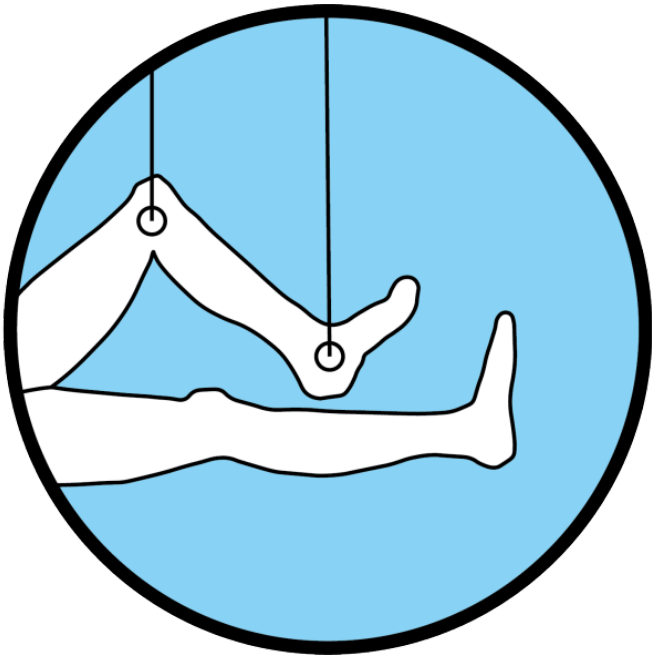
Horizontal Stepping Robot: Airstep

Sponsor: David Reinkensmeyer



Kohl Hertz
Lee McEligot
Conghao Jin
Ziyi Zhang
Yinhong Zhou
Leo Brennan

MAE 189: Capstone Design
University of California, Irvine
Dr. Copp and Dr. Walter
Dr. David J Reinkensmeyer
2/12/23

Executive Summary

The MAE 189 Capstone Horizontal Stepping Robot team was tasked with designing, manufacturing and testing a robot capable of assisting rehabilitation of patients with spinal cord paralysis. The design team is working with Dr. Reggie Edgerton of UCLA and a team at the Rancho Los Amigos National Rehabilitation Hospital on a new device. This rehabilitation robot will be used to assist patients with spinal paralysis actuate their legs. The previous rehab apparatus that the hospital was using had several issues. The device had the patient on its side, which prohibited a full range of motion. Secondly, it was attached to the ceiling, so it was not mobile. Finally, it wasn't equipped with measuring devices and data tracking equipment.

The goal of this project is to develop a mobile device that allows the patient to perform walking cycles with weighted assistance and without hindrance. The device will be rolled up to the patient, leg cradles will be strapped onto them, and they will be able to actuate their legs in a walking motion while laying on their back. The primary objective of winter quarter was to create a fully operational device equipped with an assistance system, sensors and electronics, and a digital interface to operate the device and record data.

The design team incorporated four different components into the device. The first was the frame design. The frame was designed with two main principles in mind, stability and safety. It incorporates strong beams and bracing to avoid unwanted motion or collapse. It also includes places and reinforcement for the other components within our design. The second component is the weighted assistance component, the mass spring system. The team's main objective with the assistance was to create a constant force that would be equal and opposite to the leg's force. After comprehensive testing, going through different configurations of both passive and active systems, the team determined that the best arrangement was a mass coupled with a spring. To make it adjustable, the mass can be changed via weights and the springs can be switched out as well. The third component is the sensor and electrical system. The device incorporates both force sensors and rotary encoders which measure force and distance respectively. The sensors are equipped to the device and are connected to a microcontroller. The fourth component was the interface and post processing components. The interface was designed to have a digital controller for the researcher to activate and deactivate the sensors. The interface would then output the sensor readings to a text file. That text file would be then applied to the post processing algorithm which calculates metrics such as force outputted and travel speed.



Figure 0.1: Full device

The team was able to manufacture the fully functional device. The system was equipped with both the mechanical and the sense systems, and a leg brace was used as a prototype cradle.

The frame was made from T-slotted framing and their respective fixtures and fasteners. The user had to place the leg brace on, then was attached to points closest to the center of gravity via carabiners. The mass-spring system and the sensors were both functional, collecting data during the user's walking cycle. The device is shown in the device figure.

The testing data collected was used to find quantitative data, qualitative observations and flaws with our design. Primary quantitative measurements included the force and distance of the user's walking motion, measured by the force sensors and rotary encoders respectively. This data was then used to generate kinematic models and motion simulations. The force vs distance data and kinematic model can be seen below. Using the fully designed allowed for qualitative observations to be made. This includes recording the user's experience, such as usability of the device and potential pain points. Also, watching leg actuation for kinesiological attributes of a walking cycle. Finally potential flaws and issues of the device were pointed out. This includes the potential for slippage on pulleys, which would affect the rotary encoder's output and finding the optimized weight for each patient.

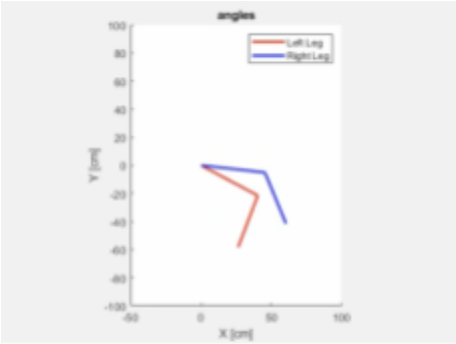


Figure 0.2: Kinematic simulation from sensor data

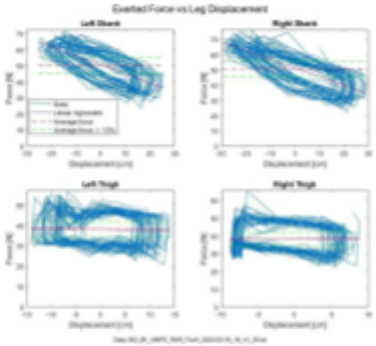


Figure 0.3: Force vs. Distance graphs from testing

The team plans to continue through spring 2023, working to fine tune each system to be usable in a hospital and rehabilitative setting. The mass spring system will be optimized to each individual regardless of size and weight, and live sensor and controller data will be available to the researcher. The cradle will be fully manufactured and usable for patients of different height and weight. Finally, the frame will incorporate covers and reinforcement for further safety and stability. The device will then be implemented and used for the rehabilitation of patients with spinal paralysis.

Table of Contents

Executive Summary **1**
List of Figures **5**
List of Tables **7**
Chapter 1: Project Definition **8**
Background: 8
Review of Existing Solutions: 8
Problem Statement: 8
Design Attribute Table: 9
High-level Work Breakdown Structure: 11
Milestones/Schedule: 12
Chapter 2: Conceptual/Preliminary Design **15**
2.1 Frame 15
2.2 Force Mechanism 16
Defining Objectives and Requirements 16
Determining SEA Requirements 17
SEA Compliance 18
Evaluating Alternative Force Mechanisms 18
Spring Only System 18
Mass Only System 19
Spring-Mass System 19
2.3 Angle and Length Measurement System 21
2.4 Sensors 25
2.5. Leg Cradle/ Cable Mount System 30
Summary of Preliminary Design 32
Swot Analysis 32
Assembly drawing/illustrations 32
Cost estimate 33
Budget: 33
Chapter 3: Detailed/Critical Design **35**
3.1 Frame 35
Design 35
Manufacturing 36
3.2 Force Mechanism 37
Design 37
Manufacturing 39

3.3 Sensors 40
3.4 Post Processor 43
Detailed Cost Estimate: 44
Chapter 4: Prototype Performance and Final Design 46
4.1 Frame 46
4.2 Force Mechanism 47
Verification 49
Calibration - Method of Filtering 49
Finalized BOM: 52
Budget: 54
Chapter 5: Design Recommendations and Conclusions 55
Appendix 56
List of Suppliers 56
Bill Of Materials: 56
Budget: 58
Arduino Code for Sensors 62
Detailed Analysis 67
Data and Results 67
Raw Data 67
Team organization 72
Midterm and Final Presentations 72

List of Figures

Figure 0.1: Full Device
Figure 0.2: Kinematic simulation from sensor data
Figure 0.3: Force vs. Distance graphs from testing
Figure 1.1: Gantt Chart of the overall schedule
Figure 2.1: Frame CAD
Figure 2.2.1: Force over ROM
Figure 2.2.2: SEA Prototype
Figure 2.2.3: SEA Speed Requirements
Figure 2.2.4: Spring Only Data
Figure 2.2.5: Mass Only Data
Figure 2.2.6: Spring-Mass Data
Figure 2.3.1 Kinematics illustration and derivation
Figure 2.3.2 Single knee support - force input with respect to angle phi
Figure 2.3.3 Range of motion of lower limbs
Figure 2.3.4: Conceptual idea about measurement system setup
Figure 2.3.5: Thigh flexion and knee flexion angle derivation
Figure 2.4.1: Length Measurement System (Rotary Sensors)
Figure 2.4.2: Detail view of how the rotary encoders are going to connect with pulley
Figure 2.4.3: Schematic of Encoders and Sensors System
Figure 2.4.5 post-processing results - test run 1
Figure 2.4.6 post-processing results - test run 2
Figure 2.4.7 sample leg segments flexion trend
Figure 2.5.1: Current Leg Cradle, (ASL Brace)
Figure 2.5.2: Current Leg Cradle in use
Figure 2.5.3: Adjustable Leg Brace Concept
Figure 2.5.4: Adjustable leg brace
Figure 2.5.6 Full Assembly
Figure 3.1.1 CAD model of the Frame
Figure 3.1.2: Back of the Frame
Figure 3.1.3 Front of the Frame
Figure 3.1.4: Cutting plan for the aluminum extrusions
Figure 3.1.5: T-slotted Framing with aluminum bar for stability
Figure 3.2.1: Detailed Conceptual Design of Force Mechanism
Figure 3.2.2: First Solid Model of Force Mechanism
Figure 3.2.3: Final Spring-Mass Design
Figure 3.2.4: Spring-Mass Drawing
Figure 3.2.5: Linear Bearing Mounting Plate Manufacturing Sketch
Figure 3.2.6: Force Sensor Mounting Bracket Manufacturing Sketch
Figure 3.3.1: Rotary Encoders System
Figure 3.3.2: Schematic of Encoders and Sensors System
Figure 3.3.3: Distribution of electric circuit
Figure 3.4.1 Regular walking - leg segments flexion angles
Figure 3.4.2 Regular walking - participant motion
Figure 4.1.1: Modal Analysis of the frame
Figure 4.2.1: Final Force Mechanism Prototype

Figure 4.2.2: Force vs Displacement
Figure 4.3.1: The Graph of Load Cell before Filt
Figure 4.3.2: Filt Parameter = 0.9
Figure 4.3.3: Filt Parameter = 0.7
Figure 4.3.4: Filt Parameter = 0.5
Figure 4.3.5: Filt Parameter = 0.3
Figure 4.3.6: Filt Parameter = 0.1

List of Tables

Table 1.1: Design Attribute
Table 1.2: Requirement Table
Table 2.1: Frame CAD
Table 2.2.1: Design Requirements of the Force Mechanism
Table 2.2.2: SEA Design Requirements
Table 2.2.3: SEA Compliance Table
Table 2.4.1: Scoring matrix of two concepts
Table 2.4.2: Compliance table of two concepts
Table 2.5: Swot analysis of Above leg pulley system
Table 4.1.1: Table of Modal Values
Table 4.2.1: Compliance Table for Force Mechanism
Table 4.3.1: Accuracy test of sense system

Chapter 1: Project Definition

Background:

Researchers at UCLA and Rancho Los Amigos National Rehabilitation hospital have asked us to design a robotic device that can roll up to a spinal cord-injured patient's bed. The device should provide weight support to each leg, and allow the legs to make an "air stepping" motion, measuring the stepping motion and providing assistance as needed. This will allow the patient to exercise the legs and to better recover movement ability. We have begun prototyping the robot based on a previously-developed wheelchair robot called Movit. This project will refine the design and build out a first, working prototype.

Review of Existing Solutions:

There is already a device which is being used to help patients to test the flexibility of their legs' motions. The device provides support to the leg of the patient, as they are laying on their side, by hanging it by a rope attached to the ceiling. As a result of hanging the leg from the ceiling, a pendulum motion is made by their leg. The device allows the patient to make walking motions with relative ease. However, it is difficult to get the patient on their side to set up the device. This is the main complaint with the current design.

There is currently a passive leg supporting system on the market, named CPM (continuous passive motion machine). This system includes a leg support attached at the lower end of the semi-circular track. An actuator is placed along the track and can be locked at any desired position. When the actuator is placed at the bottom of the track, there will be two kinds of motion (inversion/eversion) taking place on the joint of ankle; when the actuator is placed near the top of the track, both plantar/dorsiflexion movement is achievable [1].

Problem Statement:

Make a device that can unload the patients hip and knee joints so that they can better study the effects of electrical spinal cord stimulation on gait training. The device should allow the patient to walk as though there is no load from gravity on their muscles; the only force applied by the patient should go into the acceleration of their legs. This movement should be able to be measured and recorded, and be reported to the clinician.

Design Attribute Table:

Attribute	O	C	F	M
Should be under the desired budget	■			
Should be stable on the smooth floor	■			
Should be effective to lift legs/support the weight of legs	■			
Must be safe		■		
Should be easy to manufacture	■			
Should allow most individuals to work			■	
Should be durable	■			
Should be used in limited space of hospital	■			
Must not exceed the limit of humans		■		
Should be easily assembled, not over complicated in design	■			
May use an Arduino Uno				■
May use a battery				■
Should be fast in measurement and recording	■			
Should be stiff and comfortable for the users	■			
May use a 3d Printer				■
Should be reliable	■			
Might use a crane				■
Should be easy to set up, under 2 minutes for a new patient	■			
Should be automated		■		
Must allow tool storage			■	

Table 1.1: Design Attribute

The main objective of the device is to allow for patients' leg muscles to be unloaded, so that they can achieve a high range of motion with little force input from their muscles. This can be quantified by two requirements. First is the ability of the device to hold the patient's leg at an equilibrium position with no input from the patient. The second is the ability to allow the patient to achieve the full range of motion, even if they have reduced mobility. This can be quantified by reducing the force exerted by the patient to achieve a full range of motion. These major objectives must be achieved in a convenient manner, allowing for the clinician to roll the device up to a patient's bed and

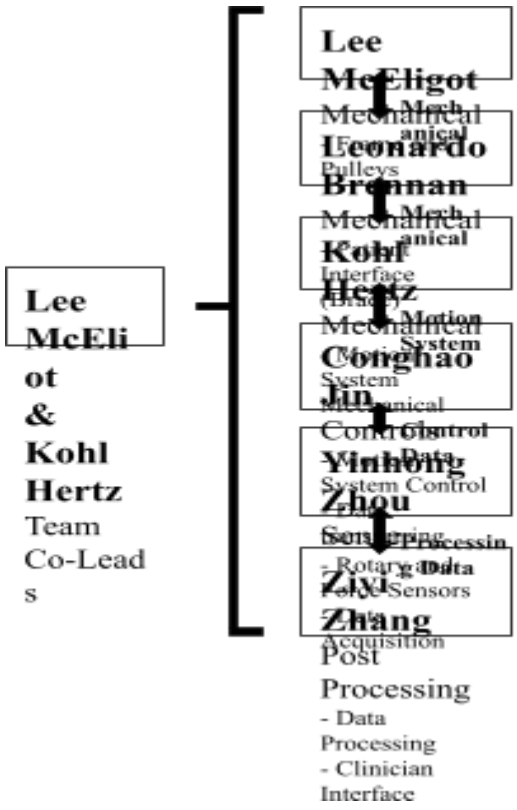
set the patient up in under 2 minutes. The portability of the device also leads to a size constraint, that it must be able to fit through standard doors (3 ft wide). The patient's movements should be tracked by an onboard sensing system, allowing for the clinician to easily track patient progress. Finally, the device should be safe and reliable, with a factor of safety of 2 for the heaviest allowed patient on all components.

Requirement Table:

90% accuracy in weight compensation of the patient's leg, for 95% of patients
The device must be safe, reliable, and durable.
Should be stable and comfortable for users.
Must be able to record the patients motion with a 4 percent accuracy in measured position to actual position
Should take less than 10 minutes to set up for a new patient
Should be under the desired budget.
Must fit the limited space in the hospital, and fit through a standard doorway.

Table 1.2: Requirement Table

High-level Work Breakdown Structure:



Milestones/Schedule:

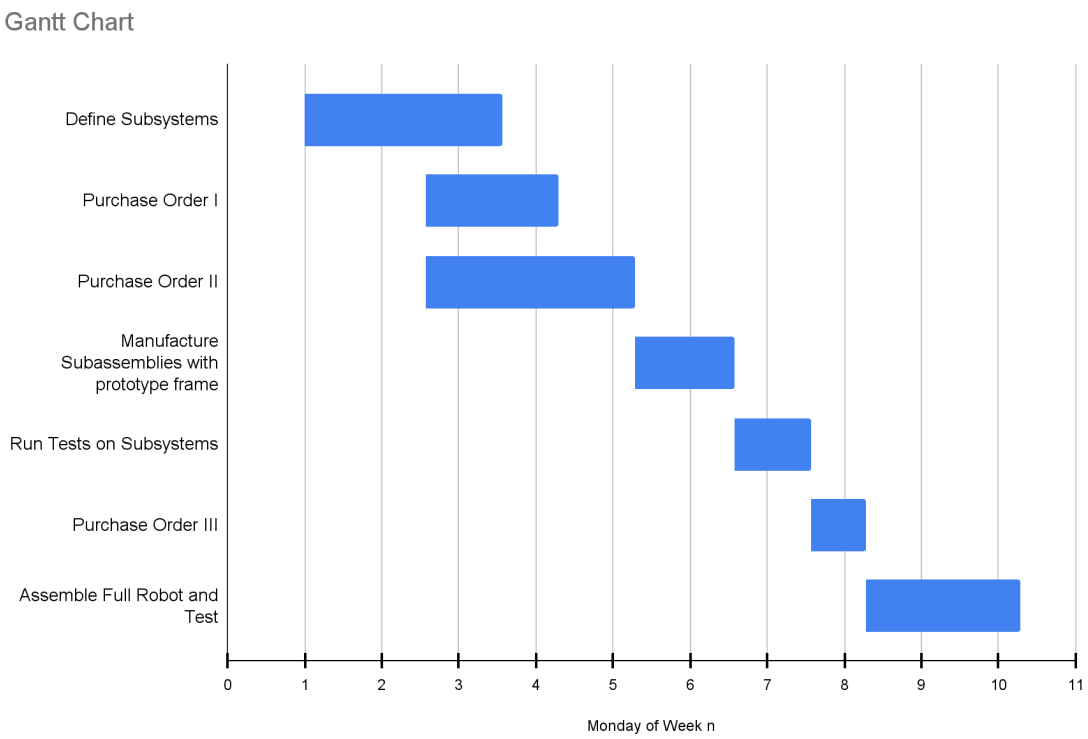


Figure 1.1: Gantt Chart about schedule

MILESTONE	DESCRIPTION	DEADLINE
Define Physical Systems and Subsystems to be worked on this quarter	+ Determine the type of Linear Actuation we are going to use (**Kohl**) + Determine what type of Knee Brace we need to buy or manufacture (**Leo**) + Upgrade frame and pulleys (**Lee**) + Determine the Force Sensor we want to use as we scale up the project (**Conghao and Yinhong**) + Determine the control board that we want to use (**Conghao and Yinhong**) + Get a real time post processing system which would record and display patient data (**Thomas**) + Medical practice and clinical interaction (**Lee and Thomas**)	2/1/23 and 2/4/23
Develop Purchase order for Materials for Smaller Items	Purchase Order Includes: + Leg Brace Materials (**Leo**) + Additional Framing components (Carabiners) (**Lee**)	2/1/23
Develop Full Purchase order for Materials for Mechanical Subsystems and Sensors	Purchase Order Includes: + Series Elastic Actuator (**Lee and Kohl**) + Linear Actuator + Springs + Materials for manufacturing (Adhesives, Rope) + Knee Brace Materials (purchasable materials or 3D printed materials) (**Leo**) + Frame components (Pulleys) (**Lee)** + Sensors (**Conghao, Yinhong, Lee, Kohl**) + Force + Linear Measurement Systems + Control board (**Conghao and Yinhong**) + Microcontroller + Interface (**Thomas)** + Monetary Programming needs, if there are any + App Builders	2/8/23
Manufacture and Assemble Subsystems	Manufacture Sub Assemblies + Series Elastic Actuator + Leg Brace + Pulley System w/ encoders Assemble on the current prototype Frame (**Everyone)** Have Post Processing ready for testing (**Thomas**) + Analyzes forces, distance traveled and interprets + Able to process into usable and interpretable data	2/17/23

Run Tests on subsystems	Run Tests on the Subsystems + SEA - Functionality and operates at high enough velocity (**Kohl**) + Leg Brace - Comfortable and adjustable (**Leo**) + Pulleys and encoders - Reads good data (error analysis) (**Conghao and Yinhong)** + Have a preliminary SOP developed (**Lee**)	2/20/23- 2/24/23
3rd Purchase Order	Purchase Order includes + Frame components (**Lee, Kohl, Leo**) + Extrusions and structural material + Adjustment Mechanisms + Cage for springs and SEA + Potential Ergonomic accessories (Table, Monitor stand) + Any further materials (**Everyone**)	3/1/23
Assemble Full Robot and Test	Assemble Full Robot (**Everyone**) + Frame is adjustable for both width and patient height + Sensors are fully operational + SEA is functional and adjustable + Leg brace in comfortable and adjustable + Post Processing Algorithm has been polished and is usable for clinicians + Interface is in barebones stage Testing (**Everyone**) + Test all systems + Have SOP Developed	3/17/23

Chapter 2: Conceptual/Preliminary Design

2.1 Frame



Figure 2.1: Frame CAD

Applicable Standards

If this device were to be put into production and be sold, the ISO 13485 standards would need to be followed. This ensures that the device functions as it is designed; by making sure that there is traceability with the suppliers of components, and that there is proper analysis of the components.

Requirements of the Component

This assembly should be able to withstand the heaviest patient we have selected in our data with a factor of safety of 2. additionally the assembly must be able to fit through an average doorway of 63 in. As the design is supposed to be portable the aluminum extrusion construction will allow us to use locking castors for moving the assembly.

Conceptual Design Description

The device will be made out of mainly 1.5 in aluminum extrusions and secured using various brackets that interface with the extrusion type.

Justification of the Final Design choice

The final design of using aluminum extrusion was selected because of their customizability and ease of use. We decided that the construction should be easily editable and be strong enough to withstand high loading.

fabrication methods

bandsaw, bit driver

2.2 Force Mechanism

Defining Objectives and Requirements

A passive force system should provide a force equal to the gravitational force on the leg member, so that the only force needed to move a patient's leg is the force to accelerate their leg. *We aim to have 90% accuracy in weight compensation of the patient's leg, for 95% of patients.* These objectives lead to the requirement table below, with requirements for displacement, force, accuracy and cost.

Target Specifications				
No.	**Requirement Metric**	**Units**	**Marginal Value**	**Ideal Value**
1	Maximum Displacement	cm	>40	60
2	Equilibrium Force Exerted on Leg	N	30-70	20-80
3	Accuracy of Force Across ROM (% of Equilibrium Force)	%	±15	±10
4	Cost	$	1000	400

Table 2.2.1: Design Requirements of the Force Mechanism

The requirement table above gives a quantitative way to analyze the needs of possible designs. The figure below gives these requirements more context. It shows how as the patient's leg moves through their full range of motion, the force exerted on their leg by the force mechanism should remain constant, with an accuracy of 10 percent as shown in table 2.1.

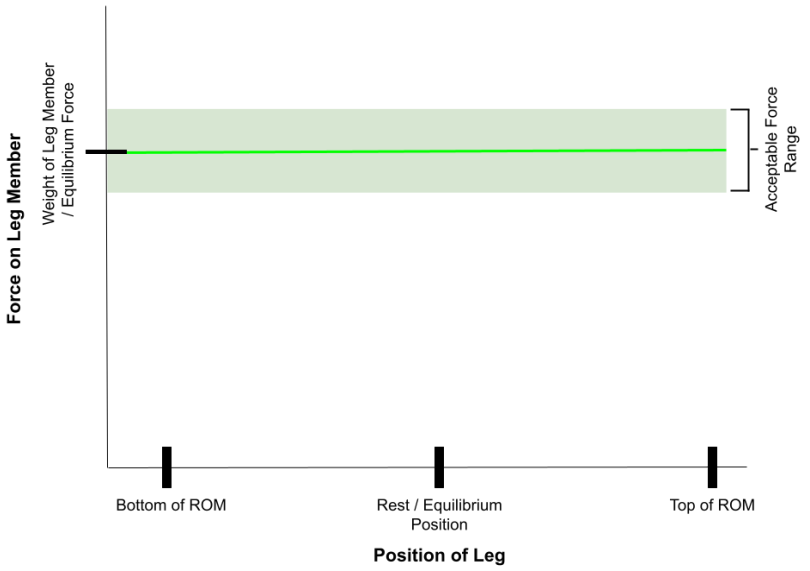


Figure 2.2.1: Force over ROM

Determining SEA Requirements

These requirements were then used to determine the design requirements for a series elastic actuator (SEA) system. At the end of last quarter, we had made a prototype SEA as seen in figure 2.2.2. However, this prototype SEA was much too slow to keep up with the patient's leg, preventing it from providing constant force. Due to this, the shank distance data taken in last quarter's testing was used to define SEA requirements. Figure 2.2.3 shows the matlab code that was used to analyze the speed that the actuator needed to go to reach the 10 percent error in force defined earlier. This code simulated a tracker with a set maximum velocity, it then followed the shank distance data and calculated the force error for actuators with a range of 0-150 cm/s max velocity. This data was then used to find the speed that was needed to reach the 10 percent error.



Figure 2.2.2: SEA Prototype

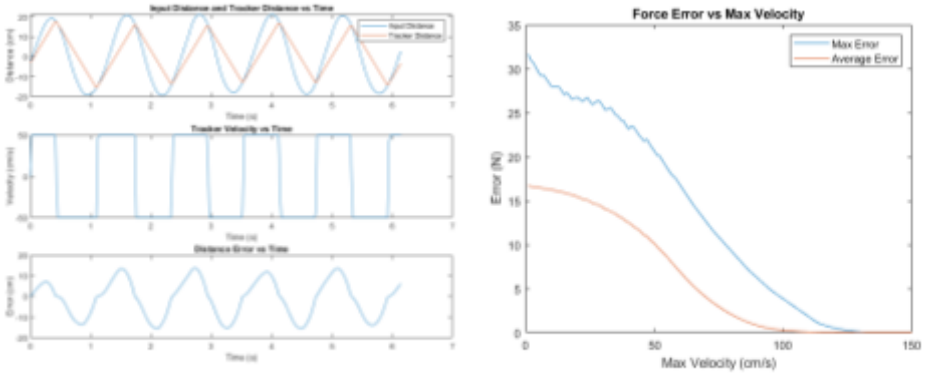


Figure 2.2.3: SEA Speed Requirements

Using this analysis, Table 2.2.2 was created, which outlines the requirements for the SEA system. This table would then be used while looking for off the shelf options for motion systems which would allow us to reach the 10 percent error.

Target Specifications				
No.	**Requirement Metric**	**Units**	**Marginal Value**	**Ideal Value**
1	Maximum Displacement	cm	>40	60
2	Equilibrium Force Exerted on Leg	N	30-70	20-80
3	Accuracy of Force Across ROM (% of Equilibrium Force)	%	15	10
4	Cost	$	1000	400
1.1	**Displacement at the Actuator**	**cm**	**>13**	**20**
2.1	**Max Dynamic Force Requirements**	**N**	**190**	**380**
3.1	**Actuator Speed Needed to Meet No.3**	**cm/s**	**>25**	**30**

Table 2.2.2: SEA Design Requirements

SEA Compliance

Then a trade study was run and the compliance table 2.2.3 was created to compare

the off the shelf offerings. The green values signify meeting the ideal requirements, yellow is within marginal, and red is outside of our requirements.

Compliance of Off the Shelf Linear Motion Systems			
Design Specifications	**Mechanisms**		
	Lead Screw 1	**Lead Screw 2**	**Actuator**
1.1	20 in	20 in	19 in
2.1	75 N	395 N	445 N
3.1	21 cm/s	2.5 cm/s	29 cm/s
4	$1,720	$1,720	$14,000

Table 2.2.3: SEA Compliance Table

Evaluating Alternative Force Mechanisms

With the data collected in Table 2.2.3, it was discovered that there were no viable off the shelf products that would allow the SEA to reach our 10 percent error requirement. Due to the failure of the SEA to meet our requirements, we decided to pivot to looking for other mechanical systems that would carry less inherent force variation. Can we find a mechanical system which reduces force error without the use of actuators?

Spring Only System

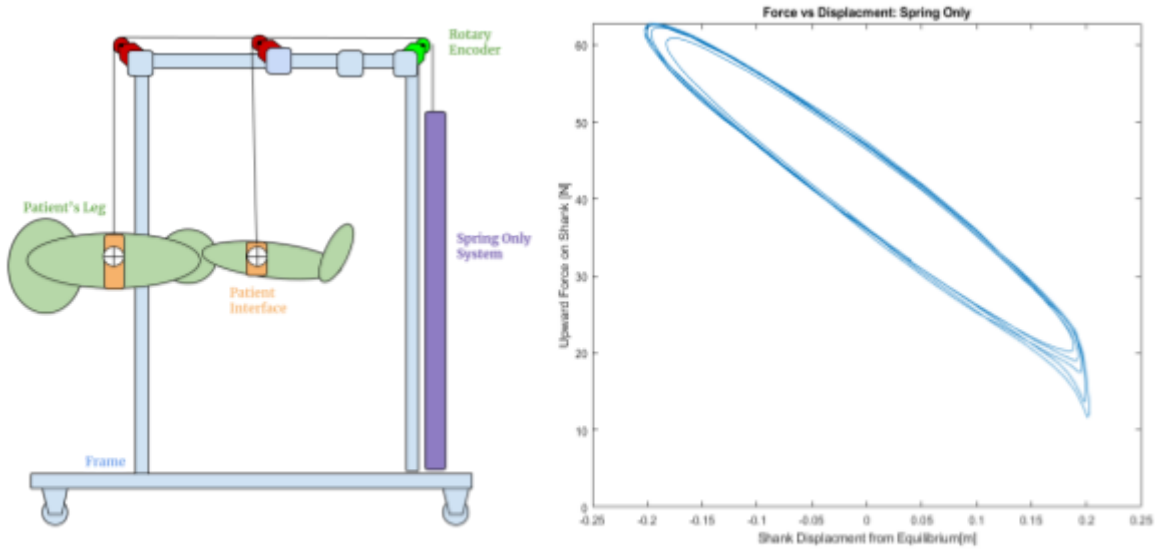


Figure 2.2.4: Spring Only Data

As seen in Figure 2.2.4, the spring system that was setup in the Fall quarter has an error of about ±50% (20N). It has a clear linear relationship between displacement and force, due to the spring constant. This large error is what initially led us to the SEA system, as we wanted to compensate for the spring constant. Is there a system which will not have this much inherent error?

Mass Only System

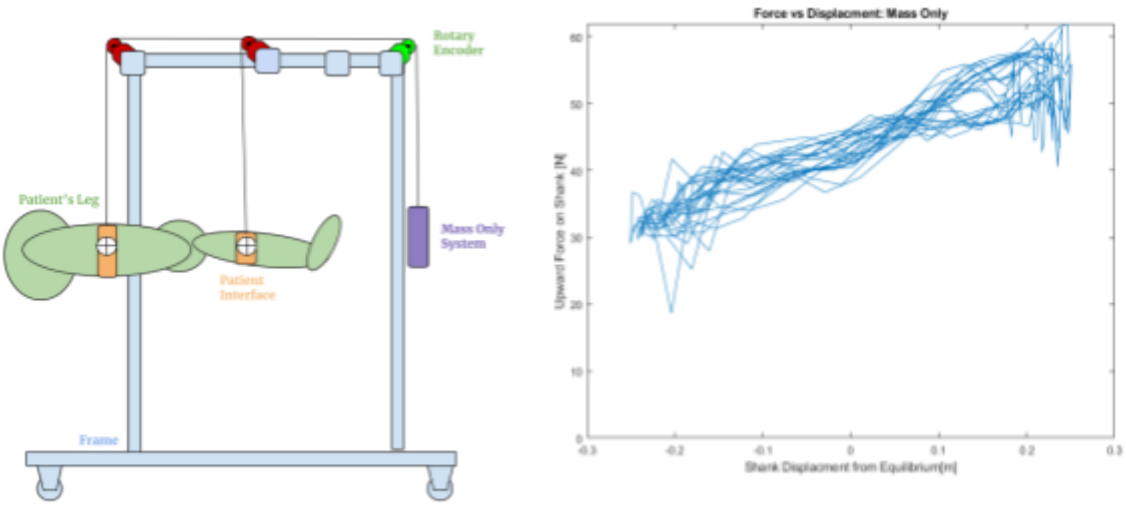


Figure 2.2.5: Mass Only Data

The mass only system has an error of ±33% (15N). The inertial forces cause a linear relationship between displacement and force, opposite to that seen in the spring data. This is due to the acceleration occurring in the opposite direction of displacement. At the top of the ROM, the leg is accelerating down, causing an increase in tension on the rope. This mass only system is better than the spring only system, but still has too much error.

Spring-Mass System

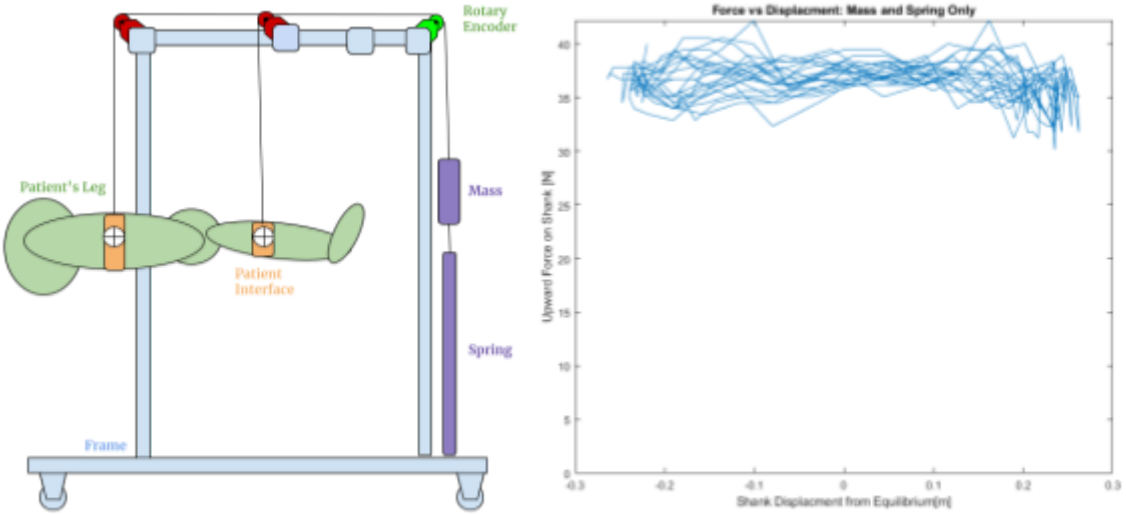


Figure 2.2.6: Spring-Mass Data

The spring-mass system has an error of ±13% (5N). The inertial force and spring force gradient cancel eachother out, creating a nearly constant force throughout the motion of the leg. This error is within our marginal value, and is likely able to be brought

down through tuning of the mass to spring ratio and with the use of more accurate sensors. More testing is needed to confirm the hypothesis that this spring-mass system is a viable way to provide constant force to the patient's leg, however this is promising preliminary data.

2.3 Angle and Length Measurement System

Applicable Standards

If this device were to be put into production and be sold, the ISO 13485 standards would need to be followed. This ensures that the device functions as it is designed; by making sure that there is traceability with the suppliers of components, and that there is proper analysis of the components.

Requirements of the Component

The force adjustment mechanism needs to be able to adjust the length of the cable to accommodate for several different sizes and weights of patients. The functional requirement of the component is to achieve the idea of "zero-gravity", which signifies that the force experienced by the patient's leg and the weight of the patient's leg should be equal to achieve a net force of zero. As the patient would exercise his/her leg during the movement, the rope connected to the patient's knee would have different length and different angles (with respect to the horizon), the force required to achieve "zero-gravity" would be different as well. The following illustration shows the derivation of force required for the linear actuator input.

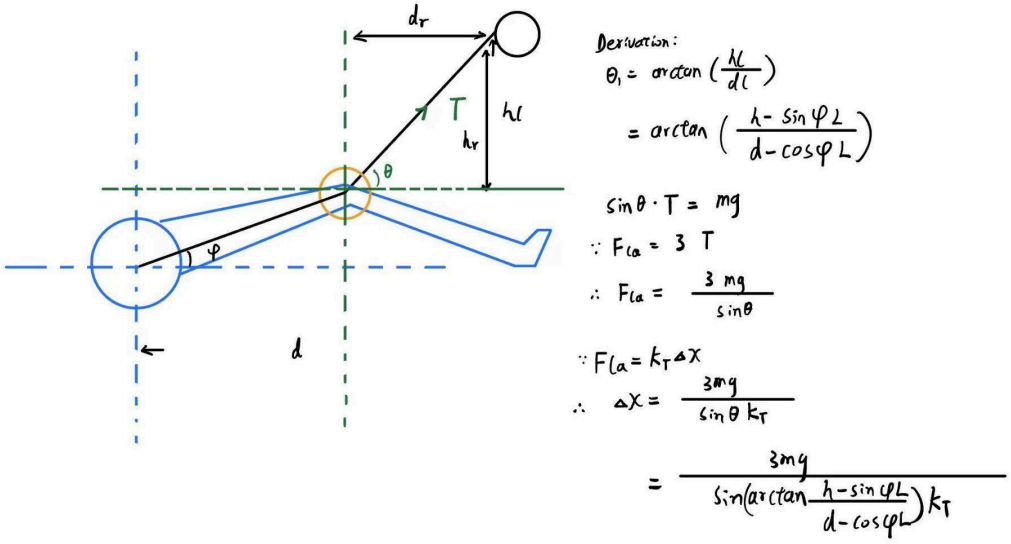


Figure 2.3.1 Kinematics illustration and derivation

By using matlab programming, the derived kinematics equations can be utilized to calculate the required forces provided by linear actuators.

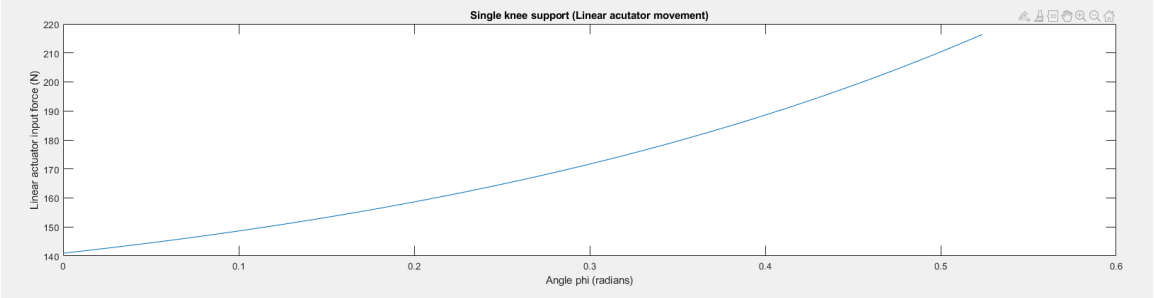


Figure 2.3.2 Single knee support - force input with respect to angle phi

Table 1 Range of motion of lower limbs

Part/joint	Degree of freedom	ROM (m; degree)
Pelvis	Superior/inferior	0.1/0.1
	Lateral	0.15/0.15
	Anterior/posterior	0.2/0.2
	Obliquity	10/10
	Tilt	6/6
	Vertical rotation	15/15
Hip	Flexion/extension	40/30
	Adduction/abduction	20/20
	Internal/external rotation	15/15
Knee	Flexion/extension	75/0
Ankle	Dorsiflexion/plantarflexion	25/35
	Adduction/abduction	10/10
	Internal/external rotation	10/20

Figure 2.3.3 Range of motion of lower limbs

According to the graph shown above, the degree of freedom for the hip of the human body is 30 degrees and approximately 0.52 radians. By considering the degree of freedom of the human body, the maximum force required for rehabilitation of patient's leg would be approximately 220 N.

Conceptual Design Description

There were multiple ideas of how to adjust the tension of the spring, from using a manual adjustment mechanism, having a lead screw and stepper motor to having a linear actuator. The final decision was to go with the linear actuator due to their strength in holding against a load, and the ability to move quickly.

Justification of the Final Design choice

The final design of the force adjustment mechanism is undetermined, as we are focussing on developing a robust passive system before we move towards an active system.

Defining Objectives and Requirements

First concept:

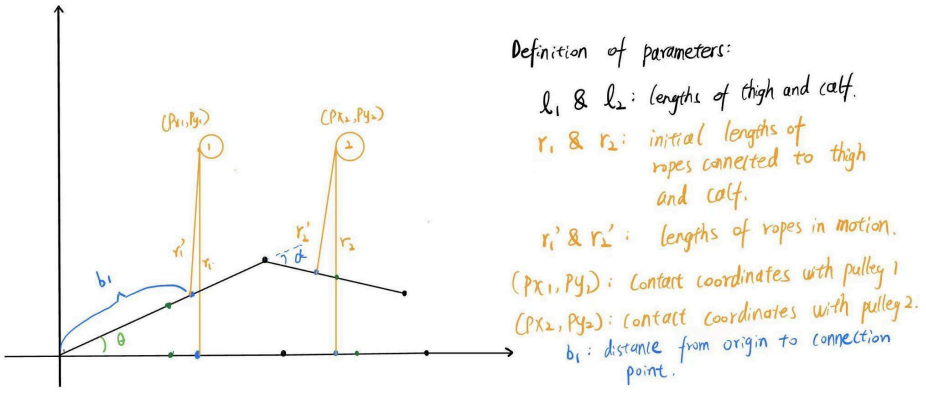


Figure 2.3.4: Conceptual idea about measurement system setup

During the rehabilitation, i.e. movement of patients' legs, the leg segments flexion are subject to change over time. The purpose here is to utilize data collected from rotary encoders that are connected to the pulleys to calculate the thigh flexion and knee flexion angles, i.e. α and β here, shown by figure 2.3.4.

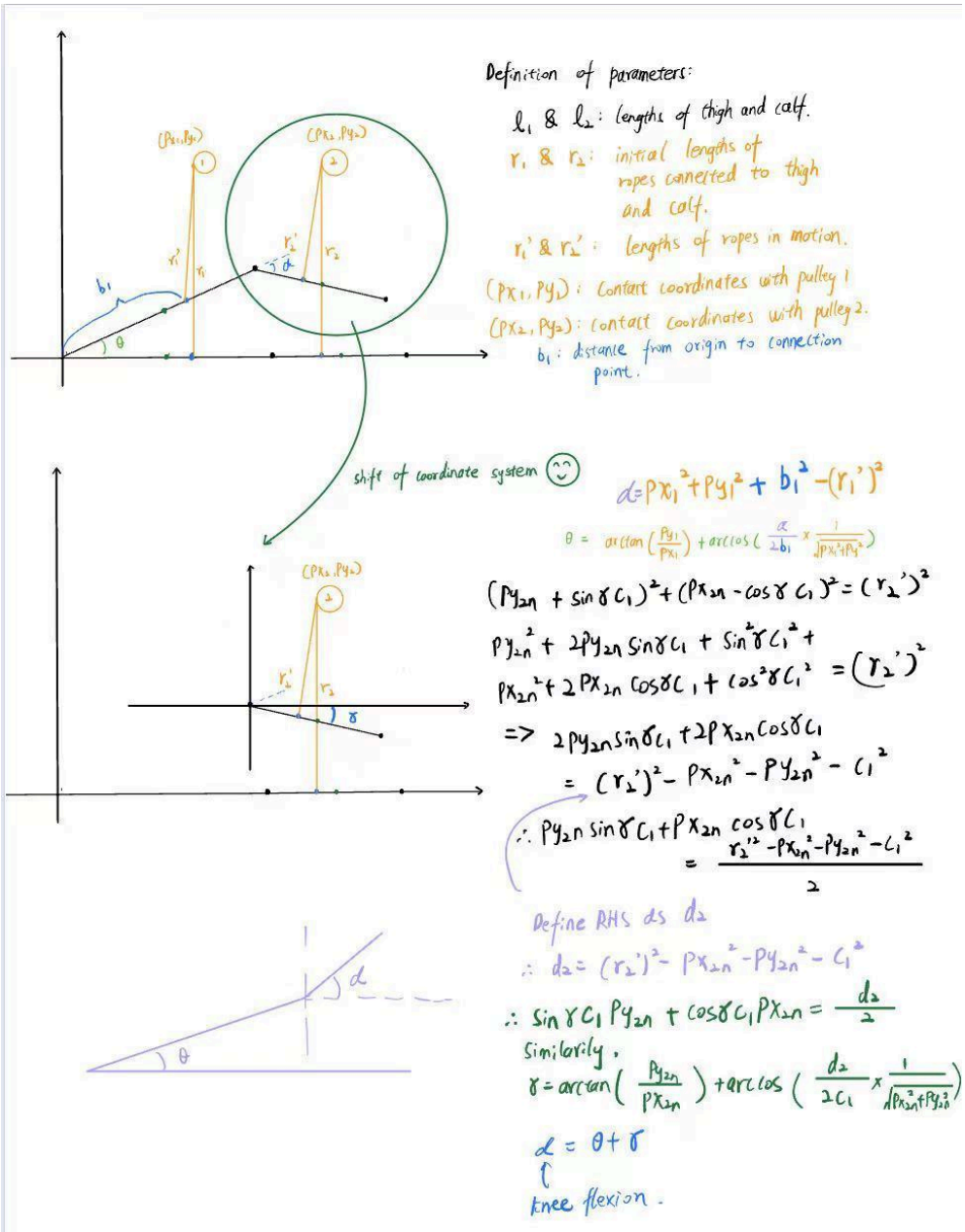


Figure 2.3.5: Thigh flexion and knee flexion angle derivation

During the fall quarter, the derivations for calculating thigh flexion were computed; by utilizing the similar algorithm and shifting the coordinate system to the knee position, the knee flexion flexion angle can also be calculated, as shown by figure 2.3.5.

2.4 Sensors



Figure 2.4.1: Length Measurement System (Rotary Sensors)

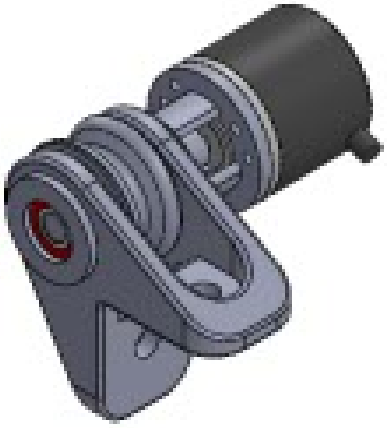


Figure 2.4.2: Detail view of how the rotary encoders are going to connect with pulley

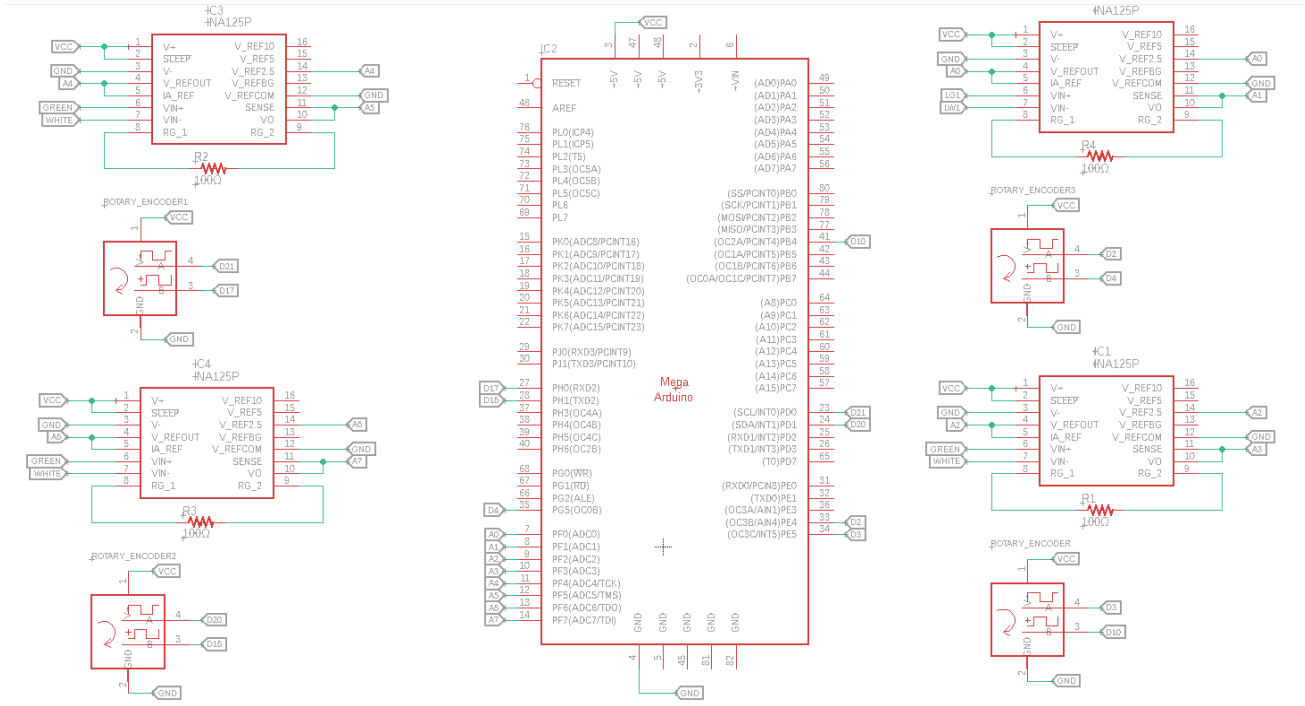


Figure 2.4.3: Schematic of Encoders and Sensors System

Applicable Standards

If this device were to be put into production and be sold, the ISO 13485 standards would need to be followed. This ensures that the device functions as it is designed; by making sure that there is traceability with the suppliers of components, and that there is proper analysis of the components.

Requirements of the Component

The system should be able to measure the changing length of rope and the change of angle that the pulley has experienced based on the changing position of rotary encoders. Thus, the system of leg's motion can be fully defined and the motion data of leg can be traced.

Conceptual Design Description

Generally, there are four ropes connected with patients' legs. Two ropes are connected with thighs and the other two are connected with shanks. We set up four rotary encoders so that each rotary encoder could measure the change of length that one of the ropes has experienced. Based on some other parameters like the length of legs and the height of the device, we are able to get the locations of joints of legs so that they can trace the legs' movement.

Justification of the Final Design choice

	Options	
Criteria (out of 5)	old concept	current concept
Cost	4	4
Complexity	4	2
Duration	4	3
Safety	4	4
Viability	4	2
Total	20	15

Table 2.4.1: Scoring matrix of two concepts

In second concepts, the gears that will be used need to be 3D printed, the gear ratio needs to be a function of degree, and there will be a big error if the component between gear and rope does behave in a linear way which we assume it will behave linearly.

Requirements	current concept	old concept
Measure the angle	good	medium
Measure the changing length	good	good
The error when angle is small	good	medium
Less customized component	medium	medium
Stable on the extrusion	good	medium
Hold the rope stably	good	good
Less friction between rope and components	good	good

Table 2.4.2: Compliance table of two concepts

Preliminary list of materials/parts

4 Rotary encoders, four specialized pulleys, four pulley mounts, four encoder mount, four encoder to pulley connection tools, one Arduino Teensy.

Post-processing algorithm and results

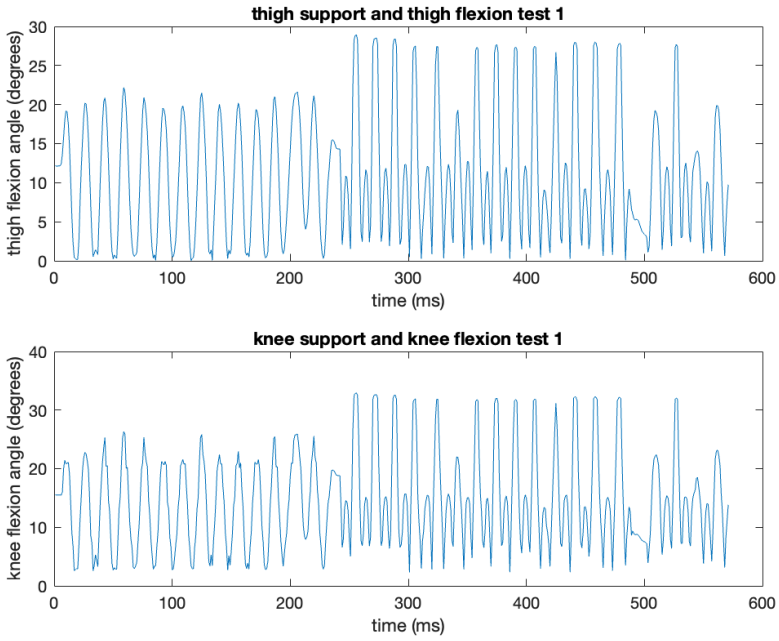


figure 2.4.5 post-processing results - test run 1

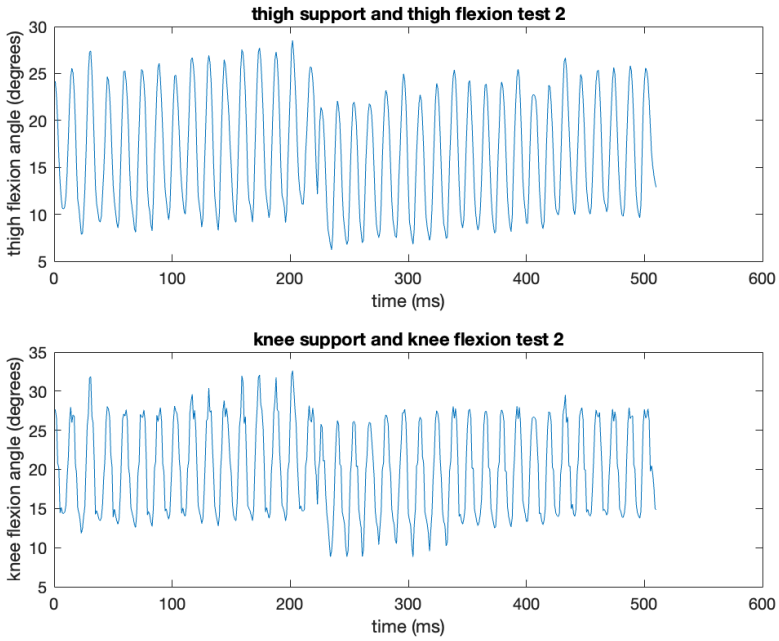


figure 2.4.6 post-processing results - test run 2

By utilizing the equations derived previously and inputting them in matlab program, the results and plots (with and without springs for first and second test runs, respectively) can be obtained as shown by figure 2.10.5 and 2.10.6. Credit would be given to Andrew and Conghao for their efforts of hardware set-up and data collection and also Kohl, for the algorithm derivation suggestions.

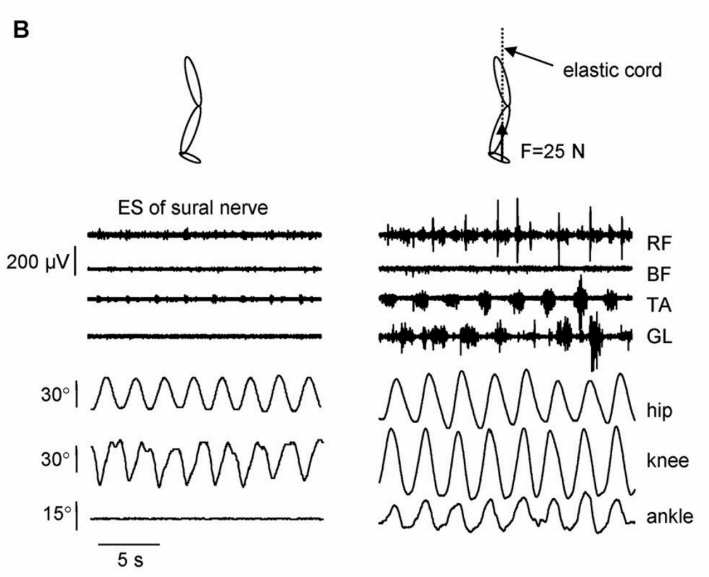


figure 2.4.7 sample leg segments flexion trend

It is satisfactory to see that encoder data post processing results are consistent with the expected results from the paper "Tapping into rhythm generation circuitry in humans during simulated weightlessness conditions" (as shown by figure 2.11), that the general trend of sinusoidal waves is followed. For future work and further verification, the following actions could be taken:

1. Use camera motion capturing to examine the accuracy of post-processing algorithms.
2. More test runs of data using different counterweights and also different participants to examine the consistency of the results.

2.5. Leg Cradle/ Cable Mount System

Current Solution

The current solution for attaching the patient's legs to the device uses an off the shelf ACL brace [Figure 2.11.1].



Figure 2.5.1: Current Leg Cradle,
(ASL Brace)

The brace is made up of 4 straps that firmly attach to the patient's shank and thigh. The upper section is an aluminum linkage with a single pivot in the middle of the brace. Using carabiners we are able to clip into the upper section on either end [Figure 2.5.2]. This provides the upward force that keeps the patient's leg suspended in the air.

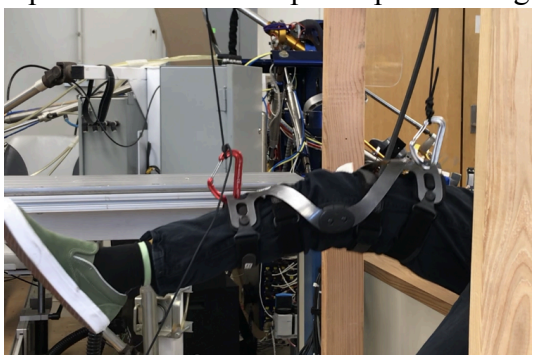


Figure 2.5.2: Current Leg Cradle in use

The current solution for supporting the legs has a few upsides and downsides to its application. Firstly the upsides. This particular brace is incredibly easy to use, only requiring a 6 step process of strapping in the clipping in. additionally the 2 part construction is rigid and is able to much more evenly distribute the force of the 2 cables across the leg over 4 strap regions. The downsides of this application are as follows. The clipping in process is unrefined and is difficult to accomplish without experience. The clip locations are in fixed positions, not allowing for adjustability along the leg. This adjustability is important for our project as we hope to have a wide range of user sizes.

Future plans

In order to remove the downsides of the current leg brace two solutions are being evaluated. The first solution is to edit the current brace by adding an adjustable clip in the

system [Figure 2.5.3]. The second solution is to look for a more aportate leg brace design that will meet our design requirements better than our current brace. An example of a prospective brace is shown in [Figure 2.5.4].

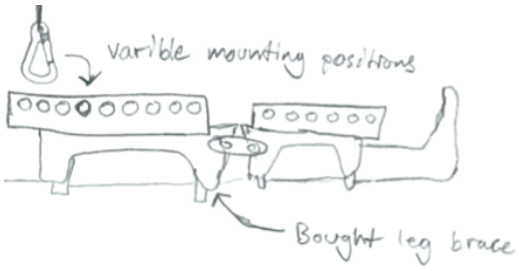


Figure 2.5.3 Adjustable Leg brace Concept



Figure 2.5.4: Adjustable leg brace

Applicable Standards

If this device were to be put into production and be sold, the ISO 13485 standards would need to be followed. This ensures that the device functions as it is designed; by making sure that there is traceability with the suppliers of components, and that there is proper analysis of the components.

Requirements of the Component

This component should be able to support the patient's knee joint through supporting the hamstring and calf section of the leg. This support must be comfortable for the patient to use for long periods of time on the scale of hours. Additionally the component should be able to apply a prescribed pressure amount to the nerves in the Popliteal Fossa to simulate leg motion.

Conceptual Design Description

The device will be made out of two main half pipes sections with a point in between the sections. the leg will rest in these sections and be secured with straps

Justification of the Final Design choice

The final design for the Leg Cradle/ Cable Mount System is still in development as there is additional testing needed before the team settles on the proper way to support the legs.

fabrication methods

3D-printing, laser-cutting, plastic forming, sewing, drilling, bandsaw cutting

Summary of Preliminary Design

Swot Analysis

Until the time of week five, the preliminary design and manufacturing of the

system was accomplished; the strengths and potential pitfalls of the system are discussed and evaluated as follows, by utilizing the SWOT analysis.

Strengths	**Weaknesses**
- Simple and Adjustable Frame and force generation system. - All moving parts are relatively robust -Design is modular; each antigravity cable is the same.	-The frame is relatively large
Opportunities	**Threats**
-The system can be adapted to have active force assistance -The cables can be connected to different parts of the leg to optimize zero g behavior	-Setup time for patients may be too long -There is a risk of patient's legs hitting one another -There is a risk of frame falling on patient

Table 2.5: Swot analysis of Above leg pulley system

For future work, the strengths and opportunities will be further utilized or improved and the weaknesses and threats will be resolved, for the purpose of better overall design and manufacturing of the cable-spring system.

Assembly drawing/illustrations

Here is the assembly drawing of the preliminary design of the cable-spring system; as shown by the illustration, the patient's knee and ankle are connected with two pulleys on the top supported by ropes, whereas the pulley connected to the ankle could slide for the purpose of flexibility and adjustment. On the right of the system, the red rectangle represents the spring/composite springs. Although the objective of this quarter would be constructing a passive system, the linear actuator is also incorporated in the design for the purpose of providing force input, for compensating the disability of patients.

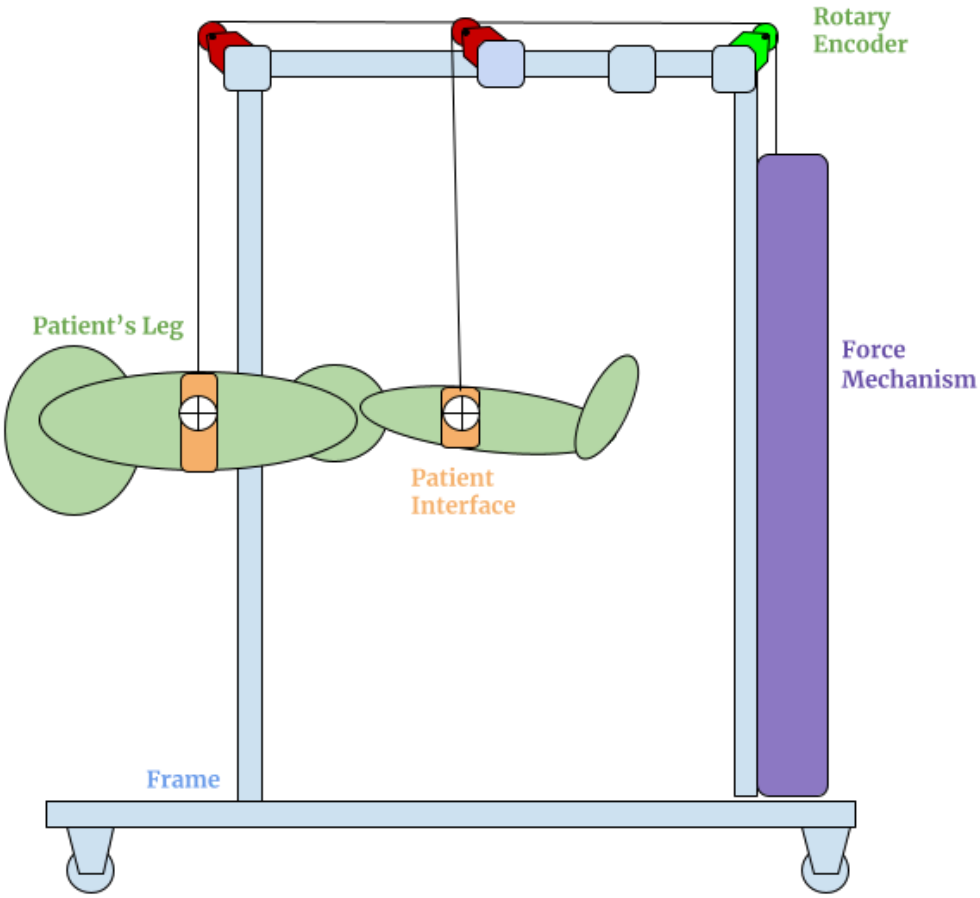


Figure 2.5.6 Full Assembly

Cost estimate

Budget:

Item	Qty	Unit Price	Total Price
1.5"x1.5" Aluminum Extrusion x 10ft	7	$87.22	$610.54
Silver Corner Bracket, 3" Long for 1-1/2" High Rail T-Slotted Framing	16	$9.54	$152.64
FRAME			**$763.18**
Springs	1	$50.00	$50.00
Cable: 3/16" Exercise Cable (50ft)	1	$50.00	$50.00
3D Printer resin:	1	$50.00	$50.00
Misc Parts	1	$50.00	$50.00
Cable-Spring System			**$200.00**
Linear Actuators: TA23 series linear actuator	4	$90.00	$360.00

Linear Actuators			**$360.00**
Arduino Teensy	2	$30.00	$60.00
Misc Parts	1	$50.00	$50.00
Rotary encoders Type: LPD3806-600BM-G5-24C	6	$18.99	$113.94
force/pressure sensor	3	$12.00	$36.00
Jump wire	2	$12.00	$24.00
Sense System			**$283.94**
Knee Brace	2	$70.00	$140.00
Ankle Brace	2	$50.00	$100.00
Human Interface			**$240.00**
TOTAL			$1,613.18

Chapter 3: Detailed/Critical Design

3.1 Frame

Design

The design of the frame was based on our preliminary models. The basic shape is an open boxlike frame with cross bracing on each corner for security. It is designed to house and incorporate all components of the project including the spring-mass system, sensors and electrical components, and a junction for a computer.



Figure 3.1.1 CAD model of the Frame

The front is left open to allow for people to be able to fit their legs through for attachment. Two long cross bars were attached to stabilize lateral motion. The back however is much more intricate. The back is designed to hold and support 4 rails with sliders and weight attachments. This was achieved by having four beams attached to the back of the frame. They rested on top of a support bar with further cross bracing.

The top consists of two pulleys per leg, one for the thigh and one for the shank. A slider was equipped to the middle bar that can move the shank pulleys based upon the user's height. Finally, the frame is equipped with wheels for mobility and floor locks to avoid any sliding motion.

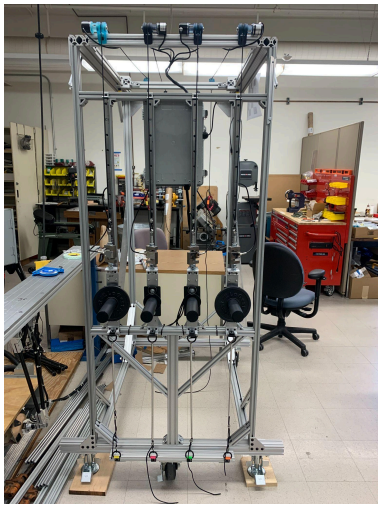


Figure 3.1.2: Back of the Frame

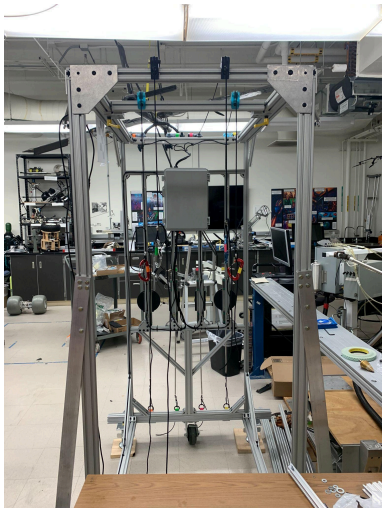


Figure 3.1.3 Front of the Frame

Manufacturing

The frame was primarily made using T-slotted aluminum extrusions from McMaster Carr. They were ordered in bulk and cut based upon the design's specifications. Different types of fixturing pieces were ordered for the T-slotted framing such as corner plating and gusseting, angled cross beams, and fasteners. The sliders were also ordered and are compatible with the bars.

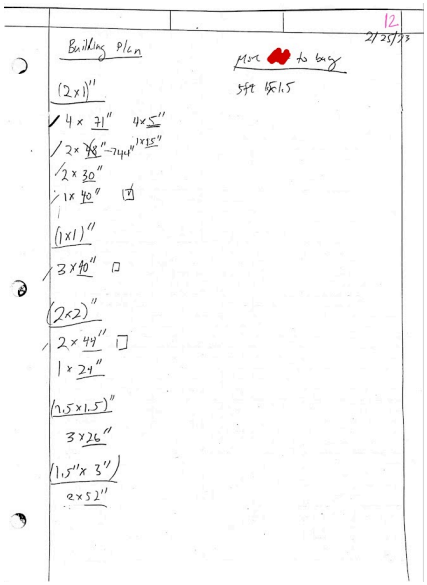


Figure 3.1.4: Cutting plan for the aluminum extrusions

Aluminum bars were also ordered to assist with stability. Two long pieces of 6061 Aluminum bars were ordered along with shorter thin bars for stability purposes. The floor plants were purchased and the wheels were inherited from the lab. Finally, an electrical box was attached to the frame to house our wiring and microcontroller. The team spent two weeks manufacturing and putting together the frame and another week to assemble the full device together.

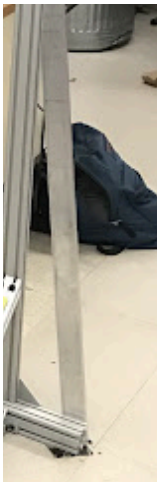


Figure 3.1.5: T-slotted Framing with aluminum bar for stability

3.2 Force Mechanism

Design

The design of the new Spring-Mass force mechanism began with a conceptual design drawing of all the necessary components. This is seen in Fig 3.2.1. The weights would be off the shelf plates, with 2” ID. These plates are attached to the frame via linear rails, so that they are constrained to only a single axis of motion. This constraining of the weights allows for increased safety and gets rid of any concerns of vibration or swinging weights.

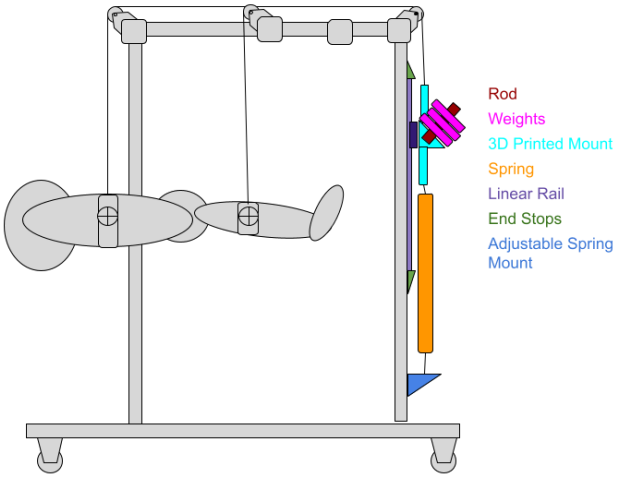


Figure 3.2.1: Detailed Conceptual Design of Force Mechanism

From the conceptual design outlined above, along with the new target specifications, the first iteration of the spring-mass system was created, as seen in figure 3.2.2. This model used an aluminum tube attached to a 3d printed part to interface between the weights and the linear bearings. This model was flagged for its potential risks of breaking, as there would be a significant amount of weight hanging from the 3d printed part.

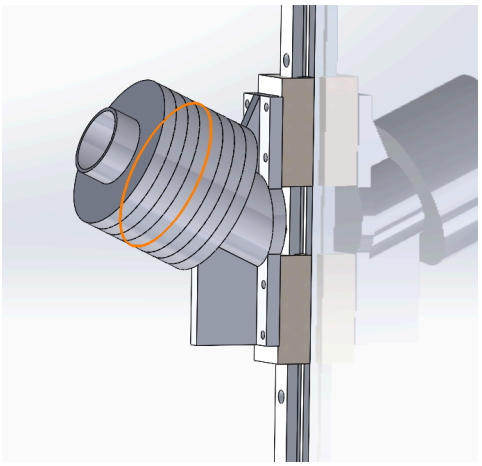


Figure 3.2.2: First Solid Model of Force Mechanism

To address these safety concerns, the aluminum tube and 3D printed interface were replaced with an off the shelf weight holder and an aluminum plate. This would allow for a more secure connection between the weight and the frame, reducing risk of failure in this critical component. This updated design can be seen below in Figure 3.2.3.

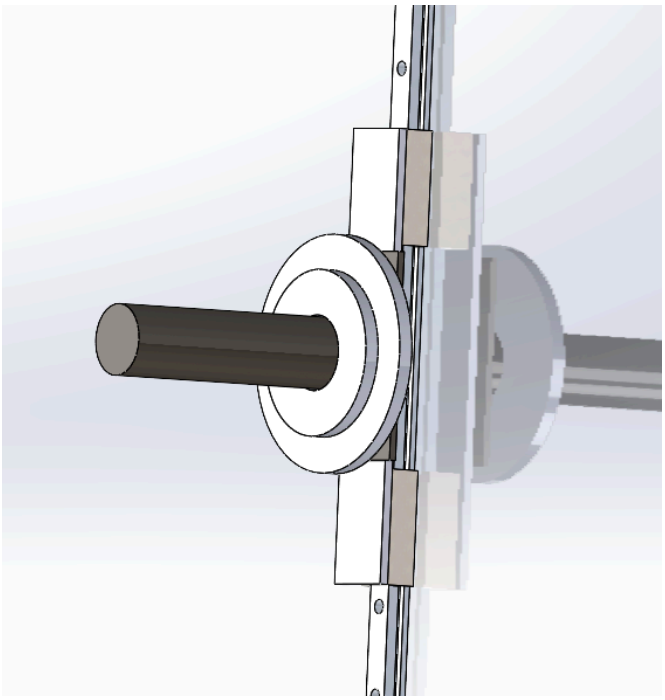


Figure 3.2.3: Final Spring-Mass Design

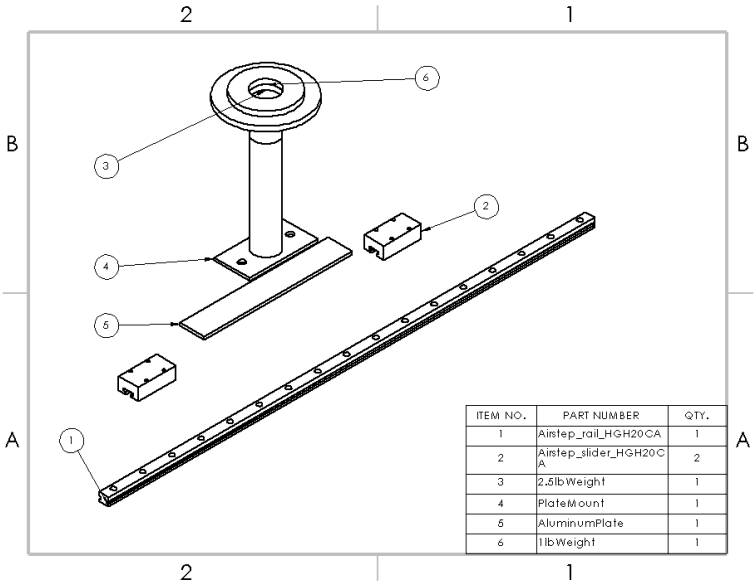


Figure 3.2.4: Spring-Mass Drawing

Manufacturing

A majority of the components for the spring-mass system were off the shelf, and did not need modification. However, a few components needed to be modified so that they would work properly. Most notably are the aluminum angle that was used to hold the springs and the force sensor, as well as the aluminum plate. Below are the drawings used to manufacture the parts.

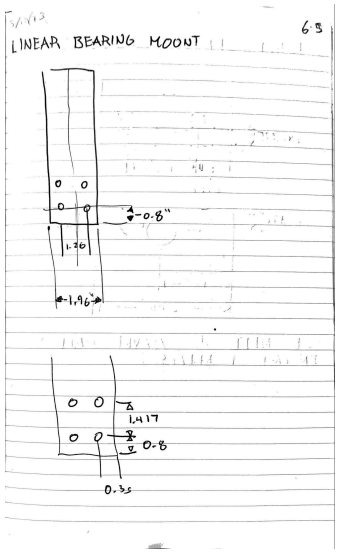


Figure 3.2.5: Linear Bearing Mounting Plate Manufacturing Sketch

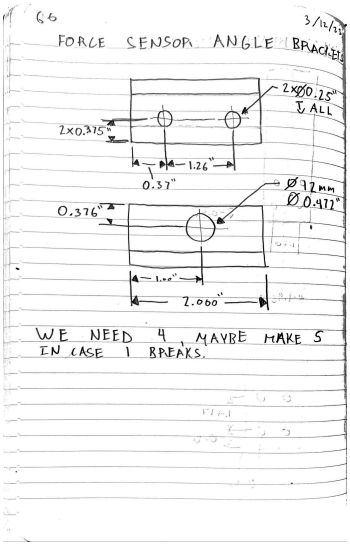


Figure 3.2.6: Force Sensor Mounting Bracket Manufacturing Sketch

3.3 Sensors



Figure 3.3.1: rotary encoders system

The rotary encoder is mounted to the extension of the pulley mount with screws to fix its position. The encoder shaft is connected to the bolt that goes through the bearings and pulley. A 3d-printed connection part will connect the steel rod and encoder shaft. When the pulley rotates, it will rotate the bolt inside, and the bolt will rotate the steel shaft to make a rotary encoder reading the data.

In the extreme case where the patients can move their legs really fast, the reading from the encoder can be inaccurate since there will be a lot of slippage between pulley and rope. To solve this problem. We add some ribs around the pulley to gain more frictions so the rope has less chance to slip. The test results show that the error between test reading and expected reading is about 5 percent which can be ignored. Therefore, our reading from the encoder is valid and valuable.

The purpose of designing this encoder mount model is to provide a system that can attach the encoder to the whole system for data collection. The encoder mount, pulley, and connection component are made by 3d printing. The material for 3d printing has a relatively high strength which makes the components not easy to break. However, by considering the various weights of patients, a stronger material may be needed to deal with the condition that the patients can have really heavy legs.

We decided to use the LPD3806-600BM type of rotary encoder. It provides 600 data points for every circle which allow us to record a degree as small as 0.6 degree. Moreover, this encoder is proper for our budget since it is about 25 dollars each and a rotary with a higher resolution will be more than 100 dollar each.

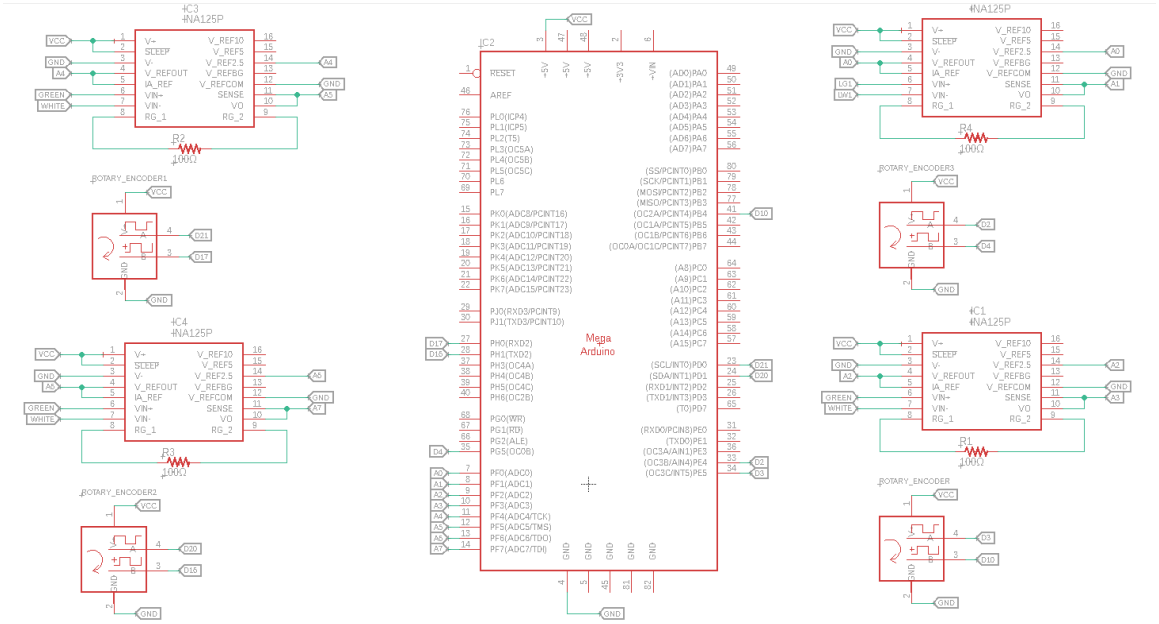


Figure 3.3.2: Schematic of Encoders and Sensors System

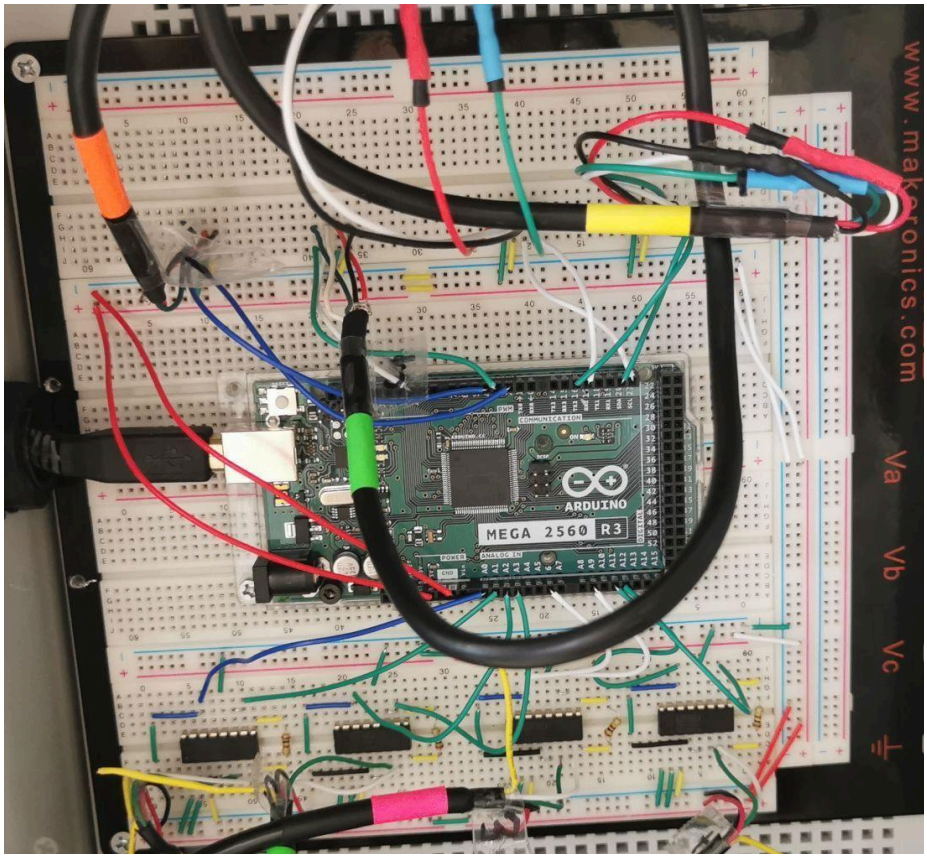


Figure 3.3.3: Distribution of electric circuit

Based on the attributes of components that we used in our system, including both rotary encoders and load cell, we firstly draw out the schematic shown in the figure 3.3.2. Within the large Arduino Mega that we are going to incorporate in the system, we need to connect four rotary encoders and four load cells. Based on the rule that one of the line of rotary encoders must be connected with one of the interrupt pin, we decide to connect the green line with interrupt digital pin 2, 3, 20, and 21 and connect the white line with non-interrupt digital pin 4, 10, 16, and 17.

To be similar to how we connect the rotary encoders, we are still going to use two analog pins on the Arduino board with the load cells. What's different is, there is no difference between the analog pins so that we can freely decide which pins we are going to connect with load cells. For convenience and neat arrangement, we connect A0 and A1 with the first load cell, A2 and A3 with the second load cell, A6 and A9 with the third load cell, and A11 and A12 with the fourth load cell.

Furthermore, because of the fact that there is only one 5V pin on the Arduino Mega used for power supply and two ground pins, we plan to connect all positive pins and negative pins shown on the side of the breadboard so that they are all interconnected. Under this situation, we just need to connect one of the positive pins with 5V to provide power supply throughout the whole breadboard. For the purpose of distinguishing each

component, we also label them with different colors so that we would clearly know which device is the target.

3.4 Post Processor

By utilizing the distance data collected from rotary encoders and utilizing the post-processing algorithm in matlab, the following results were obtained, as shown by figure 3.4.1. The code algorithm is based on the derivations of equations for leg segments, i.e. thigh and shank, in section 2.3. There exists room for improvement for the post-processing as the general trend of the leg segment angles shall be sinusoidal in comparison to square waves.

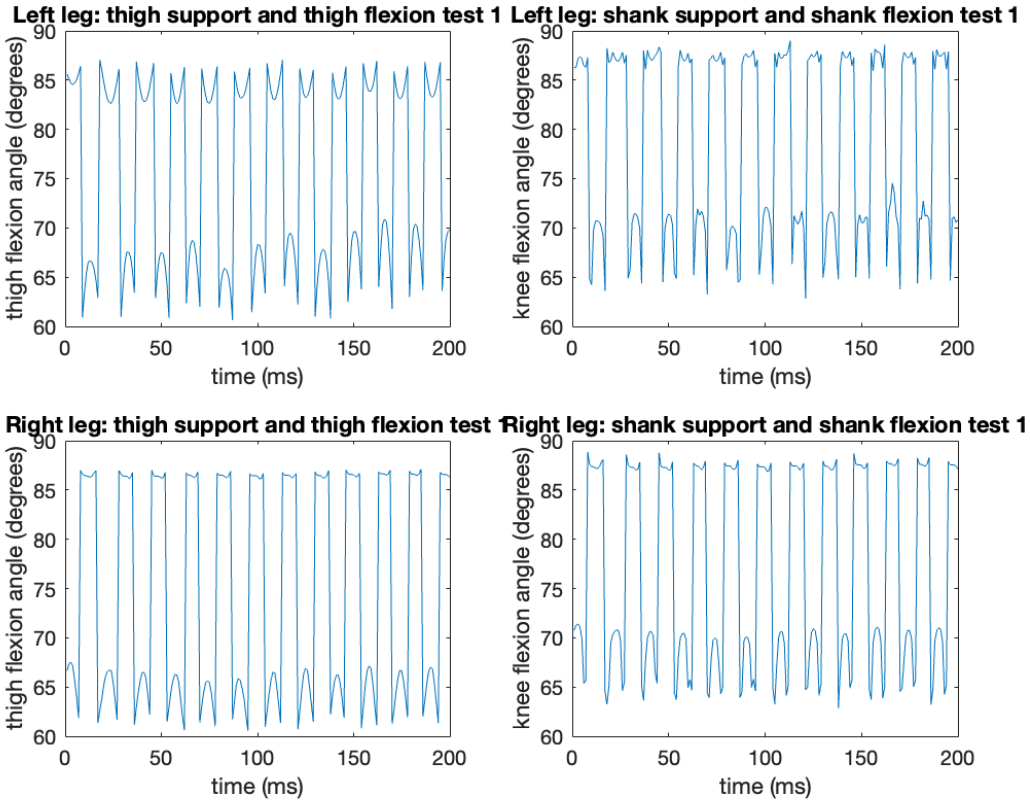


Figure 3.4.1 Regular walking - leg segments flexion angles

In addition, by utilizing the angle data obtained from the post-processing algorithm and participant leg lengths, the walking of participant's legs can be simulated as shown in figure 3.4.2. The benefit of this simulation is that it provides the visualization of motion for clinicians who would like to examine the performance of patients/participants during the leg recovery.

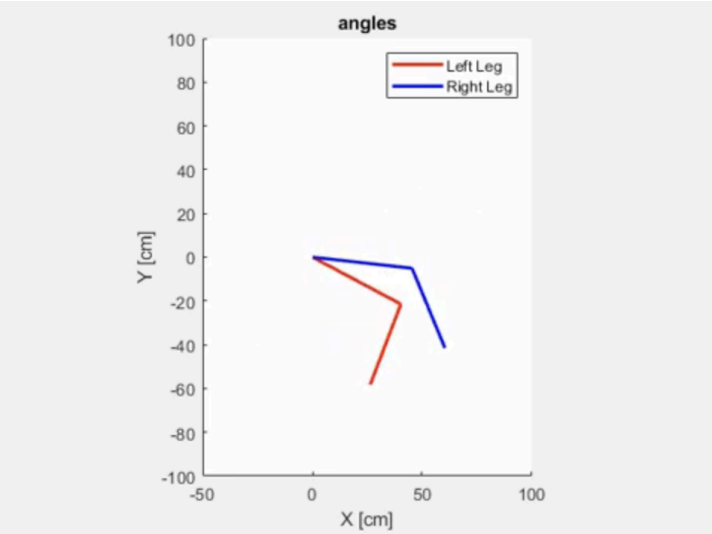


figure 3.4.2 Regular walking - participant motion

Detailed Cost Estimate:

Item	Product #	Qt.	Manufacturer/Company	Price	Total
Grand Total			**Subtotal:**	**$ 2,016.88**	**$ 2,173.19**
Leg Brace					**$ 115.96**
M MANUEKLEAR Ankle Straps pair		1	Amazon	$ 15.99	$ 15.99
Orthomen Hinged ROM Knee Brace		1	Amazon	$ 99.97	$ 99.97
The x Bands - Cable Attachments (pair)		1	Amazon	$ 18.99	$ 18.99
Sense				**TOTAL**	**$ 283.43**
rotary encoder		2	Amazon	$ 18.99	$ 37.98
S-type load cell		0	Amazon	$ 40.25	
		4	Amazon	$ 39.29	$ 157.16
		0	Amazon	$ 38.82	
Arduino mega		1	Amazon	$ 48.37	$ 48.37
HX711 amplifier		4	Amazon	$ 9.98	$ 39.92
INA125P amplifier		4	Mouser Electronics	$ 8.05	$ 32.20
Frame 1 (Single)				**TOTAL**	**$ 1,074.04**
1x1 bar	47065T101	0	McMaster	$ 27.44	$ -
2x1 bar 10ft	47065T107	3	McMaster	$ 76.88	$ 230.64
2x18 diagonal brace	47065T705	2	McMaster	$ 31.96	$ 63.92
2x6 diagonal brace	47065T187	2	McMaster	$ 23.04	$ 46.08

90deg 1" 3" brace	47065T267	8	McMaster	$ 11.60	$ 92.80
1x3 Tee brace	47065T278	2	McMaster	$ 12.10	$ 24.20
Retraction Pedal on Both Sides with Pivoting Base	2728T21	0	McMaster	$ 66.28	$ -
straight 2x4 brace	47065T262	0	McMaster	$ 18.10	$ -
Closed Corner Gusset	47065T216	10	McMaster	$ 6.11	$ 61.10
Linear bearing	47065T781	2	McMaster	$ 75.03	$ 150.06
Solid Casters	30305T66	2	McMaster	$ 39.50	$ 79.00
Rotating Casters	30305T56	2	McMaster	$ 50.80	$ 101.60
1x18 diagonal brace	47065T701	6	McMaster	$ 30.08	$ 180.48
Linear Rail Breaks	6812N306	2	McMaster	$ 22.08	$ 44.16
Wheel breaks	2422T98	2	McMaster	$ 20.51	$ 41.02
Spring Mass System				**TOTAL**	**$ 543.45**
5 lb Weight set (x2)		2	Amazon	$ 27.99	$ 55.98
2 lb Weight set (x2)		2	Amazon	$ 18.99	$ 37.98
1 lb weight set (x4)		2	Amazon	$ 23.99	$ 47.98
Linear Rails 1m	HGH20 CA	4	Amazon	$ 83.99	$ 335.96
Springs		2	The Spring Store	$ 18.03	$ 36.06
Springs		2	The Spring Store	$ 9.25	$ 18.50
Bearings For Encoders		1	Amazon	$ 10.99	$ 10.99