldable techniques = Easily manufacturable
- To public
  - Foldable techniques provide easily accessible robots and can be used to introduce more people to robotics.
    - Similar to kamigami robots
- To broader research community
  - Research of starfish podia is not as prevalent as research of sea urchin podia
  - System could be put upside down to move a horizontal plate
    - A more common experiment with podia design

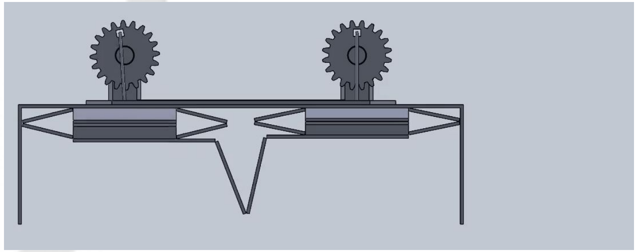
We achieve unique locomotion with a single actuator and a cardstock leg, thus answering our research question.
Possible future expansion: multi-layered foldable techniques, alternate methods of under-actuation

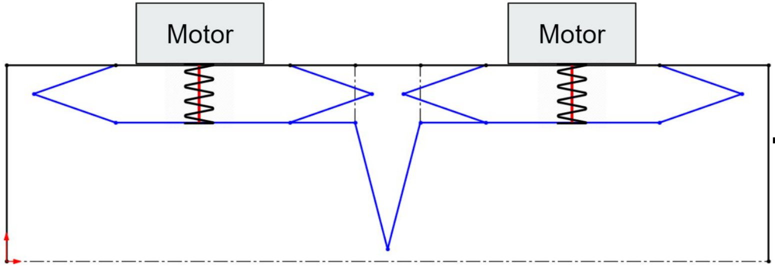
Design Iterations

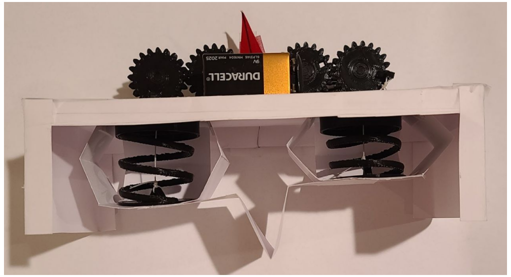












References

[1] Cronodon BioTech, Asteroid mechanics, “Asteroids 2- Hydraulic systems”
https://cronodon.com/BioTech/Asteroids_hydraulics.html