EMG TRIGGERED LOWER LIMB REHABILITATION DEVICE FOR STROKE PATIENTS

A Final Year Project Report

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ABSTRACT

Stroke is becoming a common disease in elderly people which often leads to some functional disability, mainly affecting the stride and sometime in severe case it become permanent dysfunction. It affects one out of six people in the world. This report highlights the aim of the project to manufacture a lower limb rehabilitation device that is capable of performing the duties of physiotherapist to treat the post stroke gait rehabilitation. Robotics plays important role in therapy activities for rehabilitation treatments. This report reviews to observes these perspectives through three different tools, the type of exercises, the physical implantations, and sensorimotor functions. A detailed review has been accomplished in order to meet the final goal. The Literature Review has been comprehensively mentioned in this report and after considering all of the research and data resources, the best possible solution has been chosen, and a complete methodology is designed for lower limb rehabilitation device that is capable of performing the assigned task. A complete manufacturing plan is described. The basic model is designed using the software SOLIDWORKS and the analysis is performed using MATLAB.A Finite Element Analysis is performed on the device which shows stress and strain behavior when the device is in working condition. This report describes the prototype manufacturing of device using 3D printing technology.

ACKNOWLEDGMENTS

All praise to Allah S.W.T the Almighty, for blessing us with the strength, the chance, and the endurance to progress in the project effectively and efficiently. We would like to express our sincere gratitude to our advisor Dr. Asim Waris for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped us in research and the progress of project.

We are extremely grateful to our beloved parents for their love, prayers, caring and sacrifices for educating and preparing us for future. We would like to appreciate our friends for their unconditional love and moral support.

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ABBREVIATIONS

ADLs	Activities of daily living
AAROM	Active assisted range of motion
AROM	Active range of motion
PROM	Passive range of motion
EMG	Electromyography
FSR	Force Sensing Resistor
CMRR	Common Mode Rejection Ratio

NOMENCLATURE

CHAPTER 1: INTRODUCTION

1.1 Background

1.1.1 Stroke

Stroke is a neurological disorder in which restricted blood flow to the brain results in cell death[1]. The main types of strokes are:

- Ischemic stroke: caused by the blockage of arteries that supply blood to the brain.
- Hemorrhagic stroke: caused by the leakage of artery in the brain.[2]

1.1.2 Paralysis

Stroke can lead to temporary or permanent inability to move a part of body, also called paralysis[3]. Types of paralysis include:

- Monopelgia: paralysis of a single limb
- Hemipelgia: paralysis of an arm and leg, on the same side of body
- Parapelgia: paralysis below the waist
- Quadripelgia: paralysis below the neck[4]

1.1.3 Physiotherapy

Physiotherapy is an essential part of recovery from stroke, which helps the patient to recover the function of the paralyzed limb. But there are a number of constraints associated with conventional physiotherapy, it is tedious, time consuming and requires a professional. These constraints can be eliminated by the use of robot-assisted physiotherapy.

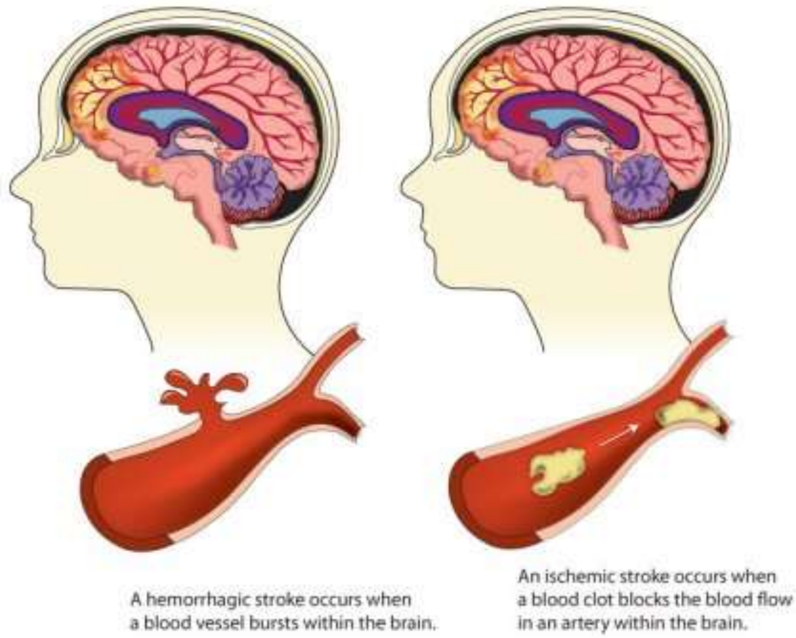


Figure 1 Haemorrhagic stroke - Ischemic

1.2 Motivation

1.2.1 Robot assisted Physiotherapy

Every year approximately 15 million people worldwide suffer from stroke[5], that can lead to motor dysfunction. With undue attention given to this critical situation, the outcome can even lead to permanent paralysis. Physiotherapy, a conventional method involving several therapeutical exercises, is still widely used aiding patients to regain control over their paralyzed limb and improve their function and mobility, enabling the patients to be independent in both short and long run. Although conventional physiotherapy has a high success rate, but several limitations should be taken into account, including requirement of a professional physiotherapist, overlooking a patient when attending multiple ones, lack of motivation from the patient to reach their centers, highly priced and time-consuming sessions. To cater for the stated problems, Robot-Assisted Physiotherapy is taken into account, which involves the use of Rehab robots which assist the different sensorimotor functions of our body. These rehabilitation robots can deliver high intensity training and eliminate the need for labor intensive procedure carried out by the physiotherapist.

1.2.2 Upper Limb Rehabilitation & Lower Limb Rehabilitation

The phrase "activities of daily living" (ADLs) is used in healthcare to describe people's everyday self-care tasks. For ADLs, upper limbs are more important as compared to lower limbs. That's why great amount of research has been done in upper limb rehabilitation. Currently, exoskeletons, rehabilitation robots and gaming devices are available for upper limb rehabilitation.[6]

On the other hand, no product is available commercially that can provide lower limb rehabilitation in a home-based environment which can help the patient regain normal function of lower limbs.

1.3 Problem Statement and Aim

"Developing a wearable lower-limb rehabilitation device for stoke patients that can be operated in home environment."

1.4 Design Objectives

The defining features of our solution include:

1. Wearable/Portable: The device must be portable, can be operated in home environment
2. Comfort: The patient must be comfortable wearing the device
3. Easy to use: Should be operatable without the need of a physiotherapist

So, our objective is to design a lower limb rehabilitation device that is portable, comfortable, and easy to use.

1.5 Project Deliverables

1. Detailed Literature Review
2. Development of Conceptual Design
3. Comprehensive Design with Detailed Analysis
4. Fabrication of the prototype
5. Clinical Testing of the prototype

CHAPTER 2: LITERATURE REVIEW

2.1 Methodology:

The methodology for the literature review was to explore about stroke rehabilitation extensively. Learning about the different types of exercises that physiotherapists perform. Once the exercise has been selected for our rehabilitation device, research on the mechanical design was done. How can the exercise be performed efficiently and what components would be used?

After the mechanical design, sensors were explored that can be used to actuate our mechanism. The sensor most suitable for our working conditions was selected.

The final step is the clinical testing of our device, which would determine whether our device is suitable for usage or not.

It should be noted that multiple resources were exhausted for carrying out the detailed Literature Review. These resources include research papers, a brief market survey and other internet resources. These resources (especially the research papers) are cited in the whole report wherever relevant.

2.2 Active and Passive Motion:

In physical therapy, range of motion exercises are performed. The purpose of these exercises is to prevent shortening of muscles, capsule, ligaments, and tendons. Another benefit of these exercises is that it provides sensory stimulation. Range of motion exercises:

a) Active range of motion (AROM): The exercise performed by the patient solely, without any external help.

b) Passive range of motion (PROM): The exercise performed externally, with no input from the patient. PROM exercises can be performed by a physiotherapist, family member, or a robot.

c) Active assisted range of motion (AAROM): The exercise performed by the patient to the extend he/she can, plus the external assistance to complete the exercise. [7]

Our device must be capable of both PROM and AAROM because stroke patients can require both types of exercises during the course of the treatment.

2.3 Lower limb exercises for stroke patients:

The table shows common exercises that are used for stroke patients to get them back on their feet. [8]

Sr.	Exercise	Procedure
1.	Seated Marching	In a seated position, lift the leg to the chest then back to the floor, repeat.
2.	Knee Extension	In a seated position, extend the leg out and then bring back to the floor, repeat.

3.	Toe Taps	In a lying position, lift up the leg until the knees are at 90°, then bring the leg down and tap the floor, repeat.
4.	Knee to Chest	In a lying position, bring the knee into the chest, then back to the floor, repeat.
5.	Flamingo Stands	While standing, lift one leg for 30 seconds, then the other one.
6.	Side Leg Raises	While standing, left one leg out to 45°, hold it there for some time, then bring it back to the floor, repeat.
7.	Ankle Dorsiflexion and Plantar Flexion	In a seated position, move the foot towards the knee(dorsiflexion), then extend the foot backwards till possible(plantar flexion), repeat.
8.	Assisted Toe Raises	In a seated position, place one foot underneath the other, then use the bottom foot to push the other foot upwards, repeat.
9.	Heel Raises	In a seated position, point the toes and lift the heels off the ground, then bring back to the floor, repeat.

Table 1 Different exercises for lower limb

From these exercises, we found that Ankle Dorsiflexion and Plantar Flexion is most suitable for our device.

2.4 Ankle Dorsiflexion and Plantar Flexion:

As explained before, ankle dorsiflexion and plantar flexion involves the full extension of the ankle joint in both directions.

Figure 2 Dorsiflexion and Plantar flexion

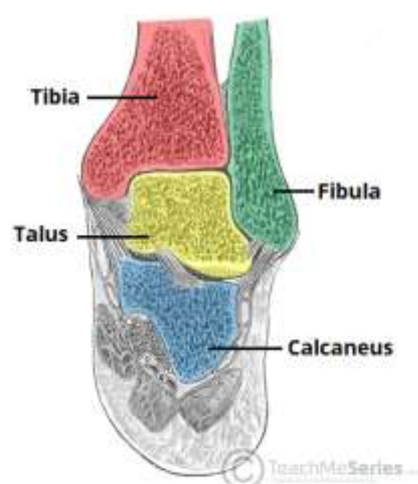


Figure 3 Bones of the ankle joint

Ankle joint is defined as a hinge type joint, only one movement is permitted in one plane. Main movements that can occur at the ankle joint are dorsiflexion and plantar flexion.

Plantar flexion is produced by the muscles in posterior part of leg, which include gastrocnemius, soleus, plantaris and posterior tibalis. Whereas dorsiflexion is produced by the anterior part of leg, which include tibalis anterioir, extensor hallcius longus and extensor digitorium longus. [9]

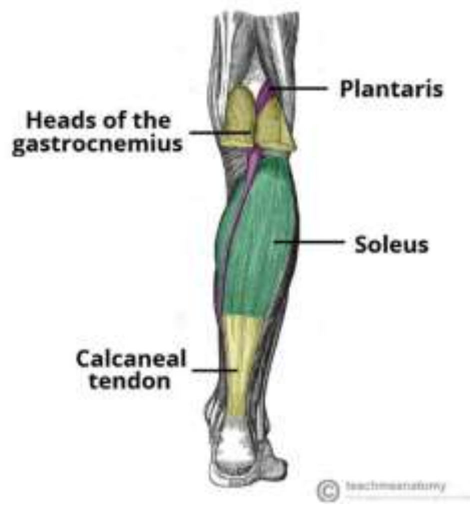


Figure 4 Superficial part of posterior leg [10]

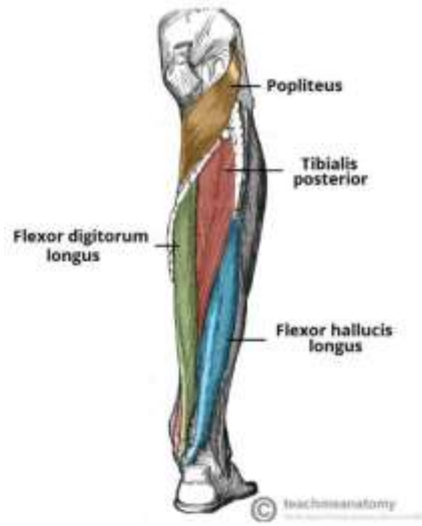


Figure 5 Deep part of posterior leg

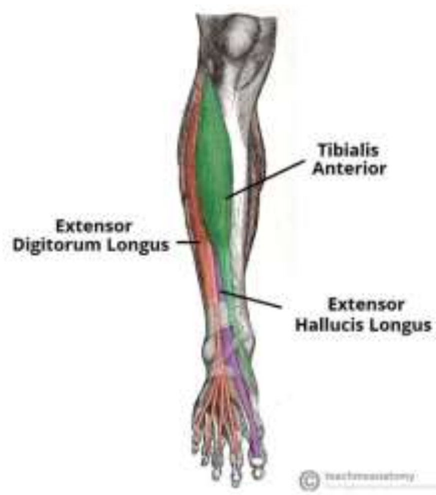


Figure 6 Muscles in the Anterior Leg [11]

In stroke patients, the muscle strength of the ankle weakens which causes decline in muscle strength, balance and normal motion. Regular dorsiflexion-plantar flexion enhances the patients' ability to perform gait as shown in [12]

2.5 Robotic Systems for Lower-Limb Rehabilitation:

The lower limb rehabilitation devices over the last decade can be classified into the following: [13]

Sr.	Robotic System	Working Principle
1.	Treadmill gait trainers	In a exoskeleton based system, partial body-weight support treadmill training (PBWSTT) is performed using the exoskeleton and treadmill.
2.	Foot-Plate Gait Trainers	Programmable foot plates for each foot, robotic system controls the plates to simulate gait patterns.
3.	Overground Gait Trainers	These robots follow the walking motion of the patients' using servos. The robotic system is present overground.
4.	Stationary Gait Trainers	These systems focus on specialized movement of the limbs for maximum benefit. This system is stationary, means the patient remains in a stationary position and exercise is performed by the robot.

5.	Stationary Ankle and Knee Rehabilitation systems	These robotic systems involve the ankle and knee exercises without walking
6.	Active Foot Orthosis	These robotic systems involve the ankle and knee exercises with exoskeletons. Users wear the exoskeletons and walk on a treadmill.

Table 2 Different Types of Lower Limb Rehabilitation Systems

Among these systems, we chose the stationary ankle and knee rehabilitation system because it was the only one which can be made portable. This is because it doesn’t need an exoskeleton. Additionally, the PROM and AAROM exercises can both be done.

2.6 Mechanical Design:

Now we’ve decided about the rehabilitation system, we can start working on the mechanical design. This portion involves the surveying and review of the components involved in the prototyping and fabrication of our actuatable design. Below subsections involve descriptions on the definition, working, types and usage of the different components and their possible choices that can be used in the assembly of our mechanical design.

2.6.1 Definitions of Mechanical Design Components:

2.6.1.1 Definition of Servo Motor

A servo motor is basically a self-contained, fast functioning electrical device which primarily rotates the parts of machinery through its output shaft with great precision and efficiency. These can be programmed to rotate for specific degrees, allowing them to be more versatile. Basic components of a servo motor include, control circuit, shaft, gearset, amplifier, potentiometer and an encoder. [14]

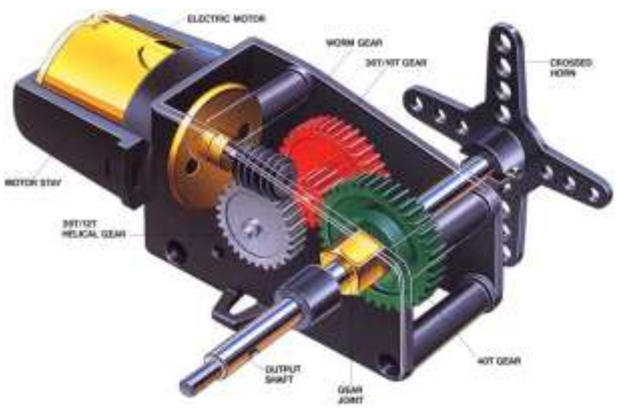


Figure 7 Generic Servo-Motor [14]

2.6.1.2 Definition of Coupler

A coupler is a mechanical component which generally connects two shafts from their ends for efficient transmission of power. In short it joins two rotating components while allowing quite minimal lateral misalignment. They are strong, rigid and prevent disconnection or slippage, but with a trade-off of efficiency during power transmission.[17]

Figure 8 Generic shaft coupler [18]

2.6.1.3 Definition of Shaft

A rotating machine element, circular in cross section that passes power from one part of the machine to another or from the machine producing power to a machine absorbing power. [19]

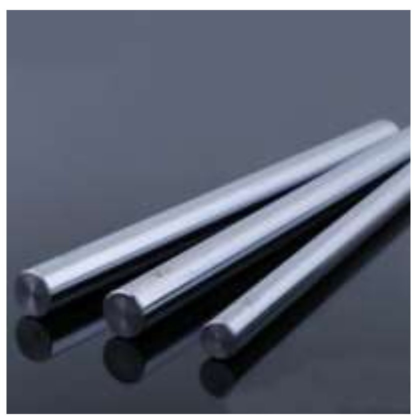


Figure 9 Generic shaft

2.6.1.4 Definition of Gears

A rotating circular machine part having evenly spaced cut or inserted teeth which mesh with another toothed part to transmit torque. The teeth prevent gear slippage.[20]

Figure 10 Generic gears

2.6.1.5 Definition of Keys

A piece of metal used to connect a rotating machine element to a shaft. It is used to prevent the relative rotation between two parts, enabling the transmission of torque to take place. [21]

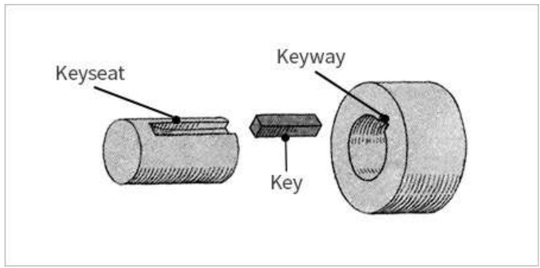


Figure 11 Generic key

2.6.1.6 Definition of Bearing

Bearing are mechanical components which assist the rotation of objects mainly shafts be reducing the friction losses. They most importantly support the misalignment of the shaft that is rotating through it.[22]

Figure 12 Generic bearings

2.6.2 Working of Mechanical Design Components:

2.6.2.1 Working of Servo Motor

As servo motor contains a position sensor, a DC motor, a gear and a control circuit. The DC motor run at excessive speed and low torque and vice versa while getting electricity from a battery. The position of shaft is sensed by the position sensor from its particular position and supplies data to the manipulate circuit. The sign is decoded by means of the manipulate circuit from the location sensor and handles the course of rotation to get the desired position. It needs a DC supply of 4.8 V to 6 V.

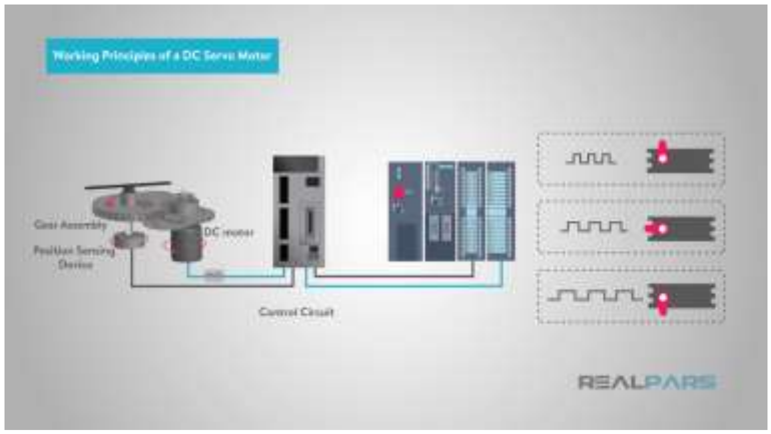


Figure 13 Working of servo motor

2.6.2.2 Working of Coupler

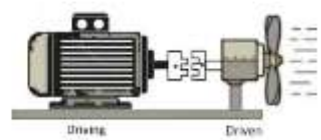
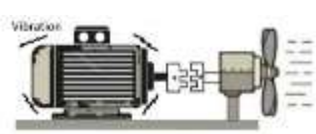
Sr	Purpose	Depiction
1	Connect 2 shafts of varying diameters	
2	Restrict transfer of heat of motor to driver side.	
3	Absorb shocks and vibrations from driving end to prevent damage.	

Table 4 Working of a coupler

2.6.2.3 Working of Shaft

Shafts are rotating elements supporting rotating parts such as gears and pulleys, helping to transmit their motion.

2.6.2.4 Working of Gears

A gear is a machine element with evenly spaced teeth cut in cylindrical or conical surfaces. Interlocking these elements transfers rotation and forces from a driveshaft to the driven shaft.

2.6.2.5 Working of Keys

The shaft has a pre-cut slot known as a key seat and the rotating element (a pulley or gear) has a keyway which is a slot provided in the hub. This system is known as a keyed joint.

2.6.2.6 Working of Bearing

Bearings basically reduce friction by providing smooth metal balls or rollers, and a smooth inner and outer metal surface for the balls to roll against. These balls or rollers "bear" the load which allows the inner component to spin smoothly. They transmit forces and transfer motion.

2.6.3 Types of Mechanical Components:

2.6.3.1 Types of Servo Motor [23]

Sr	Type	Depiction
1	**DC Servo Motor** – Runs on a DC source, can be controlled using field current. Fast response, accurate and programmable.	
2	**AC Servo Motor** – Runs on an encoder integrated with controller for feedback and closed loop control. Highly accurate, high operating voltages and Torque generation.	
3	**Position/Continuous Servo Motor** – For these the shafts can rotate about 180 degrees and for 360 for the latter. Programmable in terms of direction and speed to rotation.	
4	**Linear Servo Motor** – Similar to position servo motor but with added gears to suit the sliding motion as compared to rotation. Task specific motors.	

Table 5 Types of Servo motors

2.6.3.2 Types of Couplers [24]

Sr.	Type	Depiction
1.	**Rigid Coupling:** Used when two shafts are perfectly aligned. Suitable only in close alignment.	
2.	**Sleeve Coupling:** Also called Muff Coupling. It contains shaft, key, sleeve, and a hollow cylinder. Gib head key is fixed over the ends of the two shafts.	
3.	**Split-Muff Coupling:** The sleeve is made into two parts and joined together using bolts. The shafts are connected and a key is fitted in the keyway.	
4.	**Flange Coupling:** It contain flanges fixed at end of both shafts	

5.	**Flexible Coupling:** Shafts with both later and angular misalignment are connected using flexible coupling.	
6.	**Bushed Pin-type Coupling:** Shafts with slight parallel/angular/axial misalignment are connected using bushed pin-type coupling.	
7.	**Universal Coupling:** Shafts that intersect at an angle are connected using a universal coupling.	

8.	**Oldham Coupling:** Shafts with lateral misalignment are joined together using Oldham coupling.	
9.	**Gear Coupling:** Modified flange coupling. It can transmit high amounts of torque due to its large teeth size.	
10.	**Bellow Coupling:** Bellow couplings are used when high precision positioning is required.	
11.	**Jaw Coupling:** Jaw coupling is used when vibrations control is required.	

12.	**Diaphragm Coupling:** These are non-lubricated couplings used in turbomachinery.	
13.	**Fluid Coupling:** This coupling transmits rotating power through acceleration and deceleration of the fluid.	

Table 6 Types of Couplings

2.6.3.3 Types of Shaft [25]

Sr.	Type	Depiction
1.	**Transmission Shaft:** As the name suggests, used to transmit power from one source to the other machine. Transmission Shafts are stepped shafts, on the stepped portion gear/hub/pulley are mounted. Examples include overhead shafts, line shafts, counter shafts.	

2.	**Axle Shaft:** Axle shafts support rotating elements like wheels. They can fit in housing with the bearing. Examples include axles in automobiles.	
3.	**Spindle Shaft:** Spindle shafts are the rotating part of the machine. Spindle shafts hold the tool or workspace. Examples include spindle in lathe machine.	
4.	**Machine Shaft:** Machine shafts are present in the inside part of the assembly. Examples include crankshaft.	

Table 7 Types of Servo Motor

2.6.3.4 Types of Gears [26]

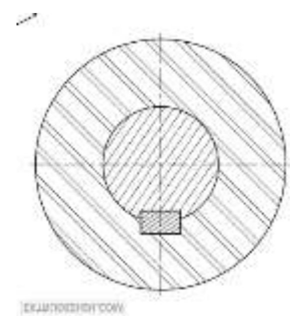
Sr.	Type	Depiction
1.	**Spur Gear:** They transmit power through parallel shafts, teeth of the gears are parallel to the shaft axis.	
2.	**Helical Gear:** The teeth of the helical gear are at an angle to the shaft axis.	
3.	**Double Helical Gear:** In this type of gear, two helical shapes are placed next to each other, with a gap in between.	

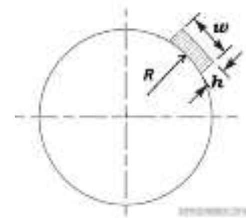
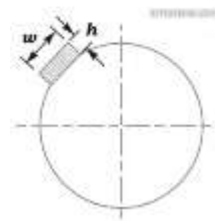
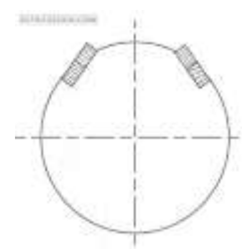
4.	**Herringbone Gear:** They are like double helical gear, but the gap between the two helical faces is absent.	
5.	**Bevel Gear:** They are used to transmit torque between shafts that intersect at 90 degrees.	
6.	**Worm Gear:** They transmit torque through right angles on shafts that don't intersect	

7.	**Hypoid Gear:** They are like spiral bevel gears but they transmit torque on shafts that don't intersect.	

Table 6 Types of Gears

2.6.3.5 Types of Keys [27]

Sr.	Type	Depiction
1.	**Sunk Keys:** In this type of key, half of the key is inserted in keyway of the shaft and the other half in keyway of the hub. Further types of sunk keys include square sunk keys, rectangular sunk keys, parallel sunk keys, gib head keys, woodruff keys and feather sunk keys.	

2.	**Saddle Keys:** Two types: Flat saddle key and Hollow saddle key. Flat saddle key fits in the keyway of hub and sits flat on the shaft. Hollow saddle key fits in the keyway of the hub but its bottom surface is shaped in order to fit the curved surface of the shaft.	 Hollow  Flat
3.	**Tangent Keys:** Pair of keys, placed at right angles to each other and tangent to the shaft's surface. Each key withstands torsion in 1 direction.	
4.	**Round Keys:** As the name suggests, these keys are round in shape and fit the holes which are drilled in hub and shaft.	

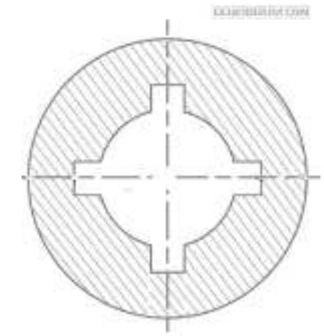
5.	**Splines:** When the keys are integral part of the shaft, they're called splines. Splined shafts can have 4, 6, 10 or 16 splines.	

Table 8 Types of Keys

2.6.3.6 Types of Bearing [28]

Sr.	Type	Depiction
1.	**Deep Grove Ball Bearings:** They absorb axial as well as radial forces. Most commonly used bearings. Features include simple design, easy to maintain. Used in wide range of applications.	
2.	**Angular Contact Ball Bearings:** Forces in angular contact ball bearings are transmitted from one raceway to the other at an angle, known as contact angle. They are	

	suitable where high axial forces are present plus radial forces.	
3.	**Self-Aligning Ball Bearings:** They contain a mechanism that allows a degree of self-alignment. They are suitable when alignment of shaft and housing is a problem. Self-Aligning Ball Bearings absorb radial forces.	
4.	**Thrust Ball Bearings:** They contain two bearing discs and raceway that contain balls. They can absorb axial forces in only one direction.	

Table 8 Types Ball bearings

Sr.	Type	Depiction
1.	**Spherical Roller Bearings:** They have a self-alignment mechanism using spherical rollers. They can be used to compensate misalignment between shaft and housing. They are suitable for absorbing high radial loads and moderate axial loads.	
2.	**Cylinder Roller Bearings:** Line contact is used between rolling elements and raceways, which enables it to sustain very high radial loads. It can also transmit limited amount of axial loads depending on the design.	
3.	**Tapered Roller Bearings:** They contain tapered raceways with conical rollers. They can absorb high radial and axial forces in one direction due to the contact angle.	

4.	**Needle Roller Bearings:** They contain long, thin rolling elements called needle rollers. They can sustain high radial forces.	

Table 9 Types Roller Bearings

2.6.4 Usage of Mechanical Components:

2.6.4.1 Usage of Servo Motor

Applications of servo motor range from movements of robotic arms, translations of conveyer belts, robotic wheels for speed and motion control, automatic door openers in markets and malls, spinning weaving machines, angle correction for solar panels and lastly (a typical example) in packaging machines as depicted in the diagram below.

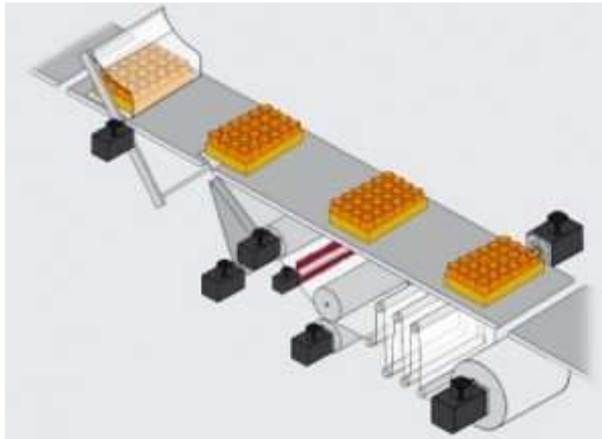


Figure 14 Servo motor in packaging machine

2.6.4.2 Usage of Coupler

Couplers have several applications ranging from connection between 2 shafts to avoid disconnections, provide misalignment for induction of flexibility, suppress the vibrations and reduce transmission shock loads.

2.6.4.3 Usage of Shaft

These include stepped shafts transferring power from the source to a machine absorbing power. E.g.: counter shafts, factory shafts, line shafts etc. Shafts inside of the machine assembly, being integral part of the machine. E.g., the crankshaft of a car.

2.6.4.4 Usage of Gears

Gears are vital when transmitting rotation from one axis to another. They are used to alter the output speed and torque of shafts. The teeth of the gear allow for more discreet control of a shaft in high load situations.

2.6.4.5 Usage of Keys

Shaft keys are used in conjunction with shafts, as a result, the application of keys would be the same as the application of shafts. (Refer to the section of shafts).

2.6.4.6 Usage of Bearing

Applications of bearings include high speed gear boxes and pumps, transmission systems, drive shafts, air compressors, seat sliders, mechanical watches, clutch release mechanisms and several industrial equipment.

2.6.5 Materials Selection:

2.6.5.1 Metals

Sr.	Material	Pros	Cons
1.	Stainless Steel	Resistant to oxidation, hardness, very high melting point	Gets dirty very easily, expensive
2.	Aluminium	Durable, lightweight, ductile, malleable	Not particularly strong, expensive
3.	Titanium	Corrosion resistant, highest strength to density ratio of any metal.	Very costly, laborious process to extract titanium from ores.

4.	Iron	Strong, durable, inexpensive	Corrodes easily, brittle in cold climates.
5.	Carbon Steel	Increased strength, hardness	Difficult to work with, less malleability and ductility.

Table 10 Metal materials

2.6.5.2 (3D) Printed Materials

Sr.	**Material**	**Pros**	**Cons**
1.	Acrylonitrile Butadiene Styrene (ABS)	Low cost, good impact/wear resistance, good heat resistance.	Heavy warping, parts tend to shrink leads to dimensional inaccuracy.
2.	Polylactic Acid (PLA)	Low cost, good dimensional accuracy, stiff	Low heat resistance, not suitable for outdoors, filament can be brittle and break.

3.	Nylon	Tough, high impact resistance, good abrasion resistance	Warping, air-tight storage to prevent water absorption, not recommended for moist environment.
4.	Glycol Modified version of Polyethylene Terephthalate (PETG)	Negligible warping, glossy and smooth surface finish, durable and touch, high impact strength	Poor bridging, thin hair can be present on the surface
5.	Polypropylene	Good impact resistance, good heat resistance.	Low strength, heavy warping, expensive.
6.	Hight Impact Polystyrene (HIPS)	Low cost, lightweight, impact and water resistant	High printing temperature, heated bed required, ventilation required.

Table 11 3D printed materials

2.6.6 Concept of Mechanical Design:

Doing initial research from various papers, we analysed different feasible designs for our device keeping in view the portability factor. The most suitable compact design that we found is shown in Figure 7 [17]. In this design, the motor shaft is aligned parallel to the leg. The torque is then transmitted by 90˚ to the foot link using bevel gears.

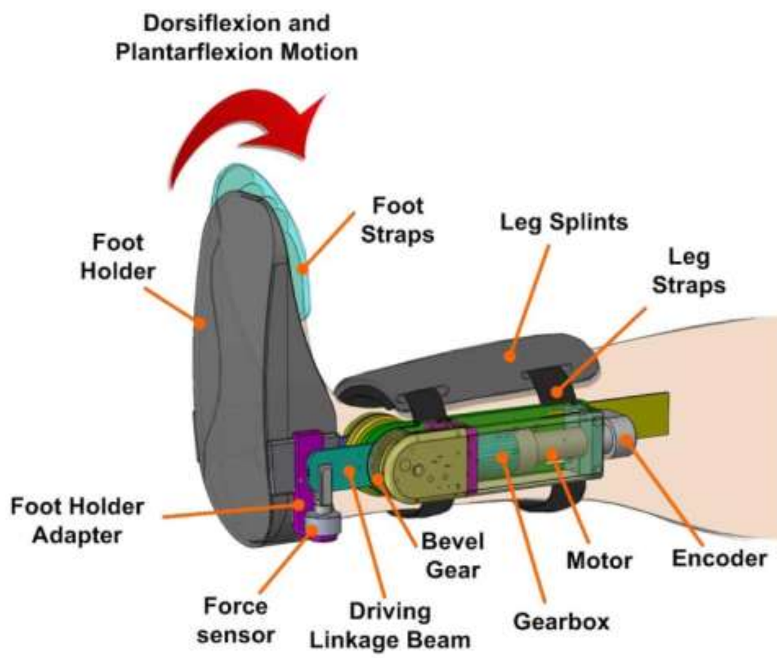


Figure 15 Sample Stroke Rehabilitation Device for Ankle Joint [17]

2.7 Sensor:

In our rehabilitation device, the motor acts as the actuator. But we also need a sensor.

- Sensor: A sensor converts physical characteristics into electrical signals.
- Actuator: An actuator converts the electrical signals into physical characteristics. [14]

For our device, we need a sensor that can distinguish between PROM and AAROM exercises. Different actuation is required in both cases.

While researching for sensor, we found two sensors that can be used:

2.7.1 Force Sensing Resistor (FSR) [15]

When a force, pressure, or stress is applied on an FSR, the resistance changes.

FSR can be used in the footrest of our device, if the patient exerts pressure, then the device can run in the AAROM mode. But when the patient doesn't exert any pressure, then the device can run in the PROM mode.

.

Figure 16 Force Sensing Resistor

2.7.2 Electromyography(EMG) sensor [16]

EMG sensor detects the electrical signals produced by muscle motion. There are two types of EMG sensors:

1. Surface EMG (sEMG) sensor: Surface EMG electrodes are placed on the skin with respect to the muscles whose electrical activity is to be measured. The electrodes are connected to a module which is responsible for the processing of the electrical signals. Main advantage of sEMG is it's non-invasive and the electrodes can be easily attached and removed. Disadvantage of sEMG is noise can be present in the electrical signal generated.

Figure 17 EMG sensor with surface electrodes

1. Intramuscular EMG: A monopolar needle electrode are inserted into the muscle tissue whose electrical activity is to be measured. The noise levels in the electrical signals of intramuscular EMG are very low. The disadvantage of intramuscular EMG is the significant discomfort caused by the insertion of the needles.

From our research about the different types of sensors, we found that the sEMG sensor would be the most appropriate sensor for our device. It's easy to use, comfortable for the patient, and widely used in biomedical devices. The surface electrodes will be connected to the muscles that move during the dorsiflexion/plantarflexion, and the electrical activity will be measured. According to the measured activity, the mode of exercise will be decided and performed.

Furthermore, [6] recommends the use of sEMG sensor for lower limb rehabilitation devices.

2.8 Control System:

A control system is necessary, which will take the input from the sEMG sensor, decide the mode of the exercise, either PROM or AAROM, and run the motor accordingly.

For the control system, we only considered Arduino Uno R3 because of the following features:

- Ease of use
- EMG sensors work well with Arduino
- Our prior work experience with Arduino
- Relatively cheap and readily available
- Extensive resources available

2.10 Summary:

Choice Required	**Decision Made**	**Reason**
Range of Motion	PROM and AAROM	Stroke patients can require both exercises during the course of treatment
Exercises	Ankle Dorsiflexion/Plantarflexion	Improves the gait ability of the patient
Robotic System	Stationary Ankle and Knee Rehabilitation System	Allows portability

Sensor	sEMG sensor	Widely used in biomedical applications, easy to use.
Control System	Arduino based control system	Ease of use, works well with EMG sensors

Table 12 Summary of all the decisions made in Literature Review

CHAPTER 3: METHODOLOGY

3.1 Electronics of Device:

The whole circuit comprises of following components:

I. Input Electrodes
II. EMG Sensor
III. Power Source for EMG Sensor
IV. Arduino
V. Servo Motor
VI. Power Source for Servo Motor

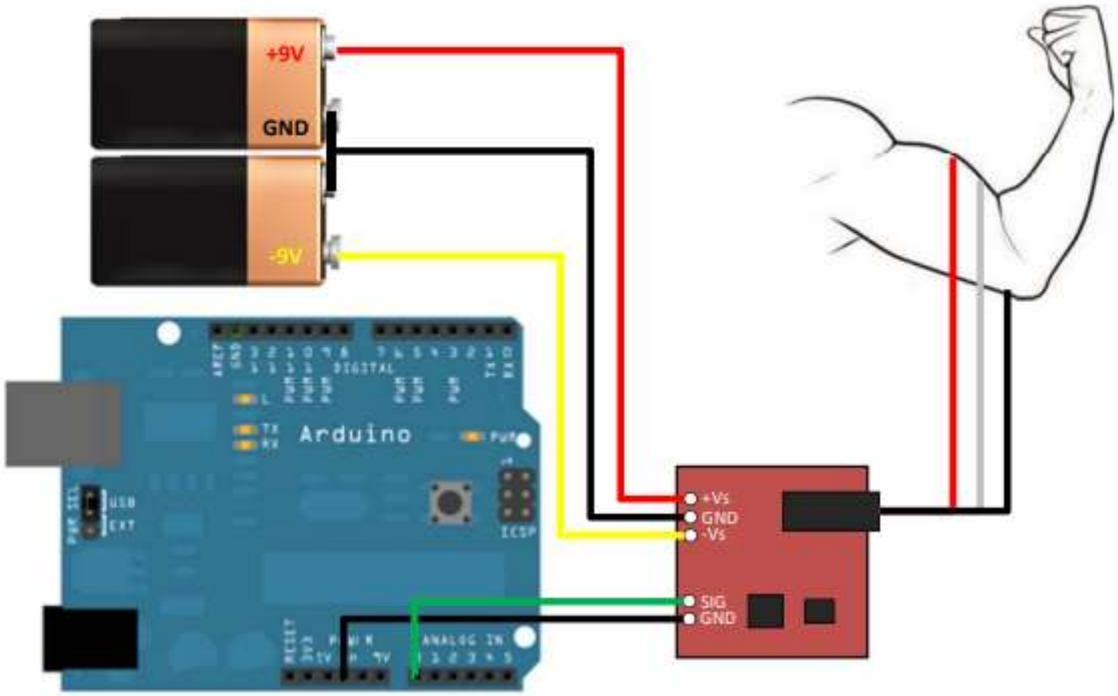


Figure 18 Basic circuit of the device

3.1.1 Input Electrodes:

The three adhesive electrodes will serve as sensors to provide input voltage to the circuit, and the circuit will give resulting output voltage from reading the corresponding muscular activity.

The electrodes that we are using are **Ambu Neuroline 720 (Ref 72000-S/25)**.

Figure 19 Neurology Surface Electrodes

3.1.2 EMG Sensor:

Our research about different types of available sensors for our device lead to believe that EMG sensors would be the most appropriate ones because of their ease of usage, comfortability of patients and wide applications in biomedical field [6].

The EMG sensor's circuit has three stages:

i. Instrumentation Amplifier

ii. Band Pass Filter

iii. Non-inverting Amplifier

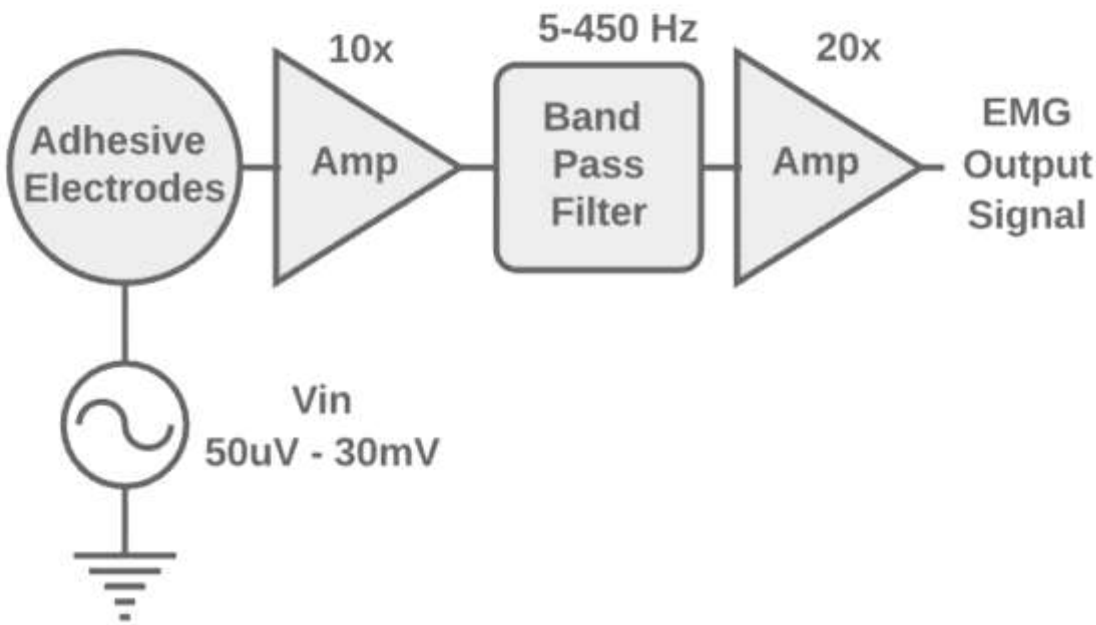


Figure 20 Basic circuitry of EMG sensor

Instrumentation Amplifier:

It provides the high input impedance to match with the high output of the skin impedance. Instrumentation amplifiers have large Common Mode Rejection Ratios (CMMR). It reduces the noise that is picked up by circuit.

Band Pass Filter:

It eliminates all those frequencies that are out of the bandwidth of an EMG sensor. Only a selected range of frequencies 5-450 Hz is allowed to pass. The filter removes the baseline drift sometimes associated with movement and removes any DC offset if present.

Non-inverting Amplifier:

It provides a large gain to the small EMG signal so that it can be made usable/readable. The value of this gain can be adjusted according to our requirement by a small screw on the circuit depending upon the muscle group and the quality of input electrodes.

The sensor that we initially tested was **Muscle Sensor v3**.

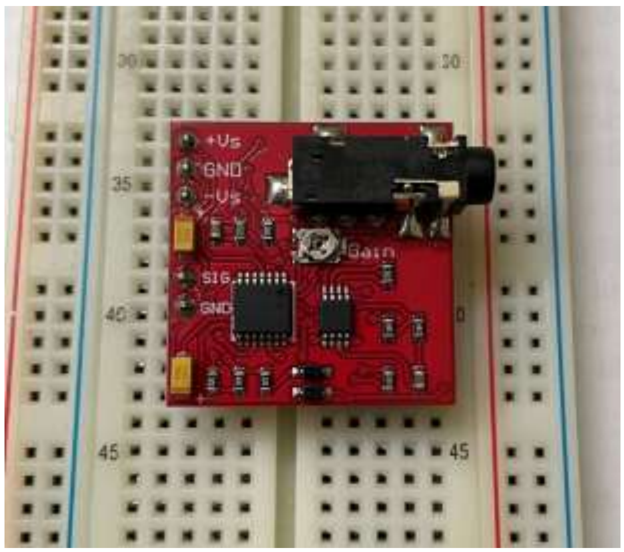


Figure 21 Muscle Sensor v3

But the output signal from this sensor was unusable due to presence of noise. We switched to Myoware sensor which provides much better output signal.

Figure 22 Myoware sensor

3.1.3 Power Source for EMG Sensor:

Two 9V batteries are connected in series by taking their grounds common and as a result, a DC power source of 18V is obtained. This power is provided to the EMG Sensor.

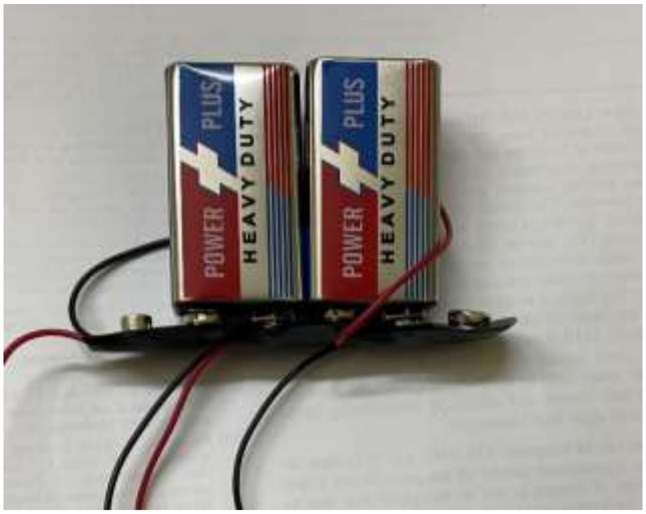
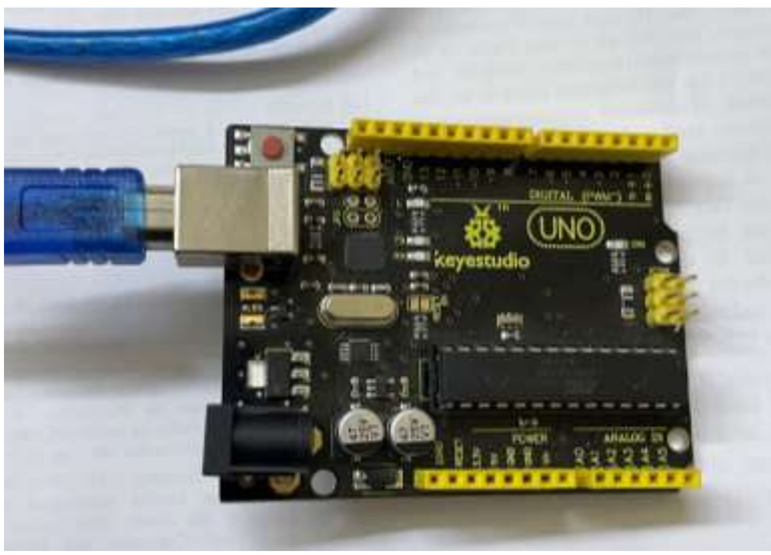


Figure 23 Two 9V batteries connected in series

3.1.4 Arduino:

Arduino will receive the analogue signal as input coming from the EMG sensor. This input voltage signal will be compared to the threshold voltage and as per the program installed in Arduino, a digital output signal will be sent to the servo motor. Consequently, the desired motion (PROM/AAROM) depending upon the input signal, will be obtained.

For controlling the motion of our device, we are using Arduino Uno R3 due to its simplicity of usage and reasonable cost.



3.1.5 Power Source for Servo Motor:

Figure 24 Arduino Uno R3

The servo motor is initially powered by Arduino which itself will be getting power from laptop during the design phases. After completion of design phase, it will be powered by an independent battery.

3.2 Mechanical Design of the Device:

3.2.1 Calculations Prior to Component Selection:

Our approach from the start was to find the Torque generated at the link joint and then back tract the required torque of the Motor, which will then give us the bench mark of the required torque from the motor output. In this section will take into account the necessary parameters that enabled us to select the desired components and the assumptions and necessary constants taken in our calculations, meanwhile explaining the bit-wise MATLAB Code. For full fledge MATLAB code (a sample and 100kg upper bound) refer to appendix section.

We will be explaining the (100kg upper bound code), how we reached to our desired selection of Servo Motor **HD-1501MG,** and how our upper bound of 100Kg was set.

So, firstly we take 100 Kg as the input mass of the user and the mass of person's foot is taken to be 1.43% of person's body weight [LL], we have assumed a larger value because we need the largest torque we can achieve, as shown from the image below:

Weight of Human Body Parts
as percentages of total body weight

Segment	Male	Female
Head	8.26%	8.20%
Whole Trunk	55.1%	53.2%
Thorax	20.1%	17.0%
Abdomen	13.1%	12.2%
Pelvis	13.7%	16.0%
Total Arm	5.70%	4.97%
Upper Arm	3.25%	2.90%
Forearm	1.87%	1.57%
Hand	0.65%	0.50%
Forearm & Hand	2.52%	2.07%
Total Leg	16.7%	18.4%
Thigh	10.5%	11.8%
Leg	4.75%	5.35%
Foot	1.43%	1.33%
Leg & Foot	6.18%	6.68%

Figure 25 Percentage weight distribution of body [29]

Now we need to know the distance from centre of gravity of foot to the foot link joint. We took a small sample consisting of 4 group members and the average moment arm was approximated to be 8cm. We have assumed not counter force is generated from the heels and that all the force is acting on the Inner and Outer ball of the foot [XX] and the traverse arch as seen below:

Figure 26 Bottom of the human foot

Now to conclude this justification, it has been researched that the most of weight of an average person standing acts on the inner and outer ball and the traverse arch and the middle heel portion, but we have neglected that to for the east of our calculation as to achieve the largest of the torques because the heel would only apply opposite force thus reducing the overall torque at the foot link joint. A typical foot-pressure map distribution of an average person is shown below:

Figure 27 Foot map distribution

The weight and the distance of COG of the foot link has been calculated using Solid Works mass properties after applying the PETG material and is found to 0.7Kg.

```
W_person = input('Enter the mass of person in KG(s)');
W_foot = W_person * 0.0143*9.81  %% Weight of the foot in Newton

W_foot = 14.0283

x = 0.08;                        %% Distance of COG of foot from Central Axis for foot
W_pad = .700*9.81                %% Weight of padding in Newton
```

Now having found the parameters, we find the weight of person's foot, but to find the torque at the total torque at the foot link join we must incorporate the human ankle ball joint resistance which can bee seen that at 90-100 degrees the human ankle offers a torque of 0.2 – 0.3 Nm. when rotated at about Plus minus 15 degrees implying planter and dorsiflexion motion.[XX] The graph below illustrates the joint resistance values at several degrees of rotation of human ankle joint:

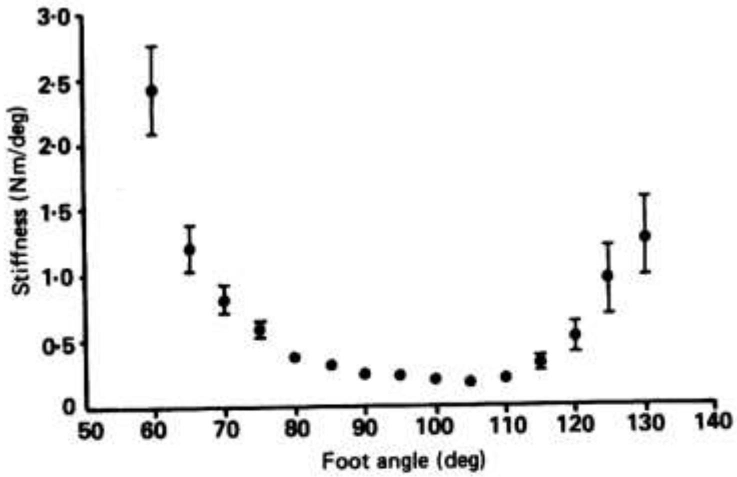


Figure 28 Stiffness of human ankle join with respect to foot angle [XX]

Now adding 0.2 Nm to the previous torque the total torque required at the foot link joint **(T_Link2)** is calculated by the following formula:

```
T_link1 = W_foot*x + W_pad*y;                %% Torque at Link 1 due to foot and padding in N
T_Jointresistance = .2 ;                     %% Resistance of ankle joint in N
T_link2 = T_link1 + T_Jointresistance;       %% Total Torque at Link 1 in N
```

Now incorporating the efficiencies of the Bearings and shaft couplings, no as such reference was found for the couplers and upon contacting of local retailers the figure for efficiency is most commonly around 0.9 respectively. For the bearings, it was found to be 0.99 .[XX] the efficiency of Servo motor is stated in the specification sheet.

```
BVG_eff = 0.9;                   %% Efficiency of Bevel gears
SSC_eff = 0.9;                   %% Efficiency of shaft to shaft coupler
MSC_eff = 0.9;                   %% Efficiency of motor to shaft coupler
Motor_eff = 0.99;                %% Efficiency of motor
Bearing_eff = 0.99;              %% Efficiency of Bearings
```

Moving onto the Gear Ratios, our main idea was to include the largest torque increment so as our selected gears were bevel gears, they offer a maximum gear ratio of 1:5 but its manufacturing and size reduction was non-implementable in our case, so an optimal gear ratio of 3:2 as output gear to input gear was used in our case with optimal size of 6 cm and 4 cm, using these gear ratios we were able to achieve sufficient torque addition. The gear ratios are shown below:

```
BG1_teeth = 20 ;                %% No:of teeth for Bevel gear [source]
BG2_teeth = 30 ;                %% No:of teeth for Bevel gear [output]
```

Now back calculating our torques from foot link and passing via gear set, couplers and bearings , we reach at about 1.65 Nm torque or higher required from the motor. In this case we had used 2 separate shafts and connected via 2 bearings and a coupler, the calculation is shown below:

IF MULTIPLE MIDDLE SHAFTS ARE BEING USED:

```
T_Bearing_M = T_BG_total / Bearing_eff;       %% Torque at Middle bearing
T_SSC = T_Bearing_M / SSC_eff ;               %% Torque at shaft to shaft coupler
T_Bearing_F = T_SSC / Bearing_eff ;           %% Torque at First bearing
T_MSC = T_Bearing_F / MSC_eff ;               %% Torque at Motor to shaft coupler
T_motor = T_MSC / Motor_eff                   %% Torque at Motor in N
```

```
T_motor = 1.6511
```

Secondly, another case was considered where a direct connection of motor was made with the gearset with using only one beating in the middle. This idea was then withdrawn as it provided a lower torque but we needed the largest of the torque and wanted more stability and rigidity in our model while trading off minimal efficiency. The sample required torque is shown below (discarded idea):

IF DIRECT CONNECTION TO MOTOR BEING USED:

```
T_MSC = T_Bearing_M / MSC_eff ;             %% Torque at Motor to shaft coupler
T_motor = T_MSC / Motor_eff                 %% Motor Torque required in N
```

```
T_motor = 1.4711
```

Now we can see that our largest Torque was 1.65 Nm and the highest torque motor with reasonable price and availability is mentioned above. Using method of trial and error 100Kgs was set as an upper bound as it provided a torque which was closest to the stall torque (1.7 Nm) of the stated Servo Motor (refer to specification sheet).

3.2.2 Final Selection of Components:

3.2.2.1 Servo Motor

Assuming a required value of torque, we initially selected the MG 995 Servo Motor having maximum torque of 0.9 Nm, but later after MATLAB calculations we found that the actual required torque is greater than what we had initially assumed. So, we switched to **HD-1501MG Servo Motor** having maximum torque of 1.7 Nm (greater than the actual required torque).

3.2.2.2 Coupler

To provide flexibility to the shaft along the leg length, we selected **XB Flexible Shaft Coupling**. It was readily available at minimal cost.

3.2.2.3 Shaft

Keeping in view the required structural rigidity, and availability of couplers and bearings, we selected the diameter of shaft to be **8 mm**.

3.2.2.4 Gear

A Standard Model of Bevel Gear set has been imported from Grab CAD, as the part will be 3D printed, but several alterations as to teeth ratio has been made to suit the gear-set as per our calculations. The gear ratio (output over input) that we are using is **3:2**.

3.2.2.5 Key

The key will be machined out of a metal having dimensions of 0.3 cm x 0.2 cm x 0.9 cm. These dimensions are adequate to avoid the slippage of shaft.

3.2.2.6 Bearing

Keeping in view the availability from local market at minimum cost, we selected **KP08 Mounted Ball Bearings**. These bearings support the 8 mm shaft.

3.2.2.7 Material

The material selected for shaft is **stainless steel**. The reason is, stainless steel shafts were readily available in market and its yield strength is quite adequate to sustain the torque transmitted by motor in our device. The material selected for foot link, base plate and bevel gears is **PETG**. The reason is, it has negligible warping, glossy and smooth surface finish, durable and has high impact strength. All these components will be 3-D printed.

3.2.4 (3D) CAD Models / Market Model of Components:

Several components have been bought, so real-time pictures will be attached in this section and for the 3D – Printed parts (under process) will be attached in the future draft. The CAD model for the 3D printed parts will be illustrated.

3.2.4.1 Servo Motor

The finalized servo Motor model HD-1501MG is shown below:

Figure 29 HD-1501MG Servo Motor

3.2.4.2 Coupler

The finalized XB Flexible shaft coupling is shown below:

Figure 30 XB Flexible shaft coupling

3.2.4.3 Shaft

The finalized 8mm Bore diameter stainless steel shaft is shown below:

Figure 31 8mm Bore diameter shaft

3.2.4.4 Gear-Set

A Standard Model of Gear set has been imported from Grab CAD, as the part will be 3D printed, but several alterations as to teeth ratio has been made to suit the gear-set as per our calculations. The CAD model of the gear-set has been shown below.

Figure 32 3D CAD Model for gear-set

3.2.4.5 Key

A 3D model of key has been generated, having 0.3 cm x 0.2 cm x 0.9 cm (depth of link). The key will be machined out of metal. The dimensions have been illustrated below.

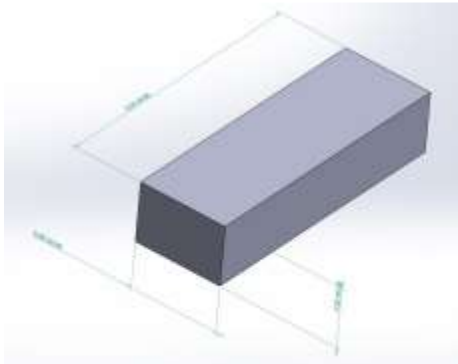


Figure 33 3D CAD Model for Key

3.2.4.6 Bearing

The finalized KP08 mounted ball bearing is shown below:

Figure 34 KP08 mounted ball bearing

3.2.4.7 Foot Link

The model has been imported from Grab CAD but several alterations, mainly formation of link rod, and other minor additions e.g. strap slots and surface finishing are made.

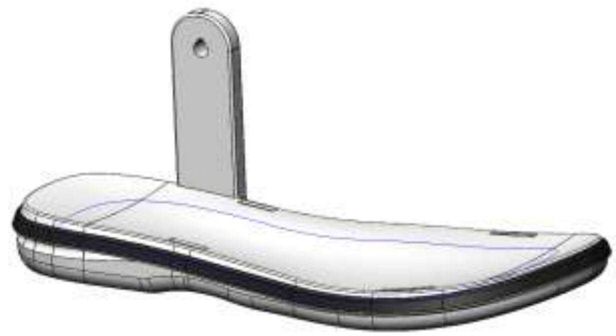


Figure 35 3D CAD Model for Foot Link

3.2.4.8 Connection Plate

For the connection plate the dimensions have been noted by measuring the group member's legs and averaging the total length which turned out to be approximately 40 cm in length The width was set using the Servo Motor's width as it had the largest width of all components. The detailed CAD drawing has been attached in the appendix section. The CAD model of the plate is shown below.

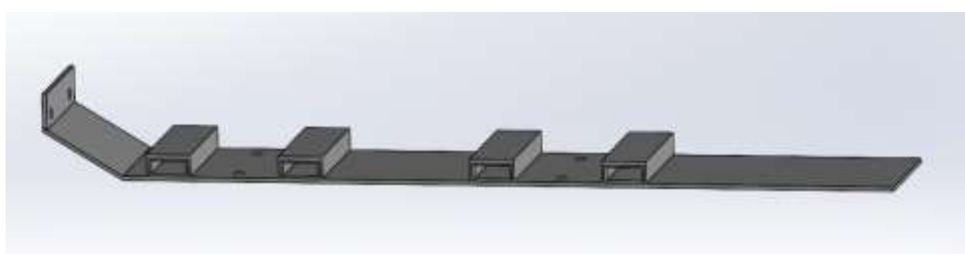


Figure 36 3D CAD Model of connection plate (horizontal)

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Mechanical Design:

For this section, we will be depicting and remarking the final CAD model assembly of the design and secondly, we will be discussing the parameters set for our FEA analysis on the foot link and analyze the results of the model simulation in brief detail.

Furthermore, we will discuss the actual assembly of the device and the coding done to achieve active and passive motion.

4.1.1 Model Assembly:

Referring to the above CAD models of the components, the exploded view of the final assembly of the mechanical design is shown below:

Figure 37 Exploded view of CAD model assembly

The main features of the final assembly include the vertical placement of the plate near to the person's leg, strapping the plate using the straps and foaming, and the connection of Servo Motor (using adhesive), bearings to that plate. Penultimately, the attachment of link the end portion and ultimately the connection of gears to the shaft using keys and couplers for shaft to shaft/motor connection. In addition, the foot link will be fixed to the person's leg using straps as well. The non-exploded view of the final assembly is shown below [strapping slots being suppressed for inclusion of text]:

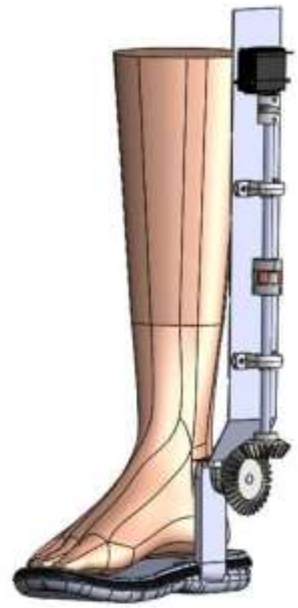


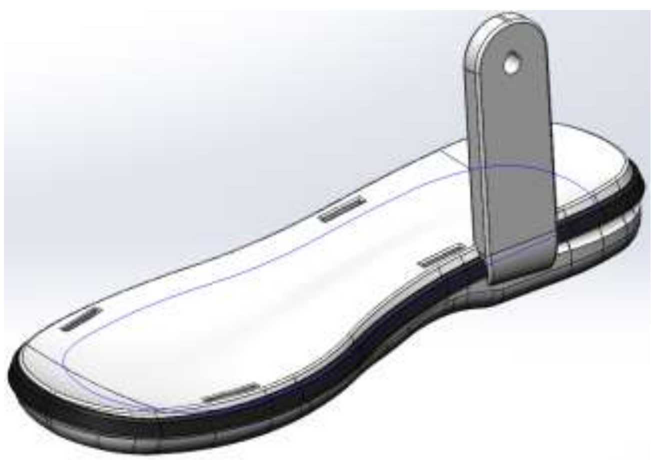
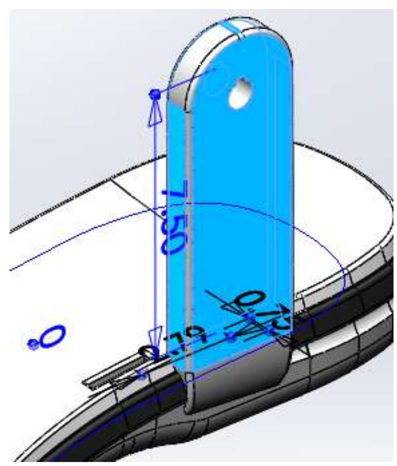
Figure 38 Final Model Assembly (side view)

Figure 39 Final Model Assembly (front view)

4.1.2 Simulation:

We will only be carrying our Stress analysis on the foot link mainly because it will be bearing the largest of the torques and secondly it is our area of interest. The analysis on the connection plate and the gears can be carried out but its results will not be as such beneficial and are not required in any of the assumptions.

4.1.2.1 Parameters

Geometry – The geometry of the Foot link was imported from Grab CAD but several alterations, mainly formation of link rod, and other minor additions e.g. strap slots and surface finishing, have been successfully carried out.
 
Applied Load – 2 Forces and 1 Torque was applied in this scenario. We assumed the max allowed wight of 100Kg of a person and resultantly we got 15N (Top surface) as the weight applied by person's foot (refer to from MATLAB Code). Secondly the weight of the foot link 6.8N was calculated after applying PETG material and using

mass properties from SolidWorks (Bottom surface), Meanwhile the Torque generated at the foot link connection was set to be 1.5N (refer to MATLAB code).

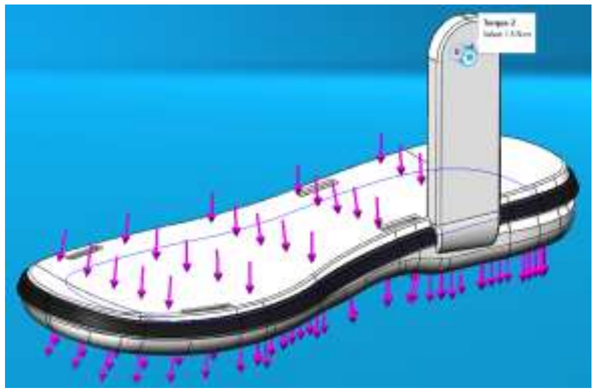


Figure 40 Applied forces and torque on footlink

Boundary conditions – We have set up a cylindrical fixed support which only allows rotation about its own axis and it restricts the lateral motion of the link depicting the keyway phenomenon.

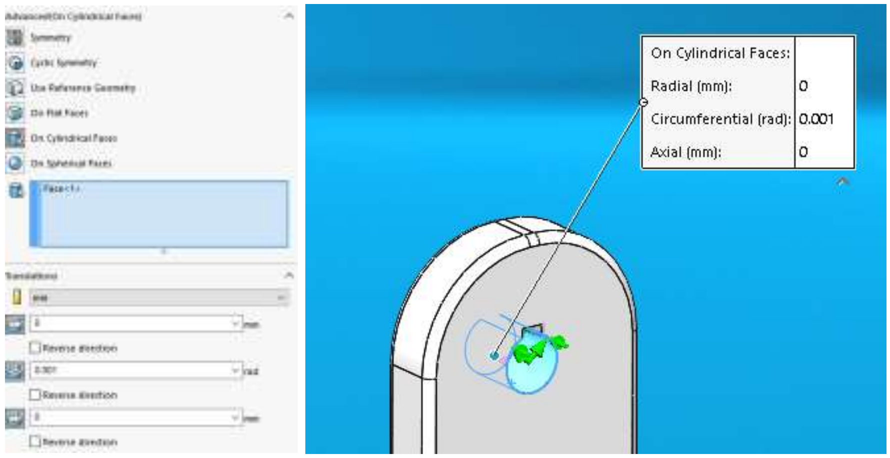


Figure 41 Boundary conditions of the connection

Meshing – We carried out our meshing using high quality mesh and standard mesh properties.

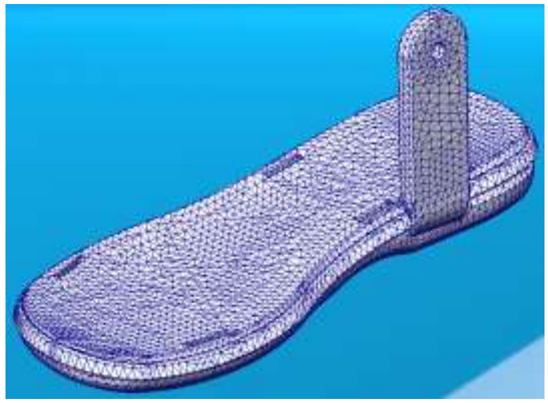


Figure 42 Meshing of footlink

Mesh Details	
Study name	Static 1 (-Default-)
Mesh type	Solid Mesh
Mesher Used	Standard mesh
Automatic Transition	Off
Include Mesh Auto Loops	Off
Jacobian points for High quality mesh	16 points
Mesh Control	Defined
Element size	1.48897 cm
Tolerance	[illegible] cm
Mesh quality	High
Total nodes	102962
Total elements	58556
Maximum Aspect Ratio	42.37
Percentage of elements with Aspect Ratio < 3	85.3
Percentage of elements with Aspect Ratio > 10	0.344
Percentage of distorted elements	0
Number of distorted elements	0
Time to complete mesh(hh;mm;ss)	00:00:11
Computer name	MSI

Figure 43 Mesh details

4.1.2.2 Deductions and Analysis

After performing our simulations for the stress and displacement, it can be observed that for the **stress plot**, our maximum stress occurs at the fixed support (as assumed) , 13.7 MPa , which is below the yield stress of the material 51 MPa (refer to PETG specification), thus our link will not deform at all. A result of the model having a deformation scale has been illustrated below:

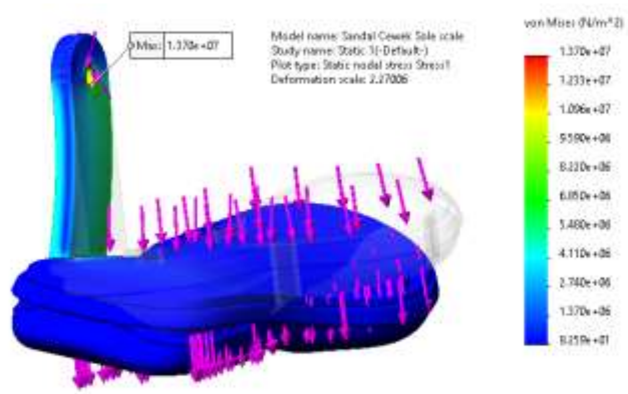


Figure 44 Stress plot of footlink with scaled deformation

Secondly for our **displacement plot**, we can observe that a deformation of 1.4 cm is occurring mainly because of the lateral bending of the link which can easily be catered for using the straps on the foot link and the connection plate. The Straps will apply an opposite force to the lateral rotation and thus minimal or no bending will occur in the foot link. Necessary action to prevent the bending of link has not yet been considered but in the re-simulation, factors will be taken into account.

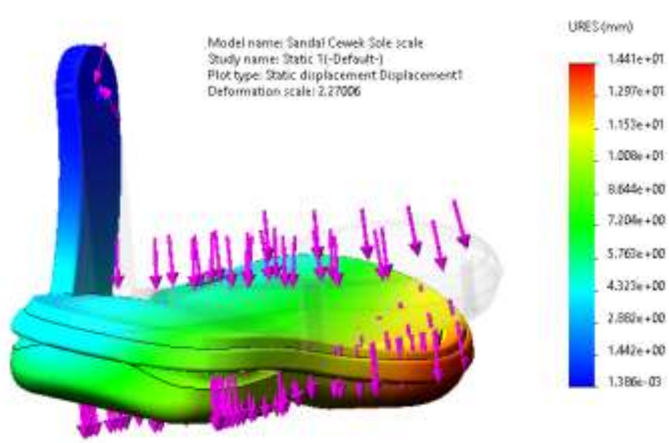


Figure 45 Displacement Plot for foot link

4.2 Electronics of the Device:

We ordered an EMG sensor online from hallroad.org, but during our testing, we found out that the sensor was faulty. Then, we visited the market by ourselves and bought a new EMG sensor from a local vendor. But then again, it didn't work. Since we were not able to acquire the working EMG sensor from local market, now we are getting it designed by using discrete components from abroad. The designed sensor also didn't work. Finally, we bought Myoware sensor which provides a useable output signal.

4.3 Assembly of the device:

The foot-link and the bevel gears were 3D printed of PETG material. The support plate is made up of stainless steel, and sheet metal techniques were used to form into desired shape. Couplers, shafts, bearings, Myoware sensor, servo motor and Arduino were procured from a local vendor. The straps on the foot-link were fabricated by a local cobbler. The foaming was done by a local sofa shop. Here is the final assembly of the device:

Figure 46 Final prototype (1)

Figure 47 Final prototype (2)

4.4 Control System:

The control system of the device consists of two parts i.e., active mode and passive mode. These modes are achieved using two separate Arduino codes.

4.4.1 Passive Mode:

Firstly, the servo library was included in the code. The servo was initialized as Myservo. The servo was attached to pin 3 of the Arduino, hence the attach command.

```
#include<Servo.h>
Servo Myservo;
int pos;
void setup()
{
Myservo.attach(3);
}
```

This is the main part of the code. Firstly, the motor is moved by 60 degrees. This is the default position of the motor. Then the loop is used which runs for 3 times (this number can be adjusted). The motor is moved first to 0 degrees, then to 60 degrees, then to 120 degrees and finally back to 60 degrees.

This will perform both dorsiflexion and plantarflexion. The exercises are performed 3 times (governed by the no. of times the loop runs).

```
void loop()
{

 Myservo.write(60);
delay(1000);
 for(int n=1;n<=3;n++
{Myservo.write(0);
delay(1000);


Myservo.write(60);
delay(1000);

Myservo.write(120);
delay(1000);
Myservo.write(60);
delay(1000);}
Myservo.write(60);
delay(1000);
exit(0);

}
```

4.4.2 Active Mode

Firstly, the servo library was included in the code. The servo was initialized as Myservo. The servo was attached to pin 3 of the Arduino, hence the attach command. EMG sensor was attached to analog 0 of the Arduino, hence the attach command. The threshold is defined which is then compared to the output value coming from the EMG sensor. If the output value is larger than the threshold value, then the exercises will be performed, otherwise nothing will happen.

```
#include <Servo.h>
#define THRESHOLD 250
#define EMG_PIN 0
#define SERVO_PIN 3
Servo Myservo;
```

The same loop used in passive mode was used here. This loop runs when the if condition is satisfied.

```
void setup(){

  Serial.begin(115200);

  Myservo.attach(SERVO_PIN);
}

void loop(){


  int value = analogRead(EMG_PIN);
Myservo.write(60);

  if(value > THRESHOLD)
    {
    Myservo.write(0);
    delay(1000);
    Myservo.write(60);
    delay(1000);
    Myservo.write(120);
    delay(1000);
    Myservo.write(60);
    delay(1000);

   }
delay(1000);
  Serial.println(value);
}
```

4.5 Detection of signals from the Myoware sensor

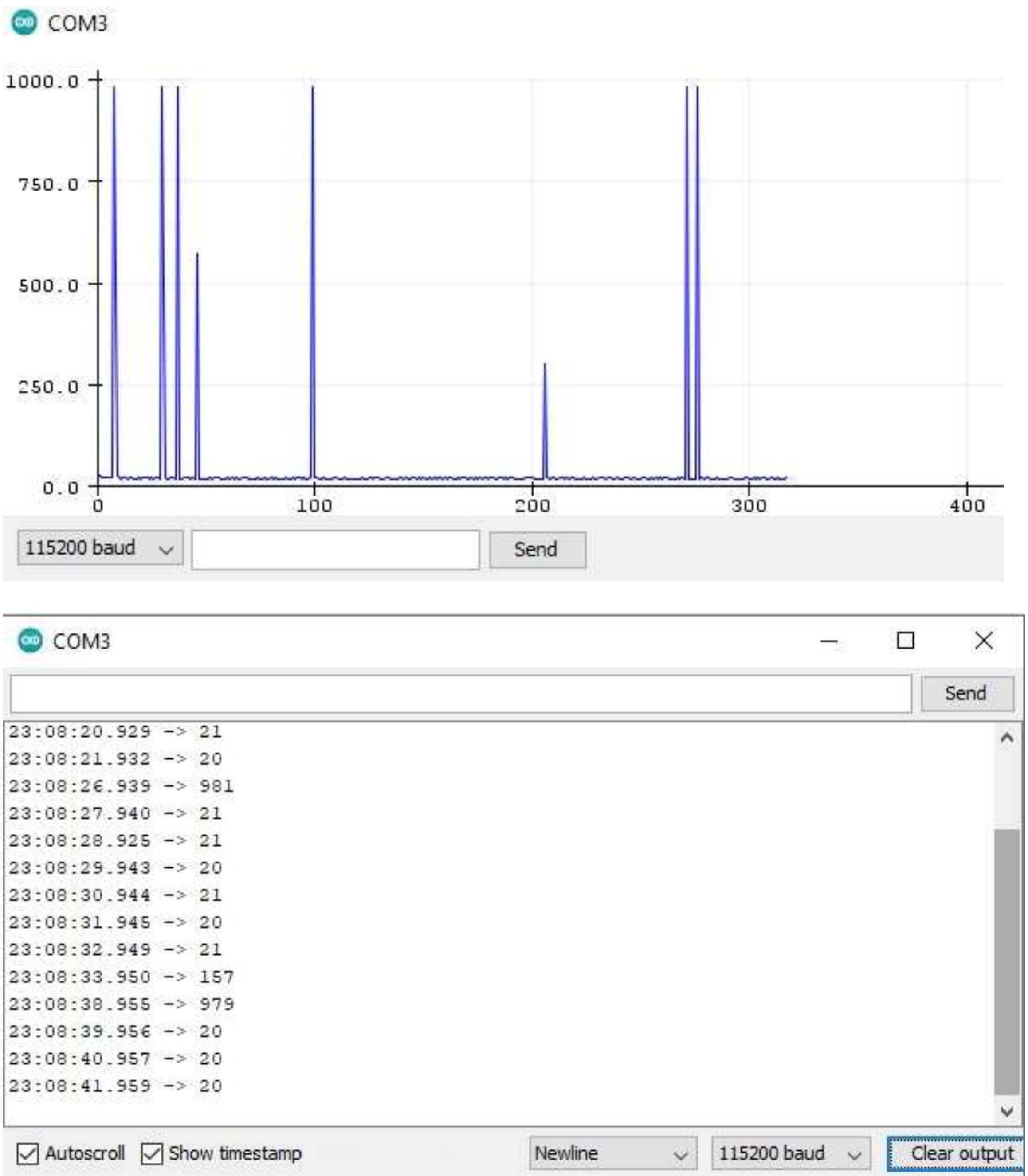


Figure 48 EMG sensor signal values and plot

We can see that when there is no muscular activity, the value of analog signal is less than 25, that is way below the threshold value. This is basically due to the noise. And when there is some muscular activity, the signal rises to about 900, which is above the threshold value. The threshold value is set at 250.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusions

Initially, we performed the stress analysis of the foot-link made of PET-G by applying appropriate loads and constraints. The results were satisfactory, the stress values generated were below the yield point. Later on, when we practically analyzed the working prototype, no deformation was observed. Therefore, validating our analysis.

The EMG sensor (Myoware) was able to detect even minute muscle activities, strong signal output was detected. Therefore, the sensor would be able to support our control system.

Our device was able to achieve both active and passive mode, providing robot assisted physiotherapy in both modes. We performed dorsiflexion and plantarflexion to the patient. The number can easily be adjusted according to the requirements.

5.2 Recommendations:

For the prototype, we used 3D printed gears. But metallic gears would provide better performance and efficiency. We used two different codes for active mode and passive mode. To further improve the experience, both modes can be incorporated into a single code for optimum use. The currently available EMG sensors provide unsatisfactory output results, which are very difficult to use. The working efficiency of EMG sensors can improve which would provide a smoother experience.

5.2.1 Testing of 3D – Printed PETG Cube:

Instead of using the general properties of PETG material for our simulations and results, a sample cube of this material can be used to perform the tensile testing on UTM. The results from this test can be used for re-simulations.

5.2.2 Advanced Signal Processing Techniques

To improve the output signal of EMG sensor, advanced signal processing techniques can be used. Furthermore, Machine Learning and Artificial Intelligence techniques can be applied to improve the control system.

5.2.3 Clinical Testing:

The final prototype can undergo clinical testing to undergo its determine its performance in real life scenarios. The clinical study will aim to evaluate the rehabilitation protocol of the wearable rehabilitation device. Group of stroke patients will receive regular training for about 2-3 weeks. Fugl-Meyer Assessment (FMA) will be used to determine the patient’s condition before and after each training session.

Fugl-Meyer Assessment (FMA) is a metric used in the rehabilitation of stroke patients. It is a performance-based impairment index. FMA assesses the motor functioning, balance, sensation and joint functioning. FMA determines the disease severity, motor recovery and treatment efficacy. After the completion of the study, feedback of the patients will be taken. Furthermore, the FMA scores of the patients before and after the clinical study will also be analysed. By doing so, we would be able to see whether our device performs to our expectations or not. [30]

5.2.4 Additional Physiotherapy Range of Motion:

The exercises offered by our device are dorsi-flexion and plantar-flexion. Both of these motions are in sagittal plane (longitudinal plane). In addition to these exercises, other vital exercises of ankle joint for stroke patients are inversion and eversion. These motions occur in the frontal plane. After successful implementation of dorsi-flexion and plantar flexion, we can modify the mechanical design to carry out these two additional exercises.

Figure 49 Inversion and eversion

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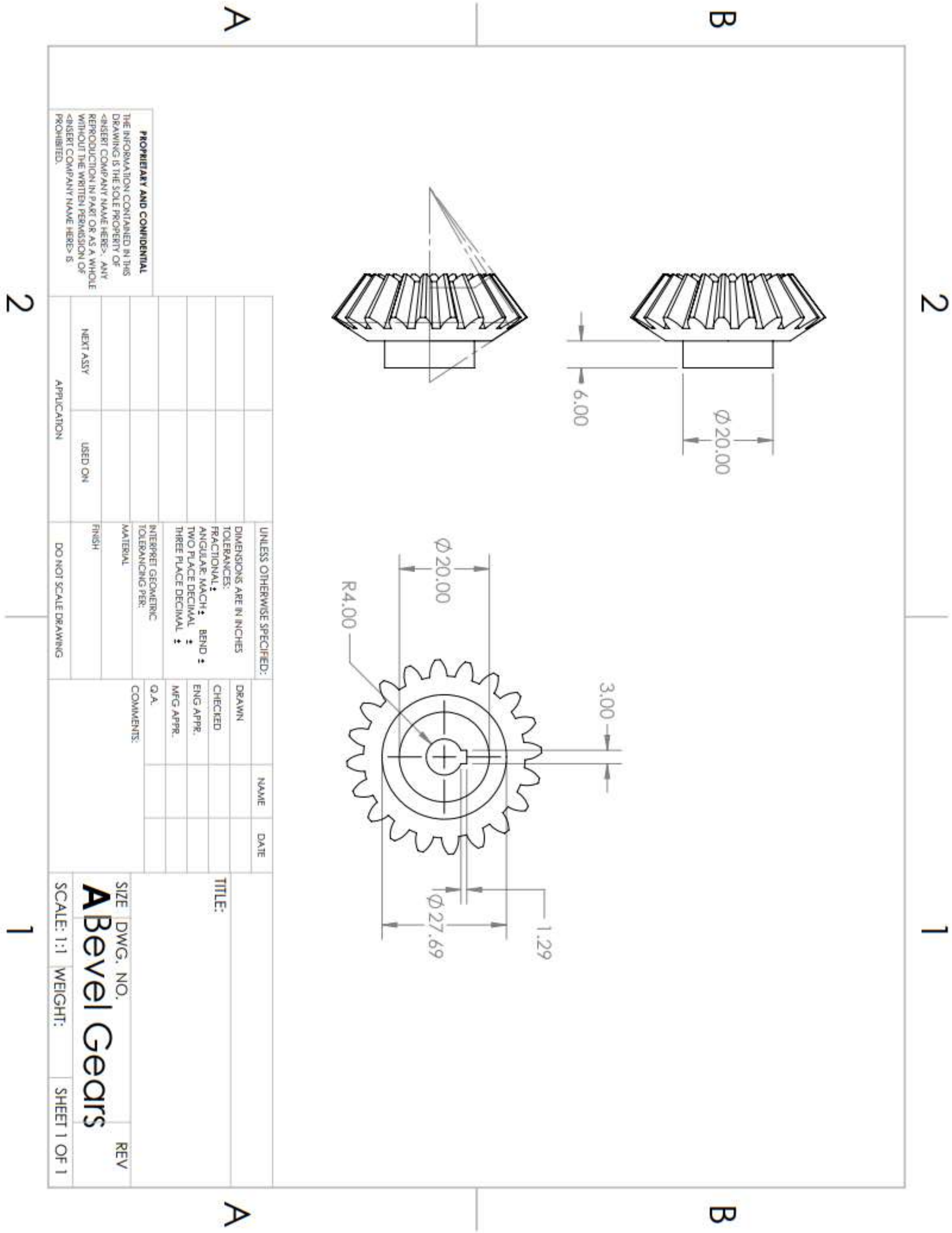
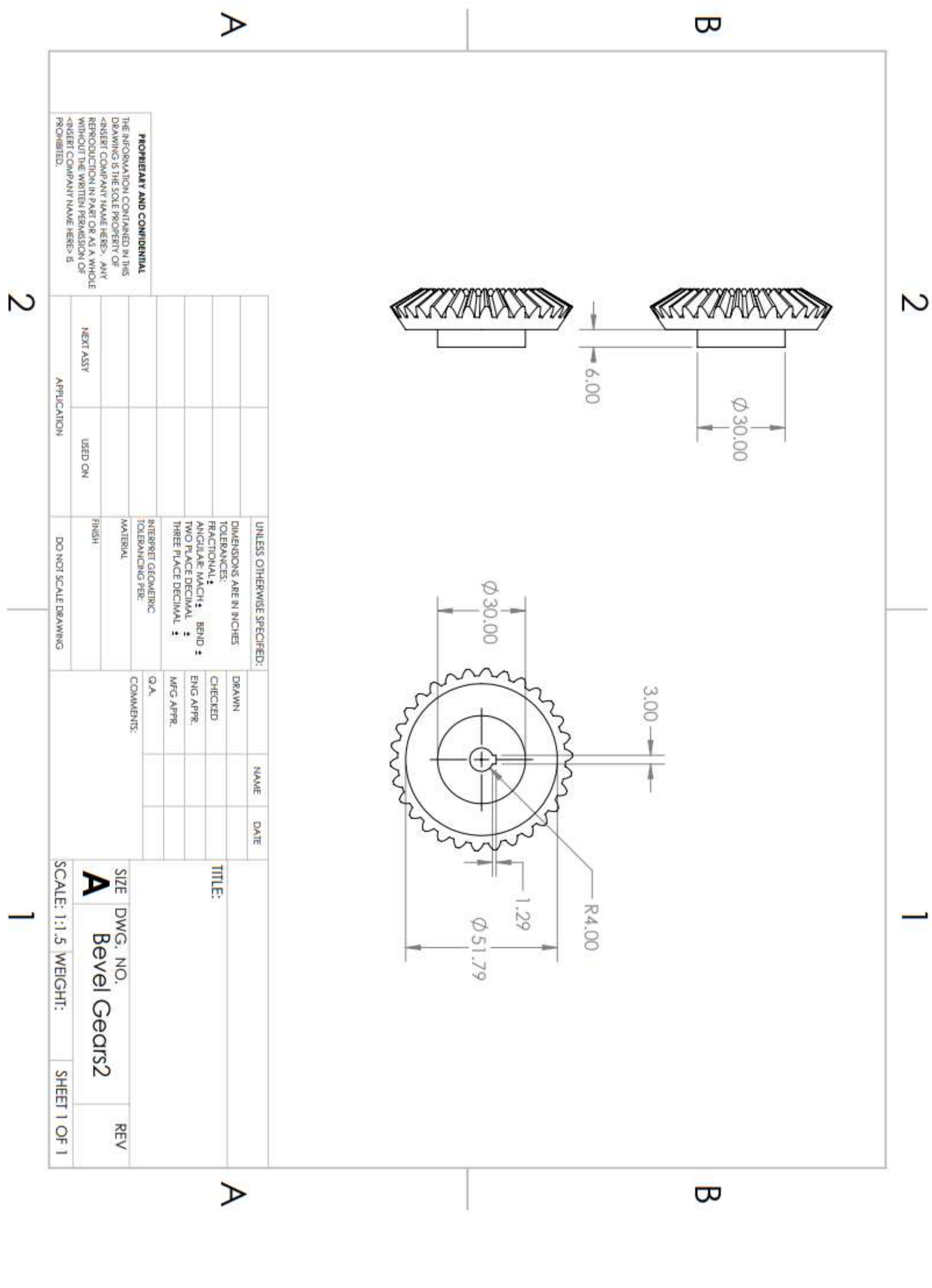
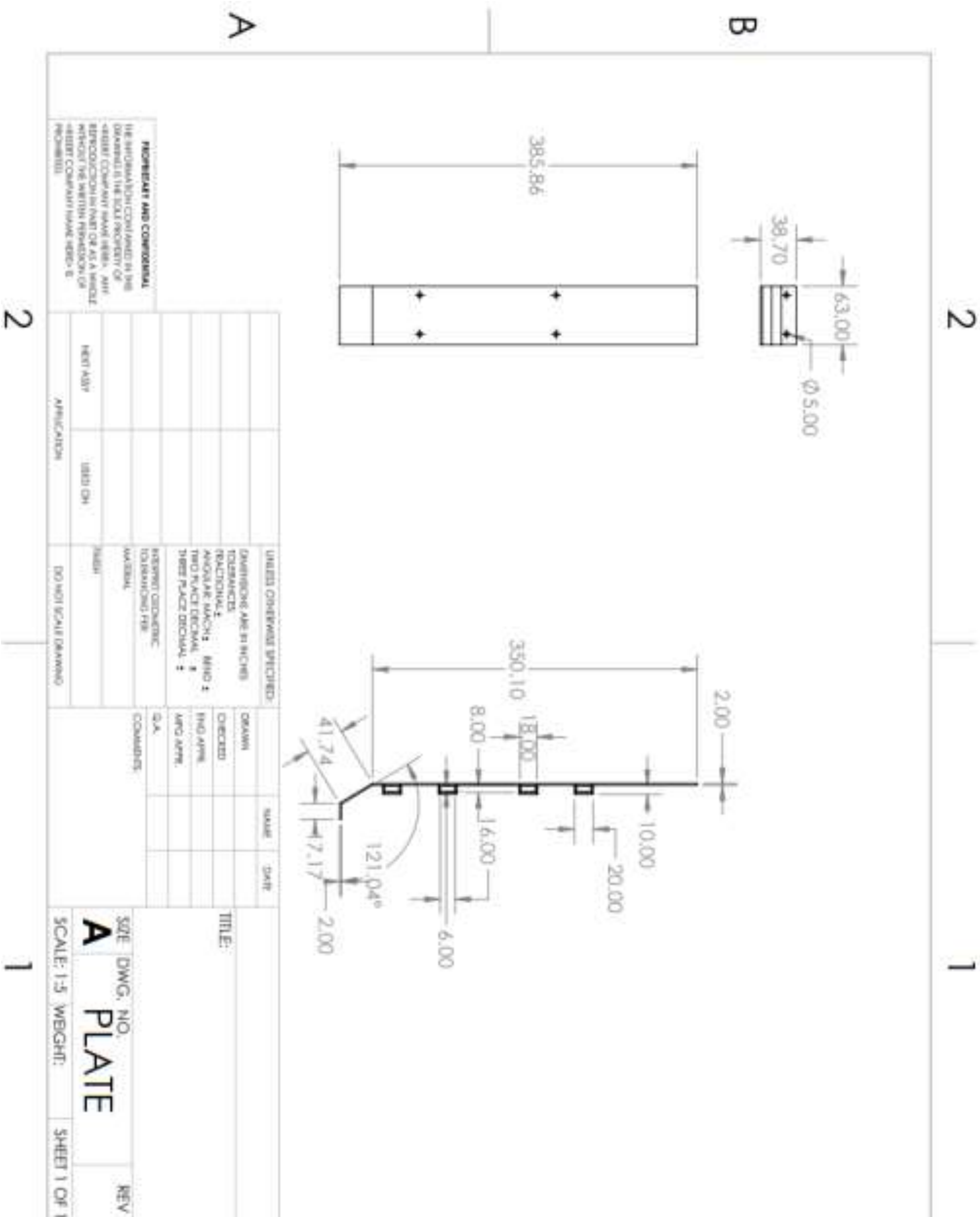
APPENDIX I: CAD DRAWING PINION



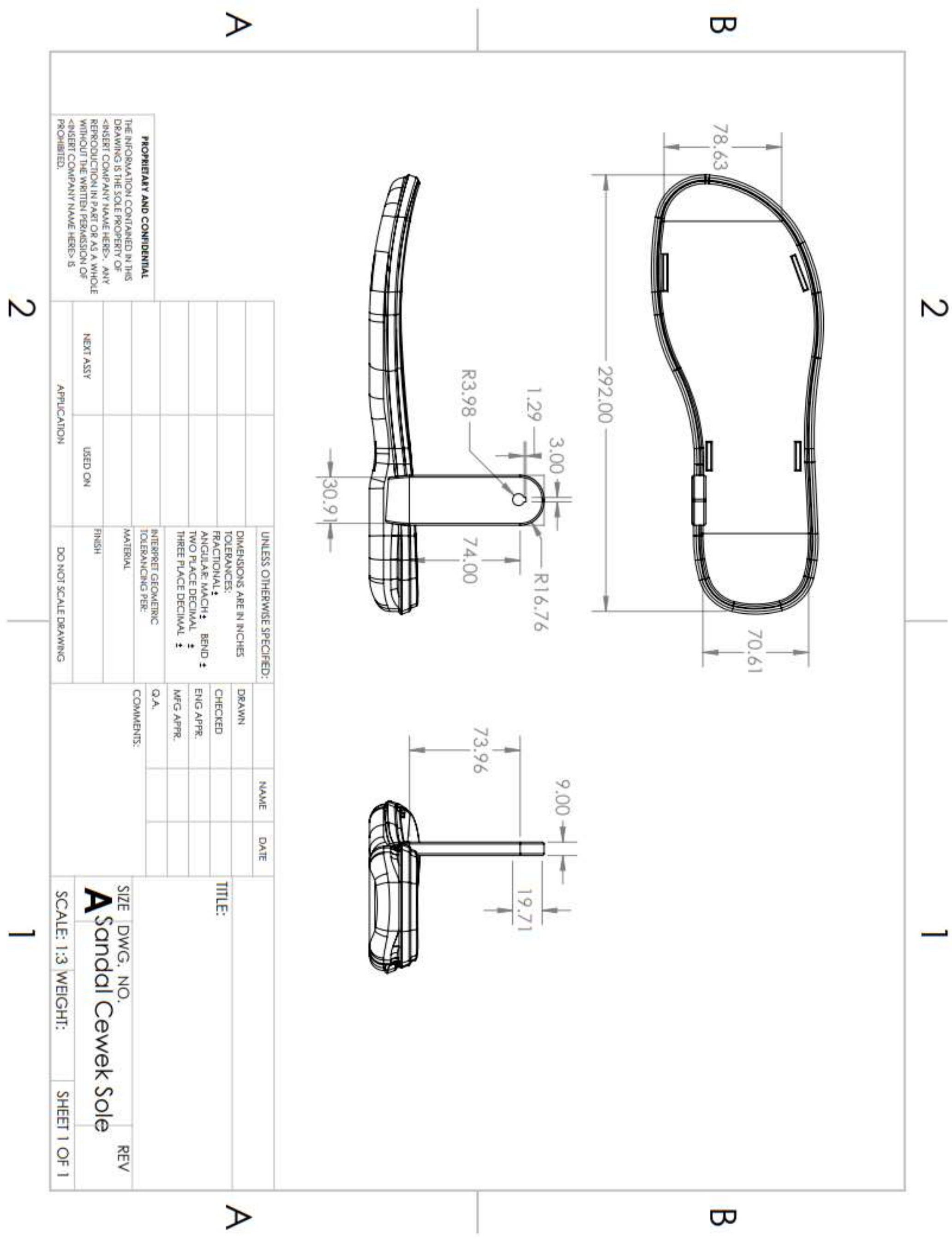
APPENDIX II: CAD DRAWING GEAR



APPENDIX III: CAD DRAWING CONNECTING PLATE



APPENDIX IV: CAD DRAWING FOOT LINK



APPENDIX V: GENERIC MATLAB CODE

MOTOR TORQUE CALUCATION:

```
W_person = input('Enter the mass of person in KG(s)');
W_foot = W_person * 0.0143*9.81  %% Weight of the foot in Newton
x = 0.08;                        %% Distance of COG of foot from Central Axis for foot
W_pad = .700*9.81                %% Weight of padding in Newton
y = 0.06;                        %% Distance of COG of foot from Central Axis for padding
```

```
BVG_eff = 0.9;              %% Efficiency of Bevel gears
SSC_eff = 0.9;              %% Efficiency of shaft to shaft coupler
MSC_eff = 0.9;              %% Efficiency of motor to shaft coupler
Motor_eff = 0.99;           %% Efficiency of motor
Bearing_eff = 0.99;         %% Efficiency of Bearings
```

```
BG1_teeth = 20 ;            %% No:of teeth for Bevel gear [source]
BG2_teeth = 30 ;            %% No:of teeth for Bevel gear [output]
```

```
T_link1 = W_foot*x + W_pad*y;           %% Torque at Link 1 due to foot and padding in N
T_Jointresistance = .2 ;                    %% Resistance of ankle joint in N
T_link2 = T_link1 + T_Jointresistance;      %% Total Torque at Link 1 in N
T_Bearing_L = T_link2 / Bearing_eff ;       %% Torque at Last bearing
T_BG1 = T_Bearing_L * (BG1_teeth/BG2_teeth); %% Torque at Source bevel Gear
T_BG_total = T_BG1 / BVG_eff ;              %% Total torque at bevel gear 1
```

IF MULTIPLE MIDDLE SHAFTS ARE BEING USED:

```
T_Bearing_M = T_BG_total / Bearing_eff;     %% Torque at Middle bearing
T_SSC = T_Bearing_M / SSC_eff ;             %% Torque at shaft to shaft coupler
T_Bearing_F = T_SSC / Bearing_eff ;         %% Torque at First bearing
T_MSC = T_Bearing_F / MSC_eff ;             %% Torque at Motor to shaft coupler
T_motor = T_MSC / Motor_eff                 %% Torque at Motor in N
```

IF DIRECT CONNECTION TO MOTOR BEING USED:

```
T_MSC = T_Bearing_M / MSC_eff ;             %% Torque at Motor to shaft coupler
T_motor = T_MSC / Motor_eff                 %% Motor Torque required in N
```

APPENDIX VI: 100KG SAMPLE MATLAB CODE

MOTOR TORQUE CALUCATION:

TEST RUN FOR UPPER BOUND 100 KG PERSON -

```
W_person = input('Enter the mass of person in KG(s)');
W_foot = W_person * 0.0143*9.81  %% Weight of the foot in Newton
```

```
W_foot = 14.0283
```

```
x = 0.08;                        %% Distance of COG of foot from Central Axis for foot
W_pad = .700*9.81                %% Weight of padding in Newton
```

```
W_pad = 6.8670
```

```
y = 0.06;                        %% Distance of COG of foot from Central Axis for padding
```

```
BVG_eff = 0.9;                 %% Efficiency of Bevel gears
SSC_eff = 0.9;                 %% Efficiency of shaft to shaft coupler
MSC_eff = 0.9;                 %% Efficiency of motor to shaft coupler
Motor_eff = 0.99;              %% Efficiency of motor
Bearing_eff = 0.99;            %% Efficiency of Bearings
```

```
BG1_teeth = 20 ;               %% No:of teeth for Bevel gear [source]
BG2_teeth = 30 ;               %% No:of teeth for Bevel gear [output]
```

```
T_link1 = W_foot*x + W_pad*y;                   %% Torque at Link 1 due to foot and padding in N
T_Jointresistance = .2 ;                        %% Resistance of ankle joint in N
T_link2 = T_link1 + T_Jointresistance;          %% Total Torque at Link 1 in N
T_Bearing_L = T_link2 / Bearing_eff ;           %% Torque at Last bearing
T_BG1 = T_Bearing_L * (BG1_teeth/BG2_teeth);    %% Torque at Source bevel Gear
T_BG_total = T_BG1 / BVG_eff ;                  %% Total torque at bevel gear 1
```

IF MULTIPLE MIDDLE SHAFTS ARE BEING USED:

```
T_Bearing_M = T_BG_total / Bearing_eff;         %% Torque at Middle bearing
T_SSC = T_Bearing_M / SSC_eff ;                 %% Torque at shaft to shaft coupler
T_Bearing_F = T_SSC / Bearing_eff ;             %% Torque at First bearing
T_MSC = T_Bearing_F / MSC_eff ;                 %% Torque at Motor to shaft coupler
T_motor = T_MSC / Motor_eff                     %% Torque at Motor in N
```

```
T_motor = 1.6511
```

IF DIRECT CONNECTION TO MOTOR BEING USED:

```
T_MSC = T_Bearing_M / MSC_eff ;              %% Torque at Motor to shaft coupler
T_motor = T_MSC / Motor_eff                  %% Motor Torque required in N
```

```
T_motor = 1.4711
```

APPENDIX VII: PETG SPECIFICATION SHEET (100% INFILL)

azure film

Technical Data Sheet

PETG TDS

AzureFilm PETG (Copolyester) for FDM 3D Printers

Product Description

AzureFilm PETG (Copolyester) filament is a plastic thread that combines the properties of the ABS filament (solid, temperature-resistant, extremely durable, flexible) and the PLA filament (easy to print). Because of these properties, PETG is a filament material for 3D printing that you must have.

Properties

Property of 3D printed specimens	Test method	Value
Material	**Copolyester**	Color Transparent
Specific Density	ASTM D-792	1,29 g/cm3
Tensile Yield Stress	ISO 527-2	51 MPa
Tensile Modulus	ISO 527-2	2980 MPa
Tensile Stress at Break	ISO 527-2	20 MPa
Elongation at yield	ISO 527-2	4%
Elongation at break	ISO 527-2	29%
Flexural Modulus	ISO 178	2040 MPa
Flexural Strength	ISO 178	68 MPa

Test specimens print settings

3D printer: AzureFilm
Slicer: Cura
Nozzle: 0,4 mm

Infill: 100 %
Shells: /
Layer height: 0,2 mm

Nozzle temperature: 230 °C
Bed temperature: 80-90 °C
Print speed: 50 mm/s

Printing Recommendations

Nozzle temperature: 220 – 240°C
Heated bed: recommended 80-90 °C
Print speed: 50 – 200 mm/s
Build platform: Blue tape, Kapton tape. Recommended: Glass bed + Dimafix spray

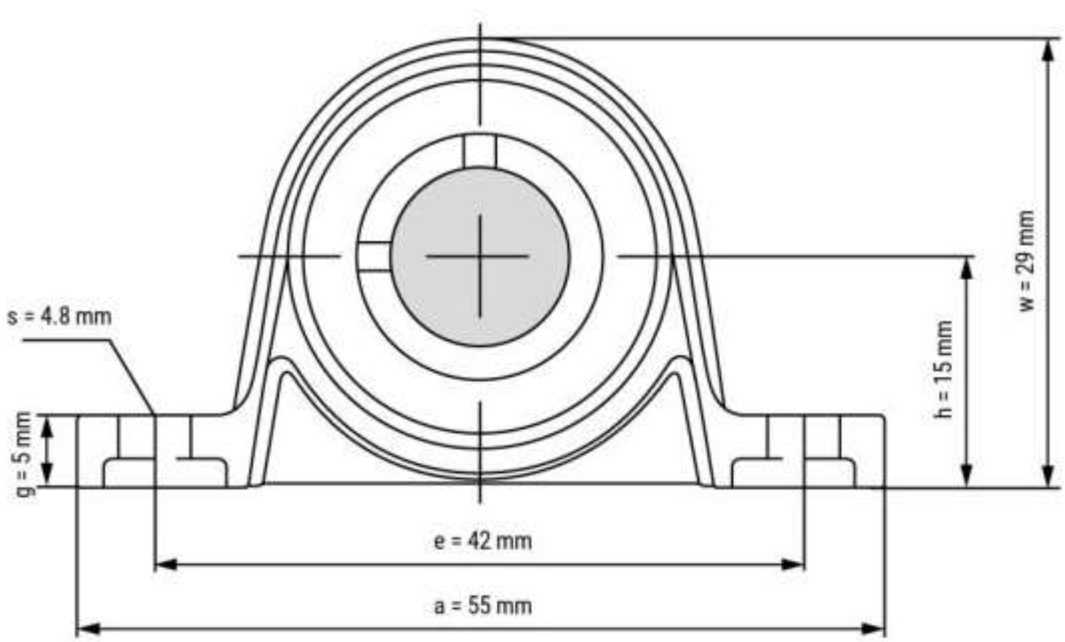
The technical information contained on this sheet is furnished without charge or obligation and accepted at the recipient's sole risk. The information provided in this data sheet corresponds to our knowledge on the subject at the date of its publication. This information may be subject to revision as new knowledge and experience becomes available. The data provided should not be used to establish specification limits or used alone as the basis of design; they are not intended to substiute for any testing you may need to conduct to determine for yourself the suitability of a specific material for your particular purposes. Since we cannot antcipate all variations in actual end-use conditions, AzureFilm d.o.o. makes no warranties and assumes no liability in connection with any use of this information.

APPENDIX VIII: KP08 BEARING SPECIFICATION SHEET

Quick Spec

- Type: Pillow Block
- Bore Size: 8mm (Inside Diameter)
- Material: Zinc Alloy
- Model: KP08
- Total Size: Approx. 55x13x28mm(L W H)
- Hole Diameter: Approx. 4.6mm
- Holes Centre Distance: Approx. 42mm
- Bearing Type: 608RS Ball Bearing
- Allen Screw Key Size: 1.5mm
- Durable with high precision
- Material: Aluminum-Zinc Alloy

Dimensions



APPENDIX IX: STAINLESS STEEL SPECIFICATION SHEET

Specification Sheet: Alloy 304/304L

(UNS S30400, S30403) W. Nr. 1.4301, 1.4307

Most Widely Used Austenitic Stainless Steel, a Versatile Corrosion Resistant Alloy for General Purpose Applications

Alloy 304/304L (UNS S30400/ S30403) is the most widely utilized "18-8" chromium-nickel austenitic stainless steel. It is an economical and versatile corrosion resistant alloy suitable for a wide range of general purpose applications.

It is common practice for 304L to be dual certified as 304 and 304L. The low carbon chemistry of 304L combined with an addition of nitrogen enables 304L to meet the mechanical properties of 304.

Alloy 304/304L resists atmospheric corrosion, as well as, moderately oxidizing and reducing environments. The alloy has excellent resistance to intergranular corrosion in the as-welded condition. Alloy 304/304L has excellent strength and toughness at cryogenic temperatures.

Alloy 304/304L is non-magnetic in the annealed condition, but can become slightly magnetic as a result of cold working or welding. It can be easily welded and processed by standard shop fabrication practices.

Applications

- Chemical and Petrochemical Processing—pressure vessels, tanks, heat exchangers, piping systems, flanges, fittings, valves and pumps
- Food and Beverage Processing
- Medical
- Mining
- Petroleum Refining
- Pharmaceutical Processing
- Power Generation—nuclear
- Pulp and Paper

Standards

ASTM .... A 240
ASME .... SA 240
AMS 5511/5513
QQ-S 766

Chemical Analysis

Weight % (all values are maximum unless a range is otherwise indicated)

Element	304	304L
Chromium	18.0 min.–20.0 max.	18.0 min.–20.0 max.
Nickel	8.0 min.–10.5 max.	8.0 min.–12.0 max.
Carbon	0.08	0.030
Manganese	2.00	2.00
Phosphorus	0.045	0.045
Sulfur	0.030	0.030
Silicon	0.75	0.75
Nitrogen	0.10	0.10
Iron	Balance	Balance

Physical Properties

Density
0.285 lbs/in³
7.90 g/cm³

Modulus of Elasticity
29.0 x 10⁶ psi
200 GPa

Melting Range
2550–2590°F
1398–1421°C

Specific Heat
0.12 BTU/lb-°F (32–212°F)
500 J/kg-°K (0–100°C)

Thermal Conductivity 212°F (100°C)
9.4 BTU/hr/ft²/ft/°F
16.3 W/m-°K

Electrical Resistivity
29.1 Microhm-in at 68°F
74 Microhm-cm at 20°C

Mean Coefficient of Thermal Expansion

Temperature Range			
°F	°C	in/in/°F	cm/cm °C
68–212	20–100	9.2×10^{-6}	16.6×10^{-6}
68–932	20–500	10.6×10^{-6}	18.2×10^{-6}
68–1600	20–870	11.0×10^{-6}	19.8×10^{-6}

Mechanical Properties

		ASTM	
	Typical*	Type 304	Type 304L
0.2% Offset Yield Strength, ksi	42	30 min.	25 min.
Ultimate Tensile Strength, ksi	87	75 min.	70 min.
Elongation in 2 inches, %	58	40 min.	40 min.
Reduction in Area, %	70	—	—
Hardness, Rockwell B	82	92 max.	92 max.

0.375 inch plate

APPENDIX X: HD-1501 MG SPECIFICATION SHEET

4. **電 氣 特 性**

Electrical Specification (Function of the Performance)：

No.	项目 item	4.8V	6.0V
4-1	空載轉速 Operating speed (at no load)	0.16 sec/60°	0.14 sec/60°
4-2	空載電流 Running current (at no load)	400 mA	500 mA
4-3	停止扭力 Stall torque (at locked)	15.5 kg-cm	17 kg-cm
4-4	停止電流 Stall current (at locked)	2300 mA	2500 mA
4-5	待機電流 Idle current (at stopped)	4 mA	5 mA

注：项目 4-2 定义平均值时，伺服器无负荷运行

Note: Item 4-2 definition is average value when the servo running with no load

5. **機 械 特 性**

Mechanical Specification：

No.	项目 item	規格 standard
5-1	外觀尺寸 Overall Dimensions	见附件 See the drawing
5-2	機構極限角度 Limit angle	180°± 10°
5-3	重量 Weight	63 ± 1g
5-4	導線規格 Connector wire gauge	#28 PVC
5-5	導線長度 Connector wire length	300± 5 mm
5-6	舵片規格 Horn gear spline	25T/ φ5.80
5-7	舵片種類 Horn type	条型.半臂舵板 Single, Double
5-8	減速比 Reduction ratio	1/298

Power HD	Product Name	Model No.	Version	Page
	模拟伺服器 Analog Servo	1501MG	V1	2/3

APPENDIX XI: PASSIVE MODE CODE

```
#include<Servo.h>
Servo Myservo;
int pos;
void setup()
{
Myservo.attach(3);
}
void loop()
{

 Myservo.write(60);
delay(1000);
 for(int n=1;n<=3;n++
{Myservo.write(0);
delay(1000);


Myservo.write(60);
delay(1000);

Myservo.write(120);
delay(1000);
Myservo.write(60);
delay(1000);}
Myservo.write(60);
delay(1000);
exit(0);

}
```

APPENDIX XII: ACTIVE MODE CODE

```
#include <Servo.h>
#define THRESHOLD 250
#define EMG_PIN 0
#define SERVO_PIN 3
Servo Myservo;


void setup(){

  Serial.begin(115200);

  Myservo.attach(SERVO_PIN);
}

void loop(){


  int value = analogRead(EMG_PIN);
Myservo.write(60);

  if(value > THRESHOLD)
    {
    Myservo.write(0);
    delay(1000);
    Myservo.write(60);
    delay(1000);
    Myservo.write(120);
    delay(1000);
    Myservo.write(60);
    delay(1000);

   }
delay(1000);
  Serial.println(value);
}
```