Prosthetic Exo-leg: A Multifunctional Robotic Leg-suit to Support Patient with Transfemoral Amputation

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A project submitted to the Department of Electrical and Electronic Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science in Electrical and Electronic Engineering

Department of Electrical and Electronic Engineering
Brac University
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Summer 2022

Declaration

It is hereby declared that

1. The project submitted is our own original work while completing degree at Brac University.
2. The project does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The project does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. We have acknowledged all main sources of help.

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Approval

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of Summer, 2022 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of BSEEE on September 1, 2022.

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Ethics Statement

Hereby, we, consciously assure that for the similarity index, the following is fulfilled:

1. The research is author's own work, and it has not been published anywhere else. We have maintained the similarity index to be below 35%.
2. The research also includes proper credits to the information used from other sources with the mention of author and co-other in the reference.
3. The research was conducted according to the principle embodied with Brac Limb and Brace Center.
4. The participant is above 18 and have given written informed consent to participate in the research.
5. We have used all the legally accepted components approved by both Brac Limb and Brace Center and Dynamic Limb Center.
6. All the authors have been involved in the project and will take full responsibility of its content.

Abstract

The fundamental underlying reason behind this project is to enable the patient with transfemoral amputation to walk, ascend stairs, sit and do basic movements. Based on the upper side muscle movements above the lower limb amputation, the patient will be able to control the robotic exo-leg by creating a muscle contraction among themselves. Even though the proposed project has a primary objective of supporting the patients with transfemoral amputation in a very cost-effective and assuring way, but this exoskeleton project is aimed to support the patients with monoplegia in the future.

The goal of constructing the model is enabling multi-functional features under prosthetic exoskeleton legs that will initially support the patients of lower limb amputation, more specifically the transfemoral amputation. To confront challenges with a socket, the module of the leg can be adapted concerning its kinematics and actuation to a wide range of users and applications.

Keywords: Prosthesis; Prosthetic Leg; Exoskeleton-leg; Cost-effective Prosthesis; Hydraulic actuation; Knee-powered leg; Amputation.

Dedication

I dedicate this Project to my friend “Tamim” who has been using a non-functional prosthetic for a long time. Watching him walk this way have made me believe that I can put an end to his misery. *Fahin Uddin Enam (18121008)*

From wanting to make an automatic fire extinguisher to a prosthetic exo-skeleton leg, I narrowed down what I wanted to do. Hence, I dedicate this project to my friends who has encouraged me, my family who has financially supported me to complete the project and my academic advisors who has been constantly supporting us. – *Fahmida Yasmin Nipa (18121009)*

I have always had a different fascination to work closely with a humanitarian project and I think my batchmate has supported me through it. I dedicate this project to my family who has been the fundamental support to us and our university that supported us eventually. -*Tashin Ahmed Abir (18121019)*

Being a technology enthusiast, I wanted to learn through teamwork. I dedicate my project to everyone who helped me learn to build a simple Line Follower Robot to a huge prosthetic exo-skeleton leg and then run it successfully on a patient. - *Musa Ahammed Mahin (18121019)*

Acknowledgement

We would like to acknowledge the people or institution that has helped us build out project successfully. We thank our family that they has allowed us to invest in this project pledging their hope. We would like to thank our ATC Panel Chair, Prof. Dr. A. H. M. Abdur Rahim for his immense supervision while guiding us towards our goal. Moreover, we thank or Co-advisers, lecturer Md. Rakibul Hasan and Mehedi Hasan Shawon for being available whenever we needed them and willingly guiding us throughout the construction of the project considering our drawbacks that might have impacted our project. An honorable mention would go to Prof. Dr. Md. Mosaddequr Rahman, Professor and Chairperson, Department of Electrical and Electronic Engineering and Dean of Engineering Prof. Arshad Chowdhury, Dean of Engineering and Computer Science who contributed during funding. Finally, we would like to acknowledge Mechamind, Brac Limb and Brace Center and Dynamic Limb Center for the support and information they have provided throughout the whole journey that made our project to be successful within a very limited period.

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List of Acronyms

IEEE	Institute of Electrical and Electronics Engineers
EMG	Electromyography
DC	Direct Current
CLK	Clock
FSYNC	File Synchronization
AD	Digital Pin
LSB	Least Significant Bit
HMI	Human-Machine Interface
ISO	International Organization for Standardization
HCPCS	Healthcare Common procedure Coding System
CAD	Computer-Aided Design
TPU	Thermoplastic Polyurethane
PLA	Polylactic Acid
CNC	Computer Numerical Control
BDT	Bangladesh Taka
IT	Information Technology
PCB	printed circuit board
MATLAB	Matrix Laboratory

OS	Operating system
IDE	Integrated Development Environment
SDO	Serial Data Out
CRP	Centre for the Rehabilitation of the Paralyzed
SACH	Solid Ankle, Cushion Heel
IRB	Institutional Review Board
BRF	Biomedical Research Foundation Bangladesh
WHO	World Health Organization
APA	American Psychological Association
EP	Engineering Problems
EA	Engineering Activities

Chapter 1: Introduction

1.1 Introduction

1.1.1 Problem Statement

According to an article posted on the website of La Trobe University, Bangladesh is a lower-middle-income country with a population of over 167 million where around 60% of the population is participating in labor force such as agriculture, constructions incorporating a high chance of workplace injuries.[1] Among the various types of workplace injuries or motor vehicle injuries, the most common is lower limb amputation. Moreover, considering the world population, about 7% to 10% of the world's population have different kinds of limb-related issues where lower limb amputation has been marked as the most common. The National Limb Loss Center has estimated that only in the United States there are an estimated 1.9 million amputees.[2] This infers the notion that Bangladesh as a developing nation has more patients suffering from Transfemoral Amputation. We can consider an amputation as Transfemoral Amputation when the amputation occurs at any level from the hip to the knee joint. Other than the injuries, the majority of lower-limb amputations are performed due to several peripheral vascular diseases; and the patients have to depend on the prosthetics for their movements.[3] Statistically, 185,000 people have an amputation each year. This means that 300 to 500 amputations are performed every day there are more than 1 million annual limb amputations globally -—one every 30 seconds.[4] Mentionable that the following amputation can be very challenging for the amputee and the surgeon. The price of a new prosthetic leg can cost anywhere from $5,000 to $50,000. Besides the most expensive prosthetic limbs are built to withstand only three to five years of wear and tear.[5]

1.1.2 Background Study

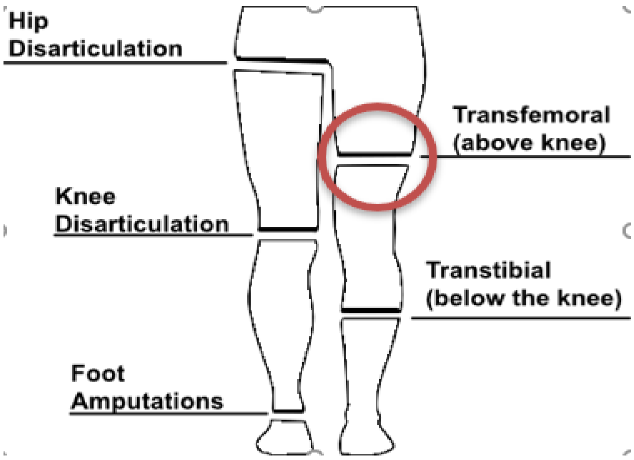

Figure 1: Types of Lower Limb Amputations [6]

Several research and project have been conducted to prevent the issues of post transfemoral amputation as the amputee always deals with increased energy consumption for ambulation, balance, and stability. They also require complicated prosthetic devices to assist them with the difficulties rising from sitting to standing, standing to walking. Comprehending the challenges faced by the patient, surgeons, the prosthesis for transfemoral amputation's cost is quite higher than any other transtibial prosthesis. More limitations arise when the transfemoral amputee tries to learn to walk with their prosthesis as they must learn to coordinate the interaction of the residual limb and the prosthetic leg. We have considered several lower limb issues, among which much previous research have demonstrated that a person with a transfemoral amputation is unable to take the body's weight directly on the transected end of the limb that requires them with a prosthesis that has a balancing system integrated within it. Besides, the patient may suffer from the weight not being loaded easily and the bone ends can press painfully against the socket used in the prosthesis. Moreover, the problem is not limited to people with lower limb amputation. Patients are suffering from monoplegia which is a kind of paralysis affecting one limb of the body or patient who needs assistive support for both legs. Normal Prosthesis legs are constructed in such a way that only people with lower limb amputation such as Transfemoral and Transtibial can be assisted and cannot be used for the patient of monoplegia. The necessity of assistance in walking and daily living for the elderly population and individual with limb dysfunction is highly demanding and incorporate a wide variety of patients. As a result, technologies are emphasizing biomedical sectors to develop assistive devices as multifunctional prostheses for a variety of target patients. These multi-functional requirements limit the use of the prosthetic leg.

1.1.3 Literature Gap

We have reviewed few of the paper before we came up with the design plan and to find our necessary alternative to the components we are using right now. The following section will carry our paper analysis of few of the paper we have inquired for our project.

Paper 1: Concept and Design of a Modular Lower Limb Exoskeleton [7]

This paper provides idea of three system consisting of an active hip support exoskeleton, a fully articulated lower limb exoskeleton for gait support and a system for treadmill based gait rehabilitation. Through which it was proved that a modular exoskeleton is feasible among the three designs as it can be used for several changing requirements. For this inquiry, only design analysis and requirement analysis has been discussed in order to come up with the result.

Paper 2: Toward the Development of a Neural Interface for Lower Limb Prosthesis Control [8]

Research has been carried out how the development of Neural Interface for Lower Limb Prosthesis is required to reduce the limitation of prosthesis usage. It appears that user must make extra movements in order to control mechanically passive prosthesis. On the other hand, Microprocessor-controlled prosthesis that uses sensors and microcomputer to read the data from the body parts or and initiate the movements doesn't require much body movements. A future work containing Neural interface instead of Gyro-based legs might produce better performance while ensuring user's safety.

Paper 3: Mechanical Design of a Hybrid Leg Exoskeleton to Augment Load-Carrying for Walking [9]

Inquiring on two different types of prosthesis, passive or quasi-passive exoskeletons and Powered exoskeletons, a pseudo-anthropomorphic exoskeleton SJTU-EX has been discussed with its performance where joint ranges are optimized on the basis of typical human motions. This paper is mostly design and performance orientated that compares how the new technology differentiate between walking, jogging, climbing stairs and squatting in order to generate output to the powered knee. Here, another fundamental factor has been discussed that in order to follow human motions and lessen several kinematic constrains, exoskeleton require an adequate level of freedom.

Paper 4: The H2 robotic exoskeleton for gait rehabilitation after stroke: early findings from a clinical study [10]

This paper inquired a prosthesis that has been constructed for lower limb impairment and disabilities following Stroke. The exoskeleton named H2 (Technaid S.L., Spain) was developed with an assistive gait control algorithm that was able to generate a force filed along a desired trajectory. Eventually, a four weeklong gait training has been evaluated in order to find out the usability and the users were post stroke hemiparetic patients.

Paper 5: Designs and performance of microprocessor-controlled knee joints [11]

Research has been carried out for a comparative purpose with several micro-processor controlled prosthesis such as C-Leg, Orion, Plié2.0, and Rel-K. I. This paper has elaborated the functionality of C-leg through technical analysis in compared to other legs. It includes that the C-leg is controlled based on the joint resistance following the principle of a hydraulic system that incorporate two different servo valves. This paper also assures how microprocessor controlled prosthetics is optimal and safe to use instead of conventional mechanical legs.

Literature Gap: All the research above are elaborated based on performance and technical analysis that mostly focuses on solving the problem of stroke, lower limb amputation and development studies concerning several future works. However, none of the paper has inquired on their stakeholders. We all know, the amputation and stroke are common in working class people and in lower economic nation, despite knowing that there is a solution to one's amputation or disability, one cannot afford to buy such a high cost prosthesis that require higher cost not only to buy the prosthesis but also to afford necessary physiotherapy, repair and testing. Moreover, the papers also considered normal walking pattern compared to prosthesis walking patter, where non-functional user's pattern has not been discussed or analyzed. Hence, our research has been carried out inclusive of technical to cost analysis with extensive pattern analysis such as non-functional prosthesis user's performance.

1.1.4 Relevance to current and future Industry:

From amputation to stroke, the exoskeleton is being commonly used based on variety of usage such as rehabilitation and augmentation. In biomedical industry, prosthesis and its physiotherapy is widely known and developing day by day. Mentionable that, lower limb amputation being so numerous within developing countries, current lower economic state, there are a lot of organization that are working on such projects to provide with the patients safer and functional legs. However, most of the prostheses barely fulfil the necessitates of high-level amputation due to the usage of Surface EMG as control source of the legs. As a result, companies or organizations are coming up with new control strategies such as neural interface. Few companies are working in two categories of prothesis such as, passive prosthesis and powered limb.

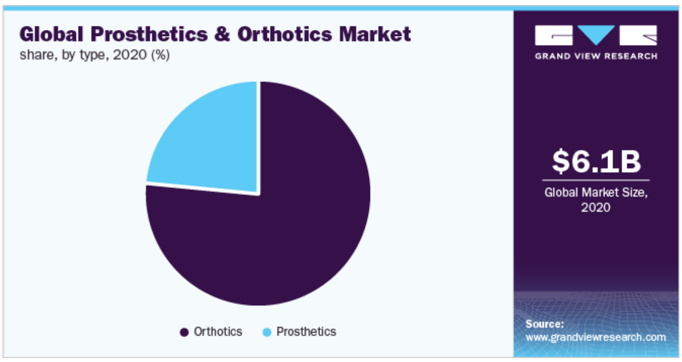

Figure 2: Global Market Size [12]

According to an article in Grand View Research, incidences of sports injuries, osteoarthritis and penetration of orthopedic technology, the orthotics segment held the dominant share of over 74% in the global market for its revenue scale. [12] Alongside medical treatment evolution the market size is expanding and with the market expansion research sector is adopting projects relevant to the industry.

1.2 Objectives, Requirements, Specification and constant

1.2.1. Objectives

The fundamental underlying reason behind this project is to enable the patient with transfemoral amputation to walk, ascend stairs, sit and do basic movements. Based on the upper side muscle movements above the lower limb amputation, the patient will be able to control the robotic exo-leg by creating a muscle contraction among themselves. Even though the proposed project has a primary objective of supporting the patients with transfemoral amputation in a very cost-effective and assuring way, but this exoskeleton project is aimed to support the patients with monoplegia in the future. The goal of constructing the model is enabling multi-functional features under prosthetic exoskeleton legs that will initially support the patients of lower limb amputation, more specifically the transfemoral amputation. To confront challenges with a socket, the module of the leg can be adapted concerning its kinematics and actuation to a wide range of users and applications.

- The exo-leg is committed to enhancing patients' capacity to walk freely by focusing on functional results
- The project considers the patient’s safety by ensuring comfortable and easy movements as he can use a portable battery.
- To provide the lower limb amputation patient with prosthetic exo-leg as a walking aid at a reasonable cost. This project includes actuation or spring stabilization as an alternative to expensive hydraulic servo valves. Incorporating the adjustment as per as the leg size
- Simple and a lightweight wearable robotic leg for the patients.
- Construct a similar system as assistive exoskeletons to function for different types of patients with lower limb amputation and patients diagnosed with monoplegia, transtibial and foot amputation

1.2.2 Functional and Nonfunctional Requirements and Specifications:

The following specifications and requirements have been analyzed based on design 2.[13]

Table 1: Specification & Requirements

System Specification		Components	Component specification	Fundamental Connection Required	Requirements
System	Sub-System				
Central Unit		ESP-32	▪	5V DC power supply	Must control the entire processing system of the prostheses.
Balancing System	N/A	Gyroscope Sensor	▪ I2C Digital-output of 6 or 9-axis MotionFusion data in rotation matrix, quaternion, Euler Angle, or raw data format ▪ Input Voltage: 2.3 – 3.4V ▪ Selectable Solder Jumpers on CLK, FSYNC, and AD0 ▪ Tri-Axis angular rate sensor (gyro) with a sensitivity up to 131 LSBs/dps and a full-scale range of ±250, ±500, ±1000, and ±2000dps ▪ Tri-Axis accelerometer with a	Gyroscope to collect data from each leg joint position	This must act as a triggering device for the motor to run based on the movement of the patient.

			programmable full-scale range of ±2g, ±4g, ±8g, and ±16g		
Measurement System (Joint Angles & Pressure)	Join Angle Measurement	Hall-Effect Sensor	• 3.5V to 24V DC operation voltage • Low current consumption • Temperature compensation • Wide operating voltage range • Open-Collector pre-driver • 50mA maximum sinking output current • Reverse polarity protection		This is required to calculate joint angles accurately and determines if the leg is in load or not.
Functioning System:	Motor Selection	High Torque servo motor	• Hip: Hyperextension Movements (0-45 Degree) & Flexion movements (0-130 Degree) • Knee: Flexion Movements (0-135 Degree) • Ankle: Dorsiflexion Movements (0-20 Degree) & Plantarflexion Movements (0-40 Degree)	Optical encoders to measure angles of motor axes	Required to allow the exoskeleton to move and hence assist the wearer's limb movement. It will receive a command from the controller and, at a specific time, produces motion per the demand.
[14]					

Non-Functional Requirements:

- **Exterior Design and Materials**: The Exo Leg suit will be designed using **an aluminum frame** since the body of the exoskeleton requires a robust and light material.[15] Furthermore, a lightweight frame requires less power to actuate the body part. However, the exoskeleton's structure must be strong enough to bear the torque created by the actuator as well as the wearer's body weight.
- **Socket:** The socket used in this Prosthetic Exo-leg is the basic interface between the amputee's residual limb with the robotic leg. This is required to be customized based on the patient's leg size where the prosthesis will be connected. The socket has to be efficiently fitted for comfort and safety. Poor fit and uncontrolled biomechanics can cause patients with amputations severe issues.[16]
- **Real-time system:** With a view to generate higher accuracy, the system's function is required to be real time. When the leg is active, it takes the sensor data and act instantly in order to generate angle trajectory and move the leg as per patient's requirement. Hence, the system with the real-time data reading cannot meet the requirement of the process.
- **Cost:** It is a fundamental aspect of this project that the cost must be reasonable as we aim to provide the leg support to lower class people who are unable to afford high cost functional prosthesis. The project is not only functional but also comprises an ESP-32 controlled leg following powered knee system. Hence, the proposed project is built with a micro-controller in order to control the leg.
- **Multi-functional Status:** As this system is very simple, other than lower limb amputation it can also be used for ankle amputation, transtibial amputation based on patient's necessity. For which the leg must be constructed part by part such as from the knee, from the ankle or from the upper limb.

1.2.3 Technical and Non-technical consideration and constraint in design process

Constraints:

Mechanical Constraints: The difficulties and challenges that we can potentially face during our design and implementation can be classified as mechanical constraints. There are some degrees of mechanical challenges that we have to face which have been listed below.

- The built of the Prosthetic which is the combination of the exoskeleton's frame and joints may not be firm enough to support the body weight of the patient unless we physically experiment with it.
- The sustainability of a total paraplegic is uncertain since the frame has to transfer the stress and torques that are required to ensure through the mechanical implementation.
- The exoskeleton can only be optimal enough to become duty specific for a healthy person's joint.
- Due to errors in surgical factors the socket shape might not be able to influence the position of the residual femur which can create complications in adjustability.

Electrical Constraints: To make our design functional, compact, and power-efficient we need to deal with some electrical constraints.

Power loss

- As the prosthetic is a mobile device it can be challenging to provide uninterrupted power delivery
- It is challenging to make the prosthetic’s power delivery system rechargeable and efficient.
- The prosthetic has to possess a removable DC power system and quick charging capabilities which is difficult to make cost-efficient.

Environmental Constraints: The impact that can occur through the environment to the Prosthetic and vice versa is the environmental constraints of our project which have been listed below.

Environment over prosthetic

- Water damage is a very common phenomenon in the open electrical design of the prosthetic.
- In a compact design shock-absorbent for both electrical and force is complicated

Prosthetic over Environment

- Prosthetics testing kits and production makes a considerable amount of carbon footprint.

Legal Constraint: To have legal rights and obligations are the legal constraints of our project, which we may face prior to or during the framework.

Human Trail:

- Full consent is difficult to attain before any project-related approach.

Risk Management Analysis:

Prosthetics Exo-leg provides the lower limb amputee with outstanding independence of mobility. However, such pros come up with necessary hazards to consider. Even though several conducted studies inferred that most of the exoskeletons turn out to be safe to use for specific specifications.[17][18][19] However, according to our system specification, we are to confront several risks which need to be mitigated responsibly. We have divided the risks into three different sections,

1. Technical Risk
2. Non-Technical Risk
3. Health Risk

Table 2: Technical Risk Analysis & Management

Risk	**Analysis**	**Person affected**	**The severity of risk:** **Catastrophic** **Critical** **Marginal** **Negligible**	**Possibility of risk:** **Frequent** **Likely** **Occasionally** **Seldom** **Unlikely**	**Mitigation plan**	**Monitoring & Responsible**
Component Unavailability	Failing to find out or get the component in time	Project Partners	Critical	Seldom	Alternative components or manual system implementation design plan	Fahin Uddin Enam
Beta Testing: System Failure	The project may technically fail during the construction	Project Partners	Critical	Occasionally	Trying other approaches/ Re-design plan	Fahmida Yasmin Nipa

Post Hand Over System Failure	The project may fail after being passed to the consumers.	Amputees, buyers.	Catastrophic	Unlikely	Refund Policy and Further research on the failure.	Tahsin Ahmed Abir
Thermal Destruction of Battery [20]	Since the use of Li-po Batteries can face thermal runaway in case of a fault and cause explosion. It will cause skin burns to traumatic injuries.	Amputees	Catastrophic	Unlikely	State of the art battery protection circuitry [in progress work]	Musa Ahammed Mahin

Table 3: Non-Technical Risk Analysis & Management

Risk	**Analysis**	**Person affected**	**Severity of risk**	**Possibility of risk**	**Mitigation plan**	**Monitoring & Responsible**
Investors	Promised investors Unwilling to invest.	Project Partners	Marginal	Occasionally	Self-fund, advertisement & Marketing	Musa Ahmed Mahin
Cost	Final budget Exceeding the planned budget or deflation situation	Project Partners	Critical	Occasionally	Project Loans, Contingency fund/savings	Tahsin Ahmed Abir
Clients /Stakeholders	Project Failure may affect consumer's trust	Project partners	Critical	Seldom	Gaining consumer's trust from community feedback with upgradeable system and	Fahmida Yasmin Nipa

					improved plans/ Changing Design approach and reach the consumers.	
Environmental	Multiple project failures may cause much component disposal	Everyone	Catastrophic	Likely	Using recyclable or repairable components, good quality product.	Fahin Uddin

Table 4: Health Risk Analysis & Management

Risk	**Analysis**	**Person affected**	**Severity of risk**	**Possibility of risk**	**Mitigation plan**	**Monitoring & Responsible**
Joint Destruction [20]	High HMI forces as the actuator might reach the highest range and extend the knee joint beyond the safe range	Amputee	Catastrophic	Unlikely	Applying an end stop reduces the chances of such incidents	Musa Ahmed Mahin, Tahsin Ahmed Abir
Unwanted movement [20]	caused by excessive actuator torque.	Amputee	Catastrophic	Unlikely	Implementation of diagnosis for obstacles and unpredicted contacts	Fahin Uddin Enam Fahmida Yasmin Nipa

1.2.4 Applicable compliance, standards, and codes

Prosthetic exo-leg is to be built with various categories of components. As we know, from the microcontroller to its aluminum body, there are necessary standards and codes we need to follow to make the project acceptable. Hence, we have considered the standard and codes below as per our system specification. The standards and codes are verified and regularized by different organizations such as IEEE, ISO, and HCPCS.

Table 5: Applicable standard and code

Required Devices	Code & Standard
• Motor Protection in Industrial and Commercial Power Systems	IEEE 3004.8-2016
• Guide for Design Operation & Maintenance of Battery Energy Storage System	IEEE 2030.2.1-2019
• Rechargeable Batteries	IEEE 1725-2021
• External limb prostheses and external orthoses — Requirements and test methods	ISO 22523:2006
• Batteries and Accessories	HCPCS Code range L7360-L7368
• Prosthetic Sockets	HCPCS Code range L5629-L5653
• Below the Knee Prosthetics	HCPCS Code range L5100-L5105
	Source: IEEE, ISO, HCPCS

1.3 Systematic Overview/summary of the proposed project

The design development process through a systematic overview for the proposed project is explained below,

- **Conceptual design:** The process of developing new product ideas is the first step in the creation of a product. This is the stage of product innovation where we have sketched a conceptual design with product ideas based on market research, concept testing, and consumer demands.
- **Design analysis:** In this process we have designed the CAD model in the software and analyzed each part for the validation and testing. We have done load analysis, stress analysis and motion analysis in the Solidworks software before developing actual product.
- **Material selection:** Based on the load analysis done in the Solidworks we have selected materials for each part in order to make a very durable low-cost prosthetic exo leg. For example, the parts where heavy loads are applied, we have used TPU plastic, aluminum molded and S.S sheet parts other than that we have used PLA 3d printed plastic.

- **Production drawing:** Production drawings are also known as engineering drawing which is a detailed and precise diagram that passes information about how the parts will look like. We have used production drawing for CNC Machining to cut the S.S sheet based on the drawings.
- **Prototyping:** Prior to production, prototyping allows designers the chance to investigate alternative solutions and test the current design. Initially for the protype stage we have 3d printed each part and tested the functionality of the mechanism to find out any error for ensuring its stability.
- **Finalized Implementation:** After the prototyping stage we have finally assembled each tested parts for the final implantation of the project. Finally, we have tested the design in the human trial process using tread mill

1.4 Conclusion

In this project, we have inquired necessary standards, constrains and risk-management analysis to develop the project. This not only ensures a higher accuracy requirement but also the constraint we might face while constructing the project. Moreover, the non-technical risk and health risk are elaborated with necessary mitigation process required. The project is constructed in a very systematic way, as an industrial level project is made and taking account of all factors such as safety, sustainability and impact, we believe the project has been constructed effectively. Eventually we believe that successful completion of the project will have a huge number of opportunity available for the prosthesis market as well as a hope for the amputee patient who are unable to afford powered prosthesis for socio-economic status.

Chapter 2: Project Design Approach

2.1 Introduction

This project idea has a numeric step-wise methodological design approach which helps the project to work as a functional extension for transfemoral, transtibial amputation and patient with lower limb deficiency. For such purpose, we have selected two different designs, among which one of the designs is widely used in higher socio-economic nations namely C-leg, and another design is innovated and customized based on currently developed exoskeleton legs worldwide, namely, Prosthetic E-leg.

2.2 Identification of Multiple Design Approach

Design 1: C-Leg: Design 1, C- leg uses hydraulic actuation method for the stance and swing phase of the leg joints. In this system microprocessor is controlling the oil flow of each valve during flexion and extension of the piston. This whole system works in a very compact and close looped environment.

Design 2: Prosthetic Exo-leg: Design 2, prosthetic Exo- leg uses a rotary actuation method to drive the ankle and knee joint. This design uses hall effect sensor to detect whether any load is applied on the leg or not and gyroscope sensor is used to determine the leg position which will eventually detect the gait cycle.

2.3 Multiple Design Approach

Design 1: C-Leg

- Used Two hydraulic servo valves for stance and swing phase of the knee ankle joint
- knee joint can identify the gait phase using different sensors (angle sensors, strain gauges)
- The damping is regulated by the hydraulic joint.
- altering the resistance in the knee automatically to ensure the correct degree of stability during each step of the Stance Phase regardless of terrain
- maintain the appropriate knee release position to start the Swing Phase, as well as sufficient foot clearance throughout this phase
- 40 to 50 hours of battery life are stated for the C-Leg
- costs between BDT 32 Lac and BDT 40,000 each leg [21],[22]

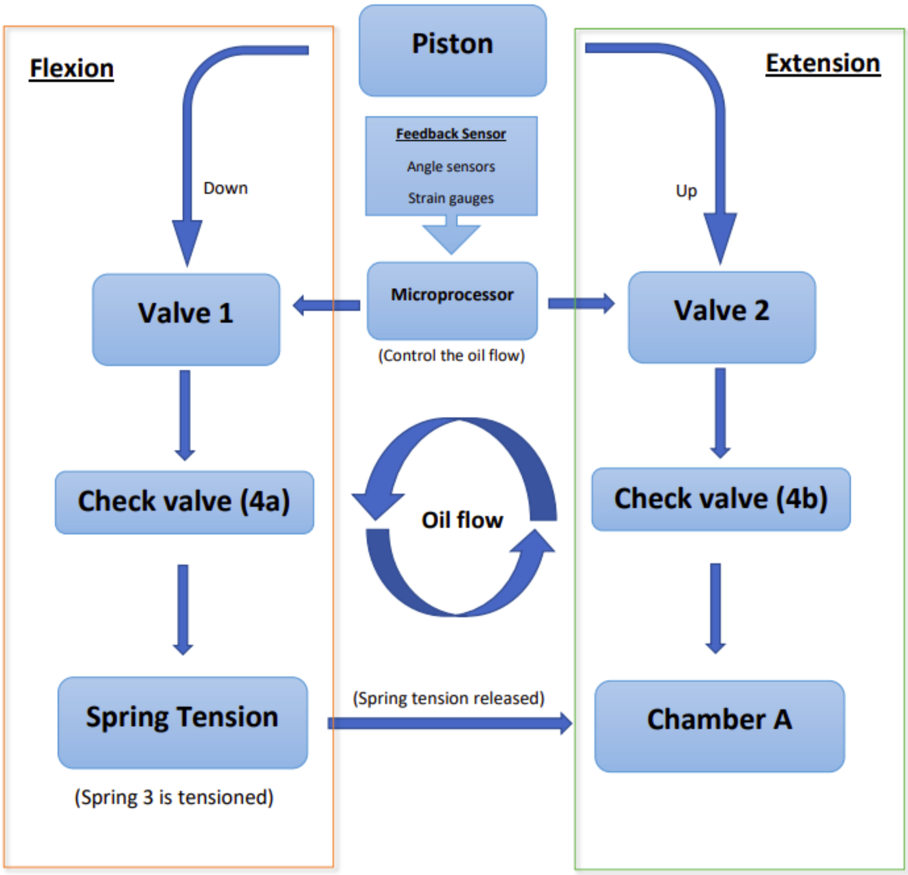

Figure 3: Workflow of C leg

Design 2: Prosthetic Exo-leg

- Using dc servo motor technology to drive the ankle and knee joints during the stance and swing phases.
- To manage the gait phase, numerous sensors such as an electromyography sensor, an accelerometer sensor, a force sensor, and a hall effect sensor are used.
- To some extent, the Damper, and spring mechanism will support the motor by storing energy in a given phase (yielding, stance phase flexion) and releasing it later.
- Can elevate foot during the swing phase to adjust to terrain and avoid accidents or falls
- Battery life may be extended to 30 to 35 hours using this mechanism.
- can vary in price from BDT 60,000 to BDT 80,000 for each leg

[23], [24]

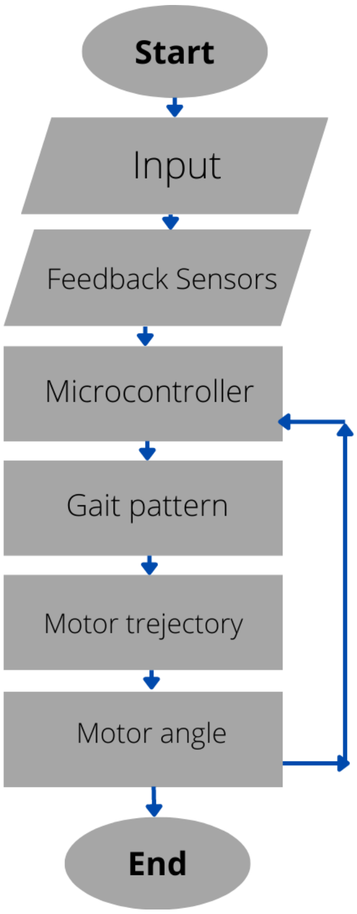

Figure 4: Rotary Actuation system

2.4 Analysis of Multiple Design Approach

Design 1: C-Leg: In our 1st approach, the hydraulic actuation method has been used to control the stance and swing phase of the C-Leg. C leg work on the principle of the Hydraulic actuation system. It is encompassed in a closed-looped hydronic system and the fluid inside is oil. As per the description, when flexion happens, Piston A compresses chamber A and the oil from A passes through valve 1 and puts pressure on piston B which gets compressed. In case of extension, piston A slowly compresses and the liquid oil flows through valve 2 and which redirects the oil flow from piston B.

Design 2: Prosthetic Exo-leg: Our system in design 2 includes a suite of sensors for gait cycle detection, muscle activation monitoring, and gait assistance control. Gyroscope sensors are used to determine the kinematics of the gait. During the stance phase, hall effect sensors are used to detect the load. We are also using force feedback control system in order to adjust the servo motor position based on the force sensed in the ankle joint to move the servo freely. Moreover, we have used hall effect sensor as a stop toggle switch for unwanted movements in the joints. We are using high torque servo motors as a power source of leg joints and a damper to benefit from the elastic energy storage and release during walking and running gaits.

2.5 Conclusion

Lastly in this section we have demonstrated the design concepts of each design. C- leg design has a very complicated hydraulic actuation process on the other hand prosthetic exo-leg uses a simple pulley gear mechanism. Both designs are very efficient in its own way.

Chapter 3: Use of Modern Engineering and IT Tool.

3.1 Introduction

We have used different types of software to implement the 3D model to circuit designs along with necessary hardware tools and workshops for hardware implementation. This also includes our design algorithm to determine the motor angle and position for the functional prosthesis to perform. Selected engineering and IT tools are mentioned, and their use has been elaborated below.

3.2 Selecting Appropriate Engineering and IT Tools

The Modern Engineering/IT tools we have considered for this project is stated below,

Table 6: Modern Engineering/IT Tools Selection

Tools Name	Selected Tools	Validation
Algorithm	Inverse Kinematics	Determine the motor angle and position
Controller	ESP-32	Processing Power is Fast and Convenient
Software	Solidworks	3D Design, Simulation, Stress Analysis, Weight Analysis, Load Analysis, Motion Analysis.
	Proteus	Circuit Simulation – Raspberry Pi
	Eagle	PCB Designing – Controller Circuit
	MATLAB	Inverse kinematics Algorithm Design
	Raspberry pi OS	Controlling the Raspberry pi Controller
Hardware/Workshops	3D Printer	To print several body parts with PLA Filaments designed in Solidworks.
	CNC Cutting	To cut particular model or part of the body such as, servo mount bracket and holding plate
	Lathe Cutter	To make customized screw

	Bending and Cutting Machine	Bending the part after CNC cut to get desired shape
	Treadmill	To test the user's performance wearing the prostheses.

3.3 Use of Modern Engineering and IT Tools

Technology is a part of modern engineering, but it is also engaged with the advancement and comprehension of technological systems, their products, effects, and applicability. To create a project like ours from ground zero we had to take various challenges head-on and mitigate these challenges with the usage of various modern engineering technologies and IT functionalities. From the design phase to project building, execution, troubleshooting and testing we have used software solutions, unique functional methods and hardware implementation methods to reach our success.

- We initially used various sketching and drawing to set our initial model.
- Based on that initial model we have created our 1st 3D model in Solid Works software

Figure 5: 3D Model of the E-Leg

This 3D model helped our project to take its first visual look and a clear idea of what we are trying to achieve and set our next stage straight. Now Solid work allows us to run various simulations regarding the structural stability of the project, material integrity and motion

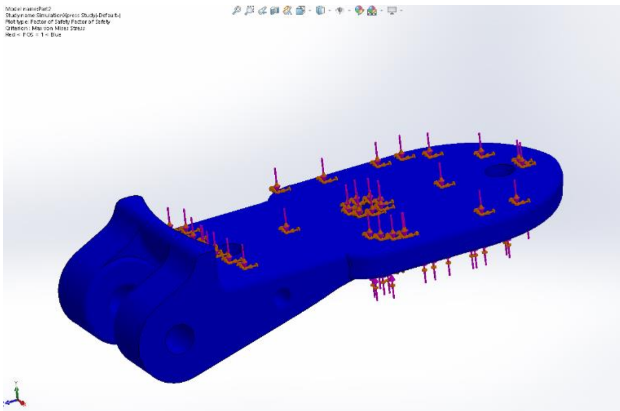

Figure 6: Design Analysis

analysis, load analysis etc. Our project required us to test the load analysis of the project which we were able to perform via Solid Works.

We also used Solid Works for various functional analyses such as movement, angle and force measurements. These designs allowed us to come to some definite conclusions about the materials and appropriate methodology that we need to attain to achieve our approximate results. We followed our designs and after acquiring the appropriate materials and tools from various collaborations with companies like BRAC Limb centre. We build our model by checking every box of objectives that we set for ourselves after we did our 3D model which includes

- Building a production drawing
- CNC cutting
- Hydraulic bending machine
- lathe machine
- 3D printing
- Prototyping

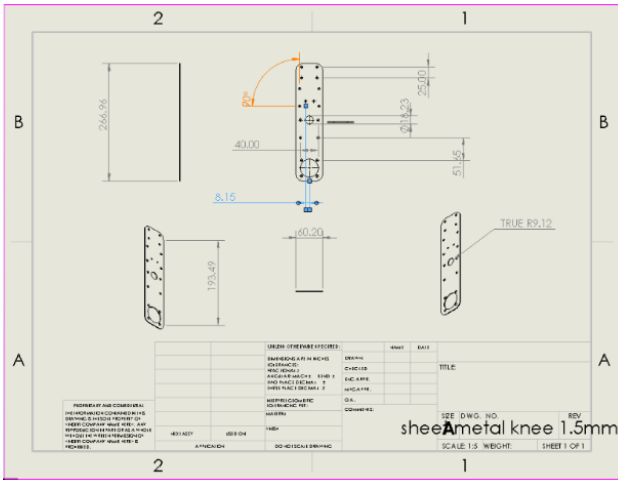

Figure 7:Production Drawing

For production drawing, we had to draw out the metal cut-outs for the CNC machines to accurately cut through the portions that we require for the building of the prototype. Based on the drawing that we provided, we used CNC cutting technology to perfectly cut out the shape modules from our desired materials which are crucial for our project.

Figure 8: CNC Cutting & Lathe Cutting

CNC cutting method helped us to cut out various parts of our project precisely and use the Hydraulic bending machine to bend the parts that as required for the project which is the holding plate for the prosthesis. We also made a Servo mount bracket using the lathe machine which acts as the cover and container for the motor and internal mechanism to reside inside.

Next, most of the body parts that make the prosthetics' outer shell are made out of PLA filament which is made out of 3D printing. 3D printing is a relatively modern technology which we fully utilized for our project as it helps us to mitigate two of the major issue which is cutting the cost lower and reducing the overall weight of the prosthetic.

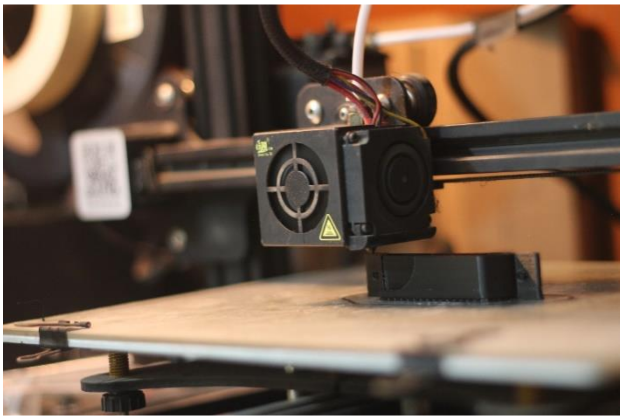

Figure 9: 3D Printer for 3D printing bodies made of PLA Filaments

We used the 3D printing method to create:

1. Footpad
2. Cover
3. Servo holder
4. TPU flexible pad
5. Spring holder

6. Plate holder

Furthermore, we made our prototype for the initial testing and troubleshooting. It was made using all Motor, spring, and 3D printed plastic. Using the prototype, we managed to accumulate the annual data that represented how much deviation was caused and what needs to be adjusted to the final design. We used various testing methods which include walking motion both for average and our subject using a treadmill and received some initial data and slowly we enhanced our prosthesis according to that data toward more suitable for the wearer to receive a better result.

3.4 Conclusion

We explained all the modern IT tools we have used for the completion of our project within the given time limit. To complete the whole project in time the selection of necessary tools and workshop was essential as we have built our device based on software tested data and results along with all the updated adjustments and changes that appear during the testing. One of the most notable is that we had to readjust the knee bending portion as it was creating a disturbance in the balance of your subject's standing and walking.

Chapter 4: Optimization of Multiple Design and Finding the Optimal Solution.

4.1 Introduction

Optimization of multiple design require a performance analysis with major component changed in both theorical and practical simulation. We were able to function Prosthetic Exo-leg as it was constructed within a lower range of cost. On the other hand, we only processed a theorical information of the C-leg due to the hydraulic actuator being very costly and will not make our design sustainable. The theorical approaches are inquired for the validation as C-leg is widely used in different countries with higher socio-economic condition.

4.2 Optimization of Multiple Design Approach

For this section, we have inquired C-leg data through software to find out how it works and its function process to find out optimal design approach.

Design 1: C-Leg – Hydraulic Actuation

A mentioned before in this design two hydraulic servo valve actuator has been used for stance and swing phase. Now we are going to perform a simulation test in Solidworks cad software. We will be observing motion analysis of this prosthetic leg based on the hydraulic linear actuator.

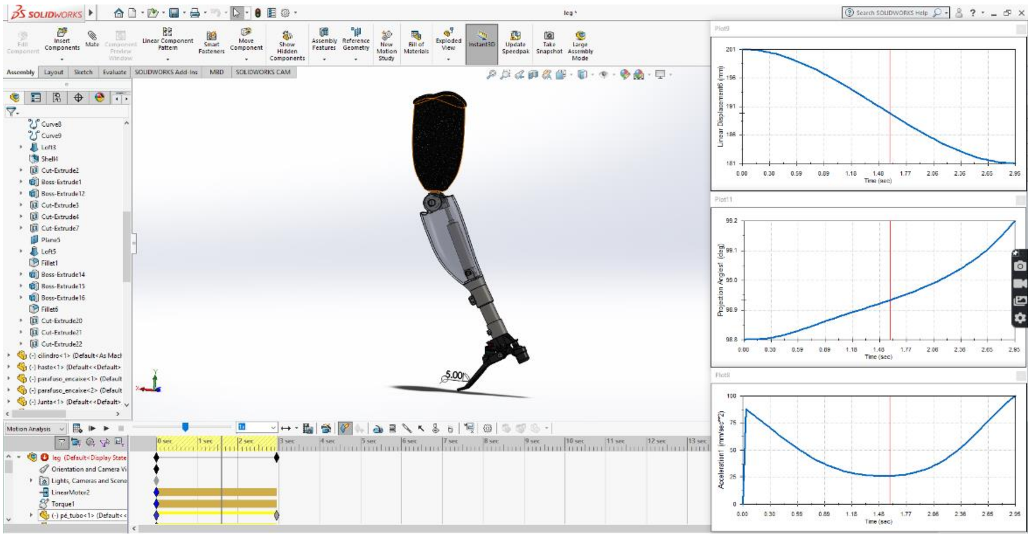

Figure 10: Theoretical Performance Test in Solidworks

To analyze the actuator efficiency at the output terminal, which generates linear output force, the actuator is modeled as a system composed of the principle of a hydraulic system with two separates servo valves, for the flexion and the extension movement. Here the duration of the motion simulation is 3 second. In fig 11 and fig 12 we have analyzed the date at 1.5 and 2.9 seconds, which shows the behavioral changes of the prosthetic leg.

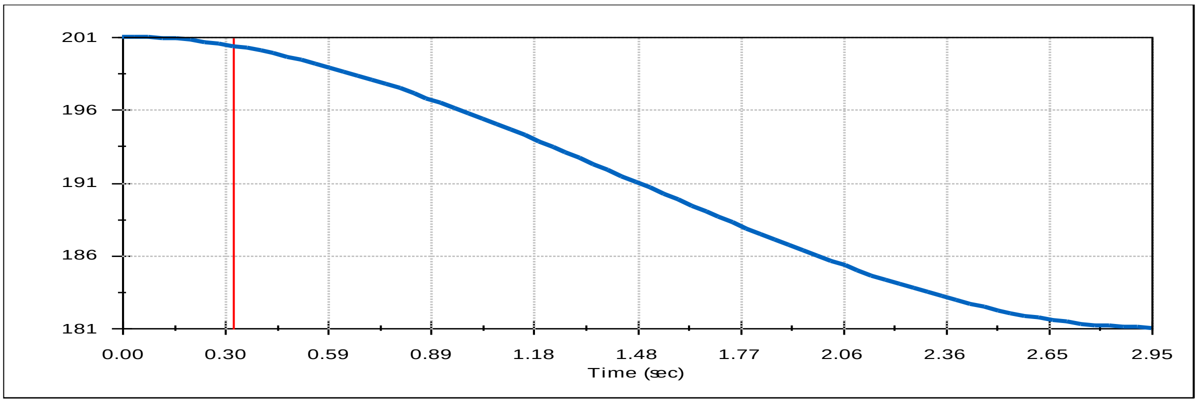

Figure 11: Performance Graph 1

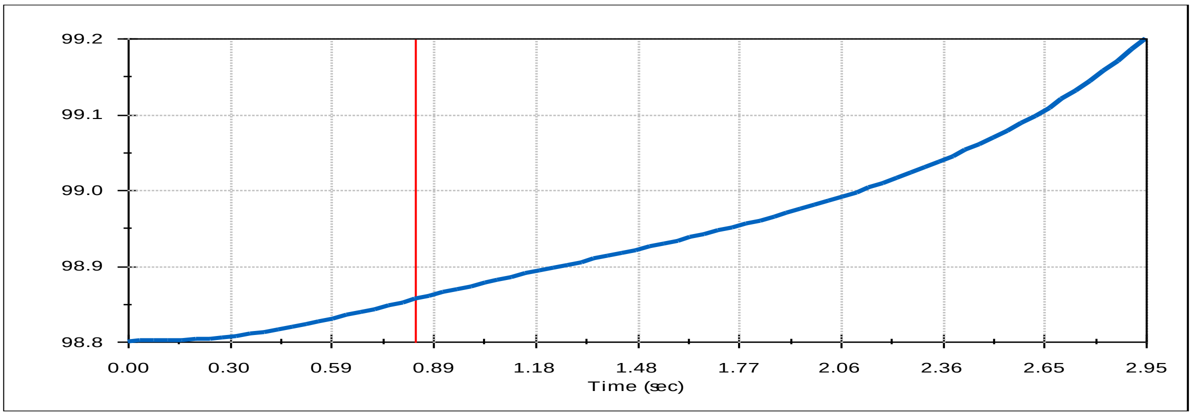

Figure 12: Performance graph 2

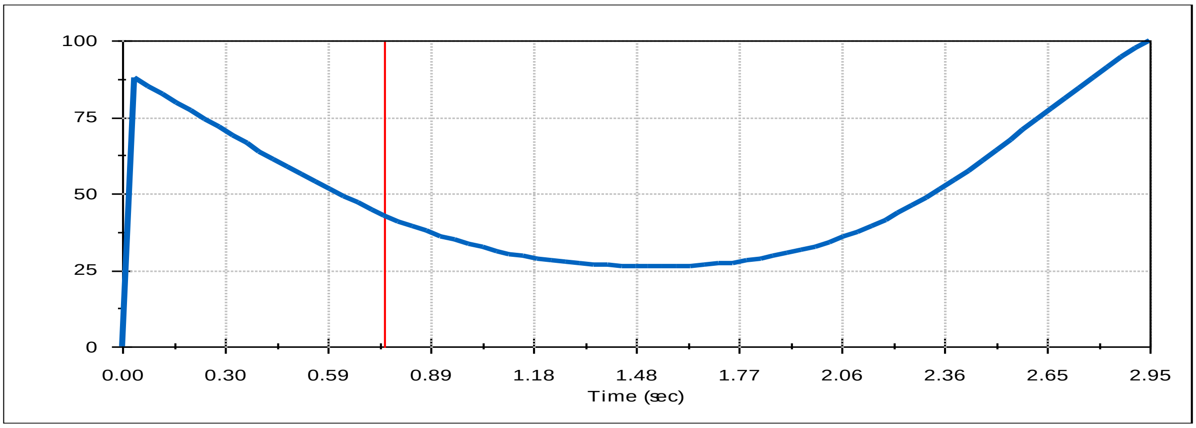

Figure 13: Performance Graph 3

Fig 13 shows the gait data of knee joints actuator displacement, angle, and acceleration. The data were used to determine actuator stroke length and gear ratio.

Design 2: Prosthetic Exo-leg – Rotary Actuation

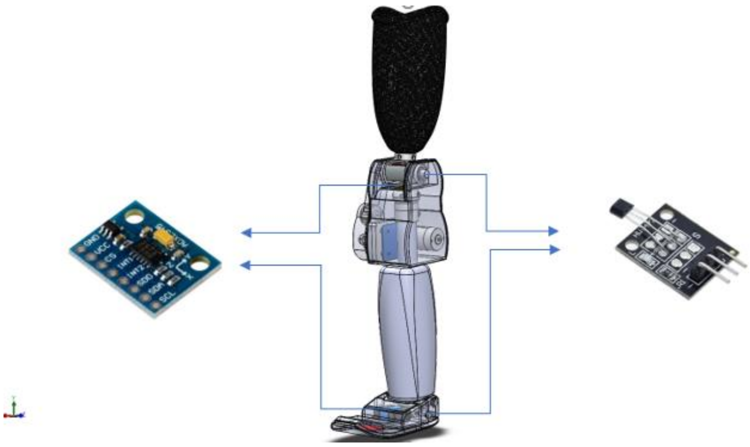

Figure 14: Control of E-leg

In Figure 14, our system in design 2 includes a suite of sensors for gait cycle detection, muscle activation monitoring, and gait assistance control. Gyroscope sensors are used to determine the kinematics of the gait. During the stance phase, hall effect sensors are used to detect gait phases.

Angle measurements of the joints: In the figure 14 we have included the gyroscope sensor in both joints to measure the angle of the of both knee and ankle joint. We have tested the gyroscope sensor in real time and got some raw values in figure 15.

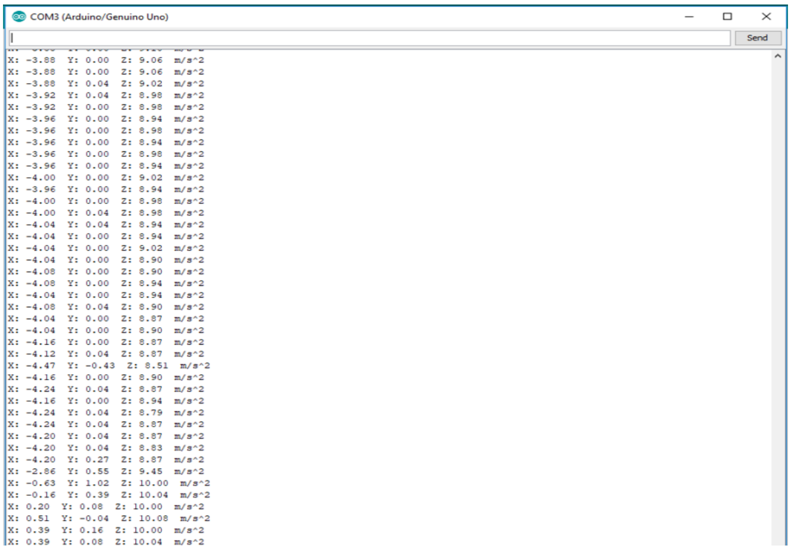

Figure 15: Gyroscope & Accelerometer Sensor Raw Data

We can further convert these raw accelerometer data into angles using the ratios of acceleration vector components. Systematic errors can occur in both accelerometer and gyroscope data. In the long run, the accelerometer offers accurate data, although it is noisy in the short run. In the near term, the gyroscope delivers correct information regarding changing orientation, but the required integration causes the results to drift over longer time scales. The solution to these problems is to fuse the accelerometer and gyroscope data together in such a way that the errors cancel out. Now by using the complementary filter method by Shane Colton, we can determine the filtered angle of each axis.[13]

Arduino IDE Code:

1. **Primary Code based on which the leg is functioning**

```
#include <ESP32Servo.h>
#include <Wire.h>  // Wire library - used for I2C communication
#include <Adafruit_Sensor.h>    // Adafruit  sensor library
#include <Adafruit_ADXL345_U.h>  // ADXL345 library
Adafruit_ADXL345_Unified accel = Adafruit_ADXL345_Unified();   // ADXL345 Object
Servo Myservo1;
Servo Myservo2;
int pos1, pos2;
int servopin1 = 15;
int servopin2 = 2;
int anglelimit = 170;
int certainangle = 140;
int defaultposition = 0;
void setup()
{
  Myservo1.attach(servopin1);
  Myservo2.attach(servopin2);
  Serial.begin(9600);
  pinMode(12, INPUT);//Button pin
  pinMode(14, INPUT);//Hall sensor
  pinMode(5, OUTPUT);//Address pin  SDO>>>> High for 0x1D.............LOW for 0x53
  pinMode(2, OUTPUT);//Address pin  SDO>>>> High for 0x1D.............LOW for 0x53
```

```
  Serial.begin(9600);
  if (!accel.begin())  // if ASXL345 sensor not found
  {
    Serial.println("ADXL345 not detected");
    while (1);
  }
}
void loop()
{
  digitalWrite(5, HIGH);
  digitalWrite(2, LOW);
  delay(100);
  sensors_event_t event;
  accel.getEvent(&event);
  Serial.print("X1: ");
  Serial.print(event.acceleration.x);
  Serial.print("  ");
  Serial.print("Y1: ");
  Serial.print(event.acceleration.y);
  Serial.print("  ");
  Serial.println("m/s^2 ");
  if (digitalRead(12) == LOW && digitalRead(14) == LOW)//motion of servo by ADXL when no hall signal and button is unpressed
  {
    float xaxis = event.acceleration.x;
    float servopos1 = map(xaxis, -10, 10, 0, 180);
    Myservo1.write(servopos1);
    Myservo2.write(0);
    if (servopos1 >= anglelimit)
    {
      Myservo2.write(certainangle);
      delay(1000);
      Myservo2.write(defaultposition);
    }
```

```
  }
  if (digitalRead(12) == LOW && digitalRead(14) == HIGH)//when hall signal dected and button is unpressed
  {
    Myservo1.write(anglelimit);
    Myservo2.write(defaultposition);
    if (anglelimit >= certainangle)
    {
      Myservo2.write(certainangle);
      delay(1000);
      Myservo2.write(defaultposition);
    }
  }
  if (digitalRead(12) == HIGH)//botton pressed
  {

    Myservo1.write(certainangle);
    Myservo2.write(certainangle);

  }
  digitalWrite(2, HIGH);
  digitalWrite(5, LOW);
  delay(100);
  accel.getEvent(&event);
  Serial.print("X2: ");
  Serial.print(event.acceleration.x);
  Serial.print("  ");
  Serial.print("Y2: ");
  Serial.print(event.acceleration.y);
  Serial.print("  ");
  Serial.println("m/s^2 ");

  delay(500);
}
```

2. **Gait detection code**

```
#include <Wire.h>
#include <Servo.h>
#include <Adafruit_Sensor.h>

#include <Adafruit_ADXL345_U.h>
Servo Myservo1;
Adafruit_ADXL345_Unified accel = Adafruit_ADXL345_Unified();

void setup(void)
{
  Serial.begin(9600);
  if(!accel.begin())
  {
    Serial.println("No valid sensor found");
    while(1);
  }
Myservo1.attach(9);
}
void loop(void)
{
  sensors_event_t event;
float xaxis = event.acceleration.x;
   float servopos1 = map(xaxis, -10, 10, 0, 180);
   Myservo1.write(servopos1);
  accel.getEvent(&event);
  Serial.print("X: "); Serial.print(event.acceleration.x); Serial.print("  ");
  Serial.print("Y: "); Serial.print(event.acceleration.y); Serial.print("  ");
  Serial.print("Z: "); Serial.print(event.acceleration.z); Serial.print("  ");
    Serial.println("m/s^2 ");
 delay(15);
}
```

Force Feedback Control and Linear Position Measurement: We are using hall effect sensor for the force feedback control system. The servo motor's position can be maintained and updated based on force sensor input for which we are using hall effect sensor. We can adjust the motor position to the corresponding direction when the force is sensed in the ankle joint. We can receive the servo motor's position all the time while moving it freely in this manner, and the servo motor can offer braking and moving speed to provide force feedback in the ankle joint. Moreover, Hall effect sensors has also been used as a stop toggle switch for unwanted

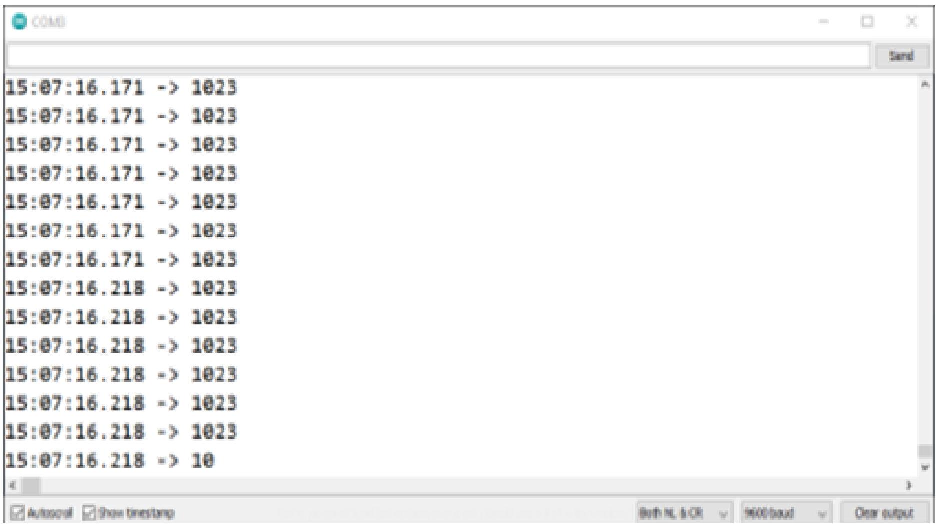

Figure 16: Realtime hall effect sensor values

movement in the joints. Figure 9 shows the values of Realtime hall effect sensor values in the serial monitor we have measured.

4.3 Identify Optimal Design Approach

Based On our analysis of the collected data and discussion we believe, that our 2nd design approach is considered to be more optimal for our goal and project development. Lets us elaborate on various comparative findings on our alternative design method so that we can establish our opinion.

Table 7: Optimal Design Findings

Criteria	**Design 1:C-leg**	**Design 2: Prosthetic Exo-leg**
Cost	Very High	Low
Complexity	High	Medium
Component Availability	Very low	High

Requirement	Fulfilled	Fulfilled
Repairability	Difficult	Easy
Repairability Cost	Very High	Low
Battery Life	High	Medium (Portable)
Operating Time	High	Medium (Changeable)
Activity Mode	2	2
Weight	Low	Medium (Variable)
Width	Compact	Hefty

Usability: The usability refers to the user-friendliness and how less the user has to adapt to the product rendering the usability scale higher or lower. In our 1st approach, From our gathered data we have found out that the C-Leg is using more of a software approach to connect the amputees and the device. Here they are providing an app-based instruction system and different modes which can vary from user to user. We declined this approach as more cost for the software development and connectivity and from the Bangladeshi perspective, people are not very enthusiastic about software support regarding devices. So our approach is more optimised for this scenario**.** For the second design approach, we are more focused on cost preservation and for that, we will be conducting on-field training to get adapt to our product and its mechanisms. So, that we can maximize the synchronization of our product and the amputee.

Manufacturability: the extent to which a product, given its design, pricing, and distribution needs, can be made efficiently is defined as manufacturability in both the approach we have analyzed and found out that the 2nd approach is more optimized.[25] Let us discuss the findings below.

1st approach: In the hydraulic sector to house the pressure sensors, hydraulic liquid and pistons we need to make custom moulds which are quite difficult to make and costly as we need to make it completely sealed as it is a small breach that can make a severe system failure. [26]

2nd approach: for the rotary actuator system every part of the body can be separately bought, and it is widely available. There is housing required for the components, but it does not have to be airtightly sealed like the hydraulic system as mentioned previously. So, it is more cost-efficient and easier to manufacture.

Impact: In this aspect, we are going to determine which approach is suitable and optimal for our design goal and has the most impact and our target audience such as the middle-class people. The most intriguing target of our project is to make it as available as possible for the general people and as previously discussed in the market analysis of both approaches the 1st approach is pricier than our 2nd approach which makes it difficult and rather inconvenient for most of the people that we aim to deliver the project.

- According to Bionics (mentioned previously), a single unit of C-leg (Hydraulic actuator) costs around $40,000 to $50,000 US which is around 35 Lac to 43 Lac. The amount is extremely high for a working-class family.
- On the other hand, if we consider our second approach the pricing of each leg can be drawn down to only BDT 56,000 to 80,000.

As per table 6, Where we can see that gap is tremendous and from this price point, we can reach out to more people than what can be achieved by following the approach 1. From all the impact perspectives,

- Social
- Health
- And safety

We believe the second approach is better suited and more optimal.

Maintainability: For both approaches, the probability that a failed component or system will be restored or repaired to a certain time and degree can be defined by their maintained protocol. Our collected data and design findings suggest That the repairability and cost of the repairability are very high for approach 1 (Hydraulic actuator) on the other hand both of these attributes are a bit more efficient in the 2nd approach (rotary actuator system). Let us discuss why we believe that. The 1st design approach uses hydraulic pistons, liquid (preferably oil) and pressure valves for passing the pressure from one end of the confined chamber to another when is swing phase or stance phase. We have already demonstrated the simulation for this design.

These designs and chambers are not detachable and tightly sealed which can be a problem if

- Some malfunction occurs such as leakage of liquid because of some damage or
- Bleeding where air may accumulate in the hydraulic unit if the product is stored for longer periods and not in an upright position. This is noticeable through sounds and irregular damping behavior.

These are not only difficult, but the only solution is to replace the whole body of the leg as it can be fixed part by part. This makes it

- Inefficient to self-diagnose
- Costly

On the other hand, the 2nd approach (rotary actuator system) is based on high torque motor and each part is detachable and can be self-diagnosed easily. So, for example if a part shows faulty

Figure 17: Separate Parts of Design two

performance, it can be easily replaced as the parts can be individually bought from various shops and are widely available as per figure 17. This helps the approach to become more attractive from the customer-specific standpoint as

- It decreases the cost of repair and
- Increases the repairability rate.

For these above mentioned attributes, the cost, we are strongly aligned that the 2nd approach is more suitable for our design method.

4.4 Performance Evaluation of Developed Solution

Performance:

In order to clearly evaluate the performance efficiency, we devised our own experiments. We were able to determine how different the walking pattern of our subject is compared to an average person and how much improvement we can get from our prosthetic. So. firstly we incorporated a normal human walking pattern by extracting test Data from a volunteer. The results show such.

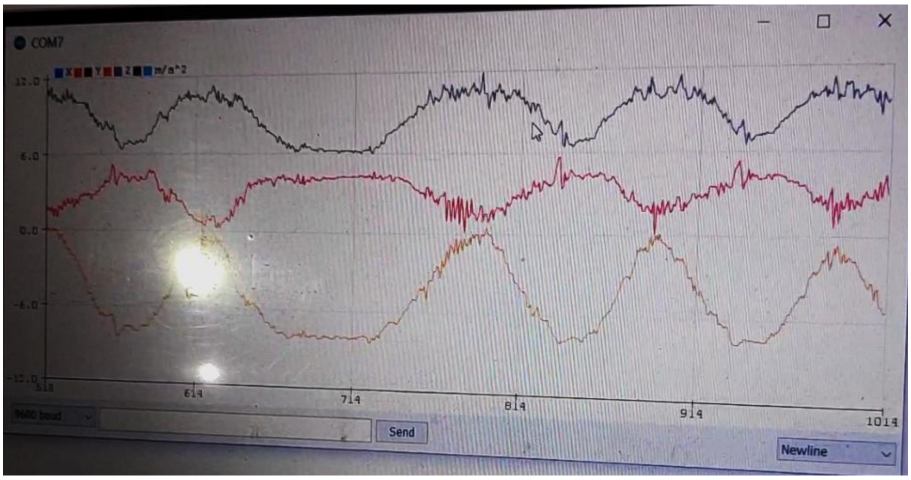

Figure 18: Normal healthy human walking pattern

As per figure 18 Here we have tracked the x,y, and z deviation of the walking movement by using the gyroscope. From the results, we can see that the movement data suggests it is a normal walking pattern as the distribution of three displacements is quite equivalent.

Now, we took two different data from our subject, one is with the poly acrylic leg that our subject previously used and another one is using our prosthetic. The first result [with polyacrelic]

Figure 19: Walking Pattern with non-functional prosthetic

Figure 19 Suggests that the movement is quite irregular as per the normal walking pattern. If we closely look at the x,y and z deviations, it is quite a straight line at first and then a stiff curve after that a straight line again. This pattern suggests the movement is more inclined towards dragging motion the stiff curve suggests the sudden uplift of the leg and the rest suggests plain movement. But let us see how different the results are when using our prosthesis in Figure 20. For the second result, we can see that it is not more a straight line and a stiff curve it has more inclined towards a curvature but not an absolute curve like a normal walking pattern.

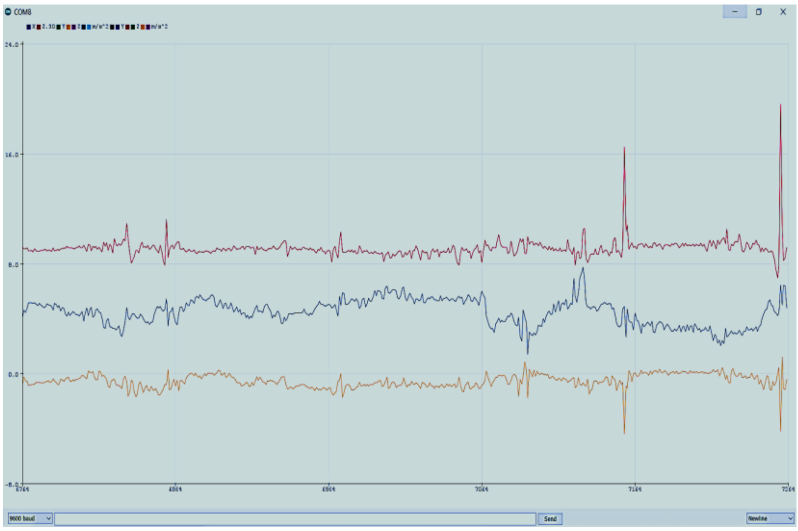

Figure 20: Walking Patterns with Prosthetic Exo-leg

Finally, considering the comparison between functional and non-functional design in figure 21, it is evident that due to the motion changes the exo-leg graph is showing motion whereas the non-functional leg does not have much motion improvement while walking as the patient is consistently dragging the leg with less freedom of movement involved.

Figure 21: Side by side comparison

From the deviation data that we have gathered, we can see a better view by comparing them with each other from the normal perspective.

Table 8: Gyro Sensor reading of normal and healthy human walking pattern

X axis	Y axis	Z axis
5.57	-8.04	4.55
5.49	-8.39	4.39
5.69	-8.36	4.35
5.33	-8.63	4.2
5.18	-9.34	3.84
4.67	-9.45	3.92
4.9	-9.26	5.14
6.2	-9.18	5.02
6.04	-9.57	4.67
4.79	-10	2.82
6.86	-9.02	4.55
4.55	-7.37	5.96
2.24	-4.82	8.98
0.12	-6.83	5.22
4.51	-5.49	2.75
2.47	-6.9	5.65
1.29	-7.69	6.12
2.51	-8.79	6
3.41	-9.18	5.3
6.04	-9.3	5.57
6.71	-9.49	4.86
7.65	-10.55	4.9
5.73	-8.79	5.14
5.45	-8.71	4.82
2	-11.3	0.78
1.69	-11.26	-0.59
6.16	-8.63	4.39
5.57	-8.04	4.55
5.49	-8.39	4.39

Table 9: Gyro Sensor reading with non-functional leg walking pattern

X axis	Y axis	Z axis
2.24	-6.2	8.79
2.12	-6.75	8.55
1.92	-6.67	8.67
2.12	-6.43	8.79

2.39	-6.43	8.67
2.43	-6.32	8.9
2.51	-6.2	8.63
2.47	-6.35	8.63
2.35	-6.47	8.59
1.92	-6.32	9.1
2.35	-6.43	8.75
2.24	-6.55	8.67
2.16	-5.92	9.02
3.37	-5.73	9.34
2.2	-5.53	8.59
2.63	-6.16	9.02
2.39	-5.53	9.53
2.31	-5.69	9.14
1.96	-5.18	9.45
2.63	-6.43	10.32
2.2	-6.47	8.98
2.79	-4.82	8.28
2.82	-4.82	8.9
3.73	-6.47	4.59
1.57	-7.96	6.32
-0.08	-7.77	7.61
2.24	-6.2	8.79
2.12	-6.75	8.55

Table 10: Gyro Sensor reading with Prosthetic Exo-leg walking pattern

X axis	Y axis	Z axis
8.79	-0.71	5.73
8.75	-0.75	5.61
8.79	-0.82	5.81
8.79	-0.71	5.61
8.79	-0.86	5.69
8.75	-0.71	5.77
8.79	-0.63	5.81
8.71	-0.75	5.73
8.71	-0.71	5.69
8.71	-0.67	5.77

8.75	-0.71	5.45
8.79	-0.71	5.73
8.79	-0.71	5.73
8.75	-0.71	5.73
8.71	-0.67	5.73
8.79	-0.71	5.77
8.75	-0.59	5.69
8.79	-0.75	5.73
8.79	-0.71	5.61
8.75	-0.67	5.81
8.75	-0.63	5.77
8.79	-0.71	5.77
8.83	-0.67	5.69
8.75	-0.67	5.81
8.79	-0.71	5.57
8.79	-0.9	5.69
8.71	-0.67	5.61
8.79	-0.71	5.73
8.75	-0.75	5.61
8.79	-0.82	5.81

Finally, we have constructed the graphs corresponding the following data to evaluate the motion:

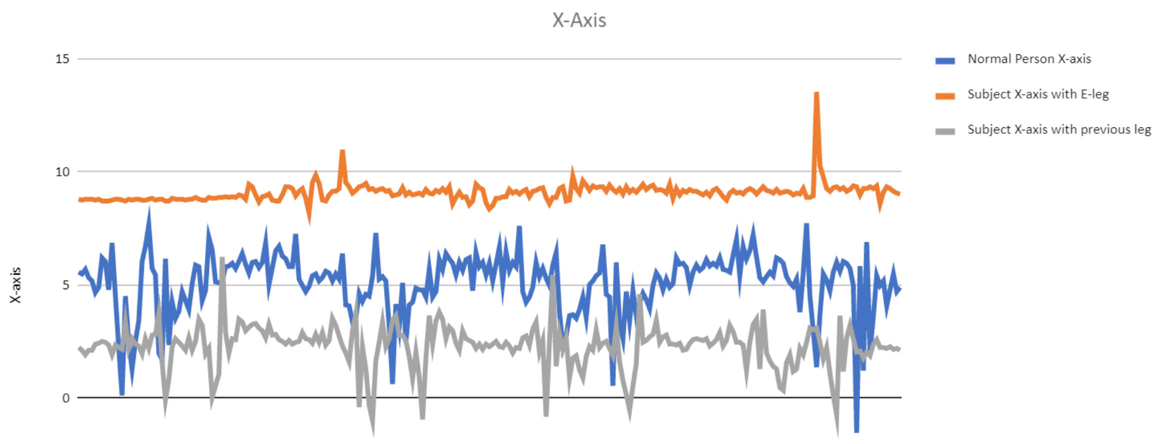

Figure 22: Against x-axis

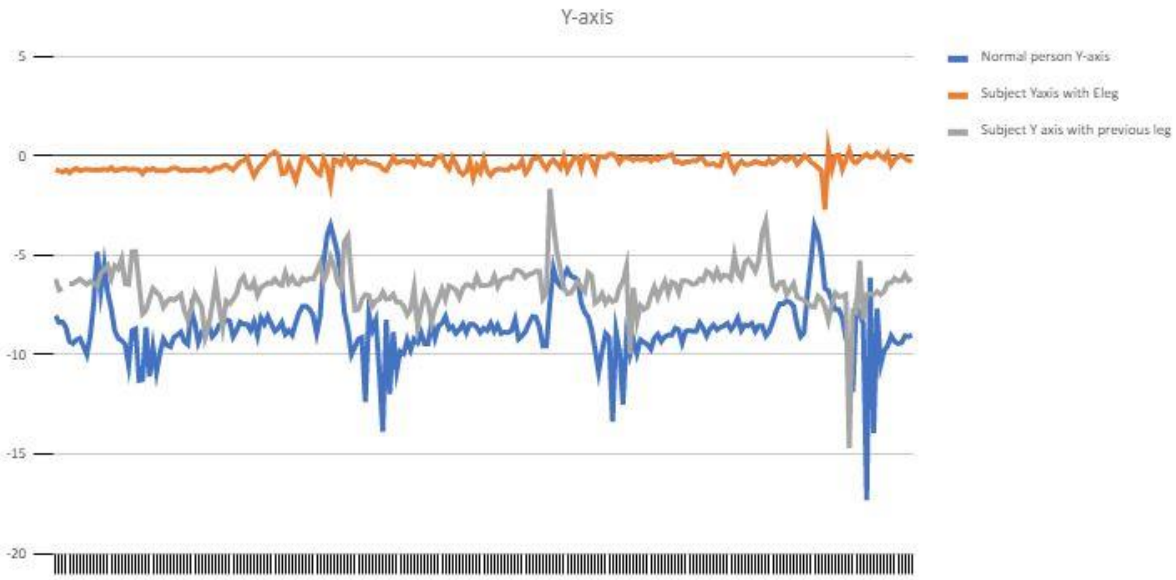

Figure 23: Against y-axis

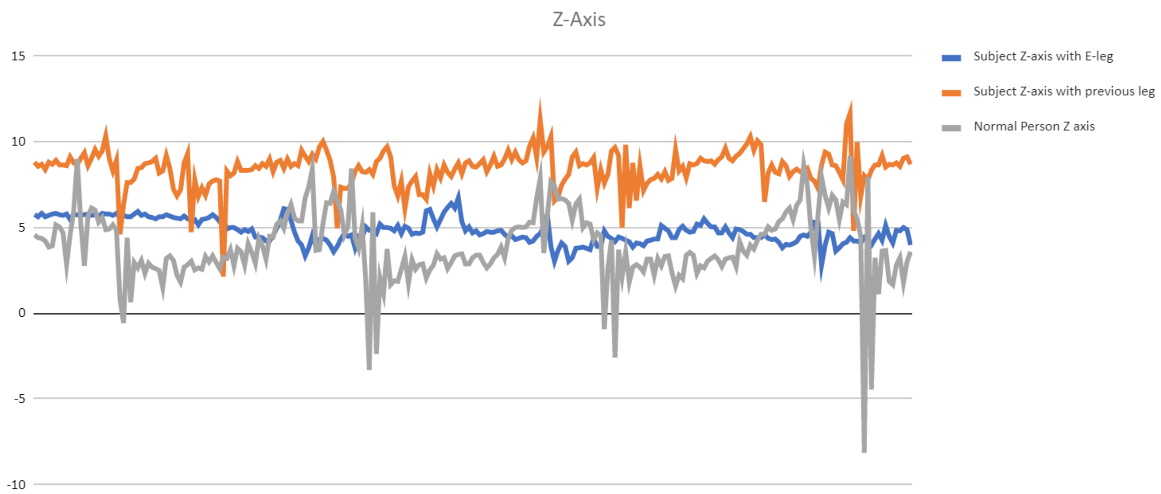

Figure 24: Against z-axis

The above graph shows far accurate graph of the value taken from the sensor reading that we have tried to discuss above in order to identify the changes. It shows, in case of the walking pattern with Prosthetic exo-leg, it is quite similar to the normal walking pattern of a healthy human. Even though data are not similar, we believe we can generate more accurate data from the testing if the patient is given around 3-4 months for physiotherapy and proper training.

Theoretical power analysis and practical operating hour:

Here, the theoretical power consumption time is calculated. Based on the power analysis, we can find out the run-time of the functional leg.

Table 11: Power Analysis (Theoritical)

Component	Minimum current consumption (mA)	Maximum current consumption (mA)	Battery (mAh)	Maximum Run-time (hours)	Minimum Run-time (Hours)	Minimum With 90% efficiency (Hours)	Minimum with 90% efficiency (Hours)
Servo	410	510	5600	13.541616	10.855869	12.187455	9.770282
Gyro-Sensor (2)	0.3	0.5					
Hall Effect Sensor	3	5					
ESP-32	0.24	0.35					
Total	413.54	515.85					

However, when we used the leg, we calculated the run time to be around 8 hours and 50 minutes. It shows that we were able to run it with minimum time of the following time with 90% efficiency.

4.5 Conclusion

In conclusion of the evaluation, it appears that the rotary actuation system is optimal and can be used with a mid-efficiency or higher than non-functional or half functional limb within a lower range of price that will be explained in the following discussion. However, it shows C-leg is quite complex to construct as it has hydraulic actuation system customized knee that deliberately increase the product cost and repairability cost. On the other hand, with the performance shown above, we through necessary physiotherapy training, we can change our performance to normal walking pattern.

Chapter 5: Completion of Final Design and Validation

5.1 Introduction

The rotary actuation system has been constructed by the end of the period of EEE400C. The project took a long time to construct as it required several reviews, permission, budget allocation process. Mentionable that, there are a smaller number of research opportunity on such projects that led us to find out necessary workshops, testing lab and equipment. We also face notable drawback

5.2 Completion of Final Design

Final 3D Design Completion: This includes the final design we have implemented in Solidworks based on our subject's requirement shown in figure 25. This part is without the socket as the socket has been constructed with customized size and width for the subject's leg size and width. The 3D design is demonstrated in wire-frame icon for the internal components to be visible.

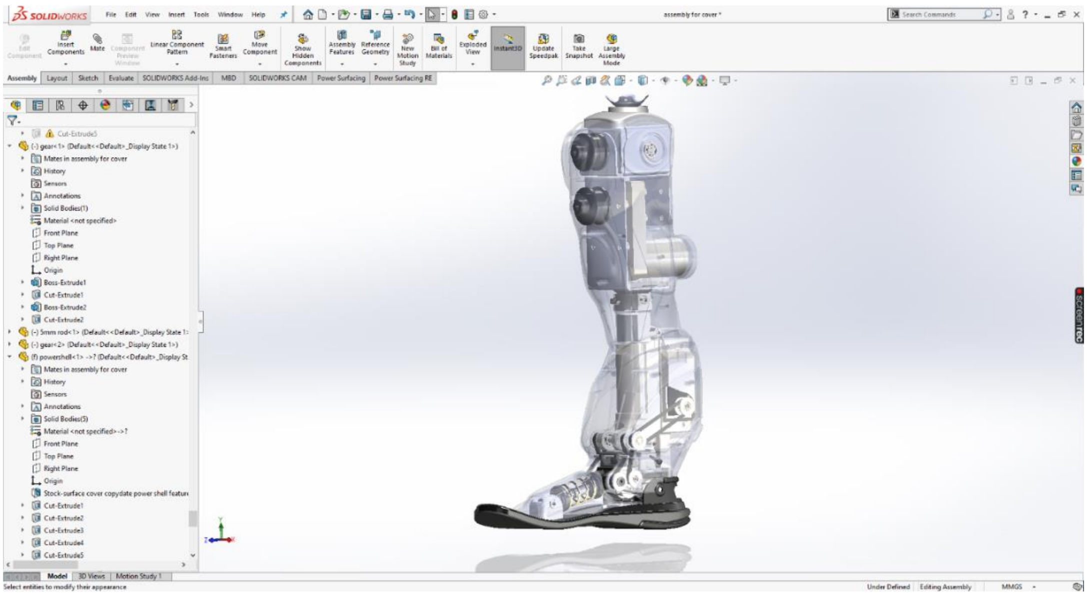

Figure 25: Final 3D Design

Final Hardware Design Completion: This includes the hardware part constructed to evaluate its performance in subject's body. Looking at the figure 26, this design had minor changes compared to the 3D design that changed our design specification such as size, width. For the hardware design completion, we not only used components bought from the limb centers but also, customized body part through CNC Cutting, Lathe machine, Bending and Cutting in several workshop. Our final design has also been efficiently tested on our Subject based on his permission.

Figure 236: Hardware Design Completion & Implementation

5.3 Evaluation of the Solution to Meet Desired Requirement:

We had few requirements to meet in order to make it cost efficient and effective to patient. Hence, we shall evaluate in this section, if our solution had met desired need or not.

Fully Functional: We have constructed the leg to be fully functional from ankle to above knee. For our test Subject it was required to shut down the ankle movement for his comfort as the Subject never learnt to walk without dragging his non-functional prosthesis leg. It appears that, without the ankle movement, the leg was still performing close to a normal walking pattern as we have discussed in our performance analysis. However, the E-leg's all functional parts were run in order to theoretically test if the project is fully functioned or not. We planned to construct a fully functional prosthesis with available components in the markets based on rotary actuation system and we achieved our goal.

Cost Effective: The functional prosthetics legs has higher cost range that is no affordable for all types of people from all socio economic condition whereas such amputation mostly require in working class people due to fatal work injuries. In order to make the leg available for them, we used rotary actuation system instead of Hydraulic Actuation for minimizing the most expensive cost factor of the project. With further innovation and combined engineering research, we were able to construct the project. We believe that during a large number of manufacturing, we can minimize the cost even further.

Mid-level or Higher Efficiency: As per the above performance analysis based on normal walking patterns, non-functional leg's walking patterns and Prosthetics E-leg's walking pattens, the data are evident that, the walking pattern with Prosthetics E-leg reflect similarities with normal walking pattern. This can be further improved with physiotherapy as our subject never learned to walk as a normal human. Our subject has been using non-functional leg from the very beginning and it is quite difficult for him to adopt newer walking pattern within few days of tasting. We believe further training and necessary physiotherapy will help him improve to walk with our E-leg and finally be able to use the fully functioned leg. For now, we will consider the efficiency level to be mid-level and anticipating further efficiency increase with patient's comfort of using.

Real Time date reading: Gyro Sensor and Hall effect Sensors take the real time data from users walking pattern and send them to Micro-controller ESP-32. It helps to create angle trajectory as per user's movement to finally change the leg's next movement. This system is instant and does not have delay as it takes frequent date during walking, sitting or running.

Power Consumption: We used a theoretical data analysis to see how long our system will operate. As per theoretical evaluation for Servo, 2 Gyro-Sensors, Hall Effect Sensor, ESP-32 we calculated the minimum operating hour to be around 9.78 hours. We have managed to use the leg for around 8.50 hours during the testing. Hence, the operating hour has more than what we have planned. We believe this is a very notable efficiency for the project development process.

Weight: Our subject's non-functional leg weigh 2400 gm. However, our design costs around 2600 gm, that is 200 gm more than what he has been using. As we have used stainless steel pipe for the design, the weight has been a bit higher than what we have expected. This can be easily mitigated if we use aluminum instead of stainless steel increasing the price a bit higher. However, for budget constraints for the prototype, we did not use Aluminum pipe during the project construction.

Width: Previously in EEE400P and EEE400D, our designed 3D model was a bit hefty that has been upgraded to a compact system after several analysis and reposition of components during implementation process. It helped us reach a compact design as widely used functional C-leg.

Comfort and Safety: As the socket has been customized for the Subject, he did not face any comfort or safety issue during the weeklong testing. However, as the subject is not used to functional walking process for using non-functional leg since his childhood, we had to shut down the ankle movement for ensuring his comfort for the time being. We believe, further training process will help us using the fully functioned leg on the subject.

5.4 Conclusion

In conclusion to the chapter, this is transparent that, our optimal design Prosthetic E-leg is very efficient and cost effective. Our fundamental objective of the project was to provide patient with transfemoral amputation a fully functional prosthetic E-leg so that one is able to do the basic movements. After several tasting of performance and power analysis, it is evident that our project has been successfully met the object and requirement of the Subject.

Chapter 6: Impact Analysis and Project Sustainability.

6.1 Introduction

While constructing a project it is important to analyze the project impact on various factor and its sustainability. The following discussion incorporate a brief idea of the impact we tend to achieve in patient and the sustainability we plan to expect after the project implementation.

6.2 Evolution of the Impact of Solution

Bangladesh has a large population pool, and these large amounts of people fight tooth and nail to meet their day’s end. Every day they go out to work uncertain of their return to home as lower-income jobs have high risk and accidents are a common phenomenon. Death is common but in a country like Bangladesh being an amputee is a fate worse than death. There are fewer job opportunities and less surety of a sustainable life. The purpose of our project is to lay a hand of hope to these unfortunate individuals. Our project will enable these people

- To give a sense of standing on their own feet
- Enable them to walk again
- Provide mechanical aid to the amputee
- Start a new window for research and development for prosthetics.

Furthermore, in order to ensure the projects' long-term viability, we are attempting to strike a balance between environmental, social, and economic factors to meet current requirements without jeopardizing or overburdening cost-effectiveness for working-class people. The impact of the optimal design solution is explained below in different aspects,

Social

The loss of a limb can be devastating, causing severe disruption in many facets of a person's life. It can also have a major impact on one's job, relationships, community activity, and leisure activities

- Change the view of society about amputees
- Making amputees self-confident
- Introducing them to new opportunities and productivity.
- Motivating them and giving them a beacon of hope

The ability to walk or stand on their own feet is a lifelong dream for a large number of people. And a functional prosthetic leg that we are providing will help them to achieve that. Which will help them to take another step to fulfill their life goal and dreams. With the help of our products, we can change the view of the society that has wrongfully shaded upon the amputee people.

Health

A healthy body and healthy mind are the most treasured possession that a person can have. Losing a limb can have a significant impact on that harmony and leave tremendous physical and phycological disruptions.

- **Physical**: After an amputation, patients reported having various physical effects for example Phantom limb, Muscle contraction, and Fatigue.
  - **Phantom limb pain** [27]: As our prosthetic will act as a therapeutic technique for managing phantom limb pain.
  - **Muscle contractures** [28]: A support device such as our prosthetic can significantly help as the primitive suggestions from the experts are to go through stretching exercises.
  - **Fatigue:** As a functional prosthetic our product can elevate this Mobility and dexterity issue from our recipient and reduce the fatigue level of the patient.
- **Psychological:** The psychological and emotional consequences of losing a limb may be devastating, not just for the afflicted individual but also for those close to them, such as family, friends, and coworkers.[29]
  - Helps provide a coping mechanism for dealing with stress and trauma.
  - Provides motivation and mental support to fight the feeling of loss of limb.
  - Helps to adapt to daily life and self-acceptance issues.

Safety

Any product that is roaming in the market at a consumer level has to have a certain degree of products safety measurements and the biggest question for an uncommon product will be how safe it is to use. As our product is a functional prosthetic, the question of safety rises even strongly such as safety from and of the electrical components, electrical and mechanical failures, and compatibility issues. From our end, we can proudly say our prosthetic design is very simple, firm, and cost-efficient. Our product does use not conductive material for the housing of the circuitries which also helps the circuits safe from water splash. The core material is built from firm aluminum for rigidity and so that the weight distribution is stable.

Our design also addresses many common prosthetic issues for example,

- Weight-bearing pressure

- Socket frustrations
- Congestion
- Dermatologic problems

By adopting universal adaptive designing and industry-grade molding for socket.

6.3 Evaluation of the Sustainability

Sustainability is the ability to be maintained at a certain rate or level. To be considered sustainable, a product must be produced and/or used in a way that does not cause harm or destruction. A product is unlikely to be deemed as environmentally sustainable if its manufacturing needs nonrenewable resources, harms the environment, or causes harm to persons or society.

1. Our product does not use any non-renewable sources, for example, natural gas or fossil fuels
2. Our prosthetic uses portable Li-po batteries and the whole system does not have any carbon or radioactive emission, making it one of the safest and chemically neutral devices.
3. The device's electrical casing components are mostly 3D printed by using PLA filament. PLA plastic or polylactic acid is a vegetable-based plastic material and is a biodegradable polymer.[8]
4. For the rigidity, as discussed, we are going to use Aluminum which is the most often used metal in the world after steel. It is incredibly flexible, lightweight, resilient, and completely recyclable.

Even though our product can be categorized as an eco-friendly and non-emitting device but for various testing and production purpose can introduce a carbon footprint. We are trying to lower the percentage as much as possible by making the product parts swappable and recyclable.

Economical Sustainability

Economic sustainability takes into account both financial costs and the benefits that come with it. It is a sort of comparative analysis of the cost and what are we getting out from the products themselves. Our main motive for this product is to make it as cost-effective as possible so that we can meet our product to every stage of people.

1. **Cost analysis:** If we do a comparative cost analysis of our product and the available products right now, we can see an astounding difference.

Table 12: Price Differences Based on available and Used products

Budget range	Category	BDT
Minimum	Static Prosthesis	260000
Maximum	Dynamic Prothesis	3500000

Here, we know there are two types of available prosthesis been used everywhere. The prosthesis with a static system and the prosthesis with a dynamic system. The static prostheses can be easy to afford but their features are not user-friendly. On the other hand, A dynamic prosthesis is user-friendly and meets users' expectations but costs more than BDT 3500000 which is almost unaffordable for the amputee with mid-income or less. However, we are proposing a dynamic system costing around only BDT 60,000.

2. **Repair and maintenance:** We can keep the repair and maintenance live and as every part will be swappable, it will not require replacing the whole product, since all the parts that we are using are replaceable, we can easily replace the damaged components.[30] It will further decrease the maintenance cost of the project.

3. **Innovative approach:** As we have mentioned before our prosthetic is upgradeable, and we can customize the working principle as per our need. Not only for walking we can use this prosthetic for therapeutic purposes as well, to treat conditions like muscle contracture. Hence, with simple adjustments, our product can become from a walking aid to a therapeutic tool which further extends its effectiveness.

Social Sustainability

Social sustainability is the cumulative impact of community development, social support, social responsibility, cultural competence, community resilience, and human adaptation, among other things, as well as the impact of any specific machinery or new innovative ideas/technologies that will lead to an increased quality of life.[31]

- **Relatively new technology:** new ideas and technology can be intimidating, and prosthetic technology is relatively new for Bangladesh and to address this we have to be more social and open about our product so that people can learn and get familiar with it.

- **Community-based feedback:** Our project will be community-based. We will take regular feedback and suggestions from our consumers so that we can adjust and modify our products for them so that they can stay connected be a part of our product advancement.
- **Amputees' community buildup:** people can communicate and connect and make the social environment more welcoming. This way amputees can freely ask for help and queries and we can reach out to them even faster and more efficiently. This will create a symbiotic relationship with the project's development.

6.4 Conclusion

The inquiry and discussion in this chapter provides us a key impact and sustainability analysis of the design project namely prosthetic exo-leg. We believe the positive impact of the project will be a remarkable achievement in prosthesis industry that works for patient with disability, amputation and more unexpected incidents causing their leg to never function that led to manual amputation. Finally, we also assessed the sustainability factor comparing several surveys incorporating patient's condition and requirements while keeping track of the economic feasibility of the design manufacturing.

Chapter 7: Engineering Project Management

7.1 Introduction

To easily complete the project, we have divided our whole system into 5 different parts and allocated the necessary time to complete them. The systems have been divided as per their functional and non-functional properties. We have started the project on November 5, 2021, and we plan to conclude the construction by mid-July 2022 inclusive of the contingency adjustment. By contingency adjustment, we are referring to the exceeded days concerning the "Days to Complete" for any of the following tasks. This can be a system failure, components replacement, data collection, and any unwanted system malfunction.

7.2 Planning and Management of Engineering Project

As we have three separating courses in order to implement our project namely EEE400P, EEE400D and EEE400C, we have designed out project plan considering several timeframe and estimation. As per our ACT panel we have tried to follow the project Plan. Initially in 400P, during the 1st phase of the project we planned a project plan, where we did not take account of several activities need to be carried out in order to efficiently construct the project. However, with proper suggestion and concept regarding the time of constructing each section of the design, we came up with a project plan in 400D, based on which our project is supposed be completed by May 2022. However, due to delay in approval, fund and managing several factors affecting the project development, we have completed the whole process by August 31, 2022. Even though we estimated the data collection will cross September till 10 to 11 days, it appears we were able to complete it by the planned time of EEE400C.

The final project plan made for implementation phase is given below with its respective timeframe in Table 13 and graph (Figure 27):

Table 13: Project Plan Time-frame (EEE400P-EEE400C)

Timeframe	Task	Start Date	Days to Complete
EEE400P	Project Selection	5-Nov-21	5
	Concept Note	11-Nov-21	20
	Final Proposal & Components Selection	12-Dec-21	30
	Tools Selection & Component Finalization	25-Jan-22	20

	Field Visit (Dynamic Limb Center& CRP)	25-Jan-22	15
	Solidworks Design Draft	10-Feb-22	30
	Solidworks Final	28-Feb-22	25
EEE400D	Multiple Design Approach Simulations	16-Feb-22	60
	Component Collection	5-May-22	30
	Building system 1: Central Unit	8-May-22	90
	Building system 2: Input & Triggering Device	12-Jun-22	30
	Building system 3: Balancing System	16-Jun-22	30
	Building system 4: Measurement System	22-Jun-22	25
EEE400C	Building system 5: Functioning System:	1-Jul-22	30
	Testing & Data Collection	10-Jul-22	65
	Necessary upgrade	1-Aug-22	25
	Final Data Collection & Comparison	16-Aug-22	20
	Draft Report	20-Aug-22	18
	Final Report	25-Aug-22	20
	Contingency Adjustment	30-Aug-22	30

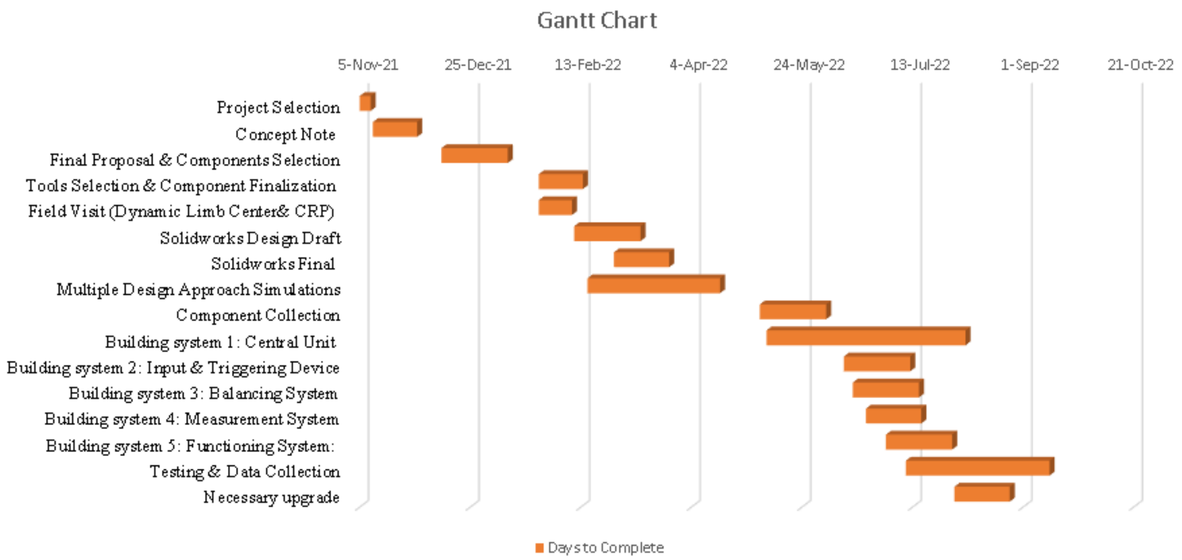

Figure 27: Gantt Chart

7.3 Evaluation of Project Progress:

We had to face few drawbacks during the component collection as none of the online sources provides individual products rather wholesale, we could not order them online during our proposed time. As a result, we had to collect the component separately. We collected few of the components from electronics shops and market such as Patuatoli and few from Brac Limb Center and Dynamic Limb Center. The whole process consists of approval and permission took a long time to complete. After the component collection process, we had to find adequate research lab for testing, which was eventually difficult as there are a smaller number of open lab facilities in Bangladesh. However, considering these drawbacks we constructed a final project plan during the starting phase of our EEE400C and worked accordingly. Our project is now fully built and has been used by our Human Subject in order to collect testing data to evaluate the performance. Currently, we are working on the physiotherapy and necessary training for our Subject so that we can achieve better performance.

Our prosthetic Exo-leg project started on November 5, 2021, and we have finished the design implementation inclusive of the data collection by August 30,2022. Everyone from our group has participated in the project and working for the post implementation tasks. Since all of the task has been distributed among ourselves so that we can understand every stage of the project, everyone participated accordingly under the supervision of respected ATC members and FYDP committee. We stayed updated with our assigned ATC Sir Mehedi Hasan Shawon via email and informed our update when required. Moreover, for several approval purpose, we have been in touch with every member of the committee as well as Sir Arshad M. Chowdhury, PhD, Professor and Dean, School of Engineering.

7.4 Conclusion

Finally, it is evident that we have concluded our project through several time constraints. We believe such project require further time to implement and yet we have been able to construct an industrial level design that has been used by a patient who never walked in his life of 25 years old. For further training and further testing we require more 3-4 months for ensuring highest accuracy possible.

Chapter 8: Economical Analysis.

8.1 Introduction

The budget has been inquired in order to find out if the project is sustainable based on its efficiently level. As we know, our main purpose of this project is to construct a cost efficient project that will functional like a C-leg within a very reasonable manufacture cost in order to make it affordable for the users of all socio-economic classes. Mentionable that, we have constructed this project within the price range of a non-functional leg, which is mostly dragged by the patient and shows stiffed movement of the leg.

8.2 Economic Analysis

For each design method, we have 2 different parts to consider one is the Knee joint and another one is the ankle joint. This knee joint in this design method is based on a hydraulic actuator that costs around 4 Lac according to India Mart [32]

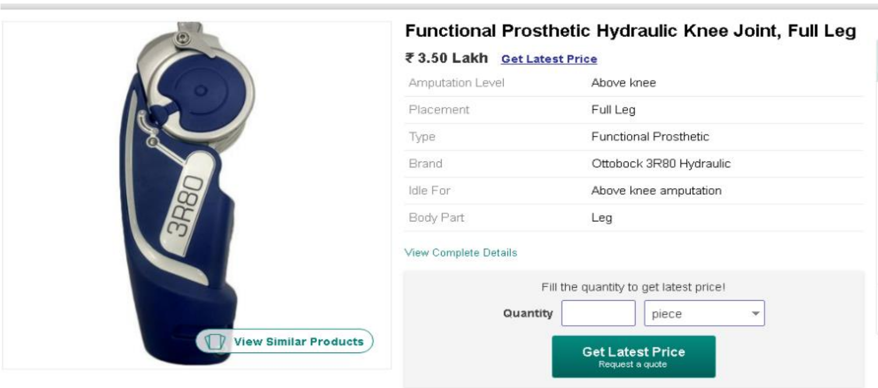

Figure 28: Hydraulic Actuator Knee Joint (Source: India Mart)

And for the Ankle joint the system for the C-leg is around BDT 56133.05 take (after conversion) as per Alibaba's wholesale price. [14]

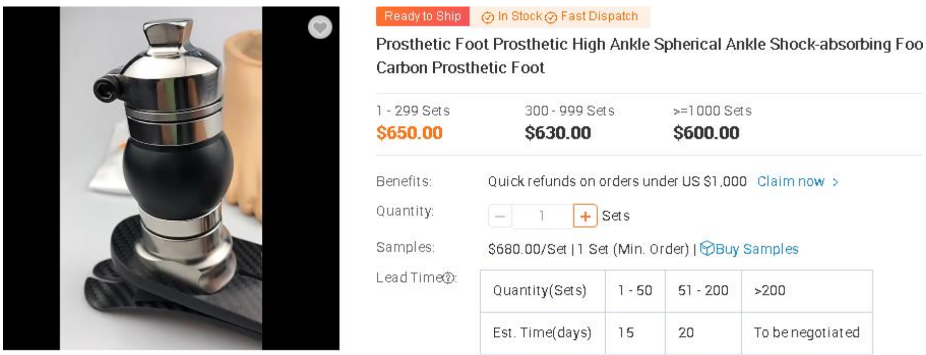

Figure 29: Hydraulic Actuator system ankle joint Price

According to Bionics for Everyone, the C-legs [15] sell for between $40,000 and $50,000 US which is around 35 Lac to 43 Lac per leg. This sells even more expensive in Bangladesh. Bangladeshi Prosthetic Leg: As per Dynamic Limb Center [16], We have discussed with them the price of each leg within 5 to 6 Lac while they are using a hydraulic damping mechanism.

Now coming to our planned budget vs our final budget,

Table 14: Initial Planned Budget

Components	Unit Price (BDT)	Quantity	Total Cost (BDT)	Source
Raspberry pi	4375	1	4375	roboticsbd
EMG Sensor	4995	1	4995	techbazar
Gyroscope Sensor	1690	2	3380	techshopbd
Hall-Effect Sensor	115	2	230	eeeshopbd
Pressure sensor	160	1	160	aliexpres
High Torque Servo motor (400kgcm)	11000	1	11000	aliexpres
High Torque Servo motor (150kgcm)	10000	1	10000	aliexpres
Sack Ankle adapter	891	1	891	indiamart
Sach foot adapter	891	1	891	indiamart
Four-hole socket adapter	891	1	891	indiamart
Tube Pylon	891	1	891	indiamart
Tube clamp adapter	2575	1	2575	Alibaba
Rubber shock absorber	168	1	168	Alibaba
Lipo Battery	4900	2	9800	Alibaba
Carbon fiber foot	7000	1	7000	Alibaba
Subtotal			**57247**	

Miscellaneous Cost			1000	
Total Budget			58247	

Finally, our final budget used for the implementation,

Table 15: Final Budget

Components + Cost	**Unit Price (BDT)**	**Quantity**	**Total Cost (BDT)**
Gyroscope Sensor + Hall-Effect Sensor	479 + 93	2	1078
High Torque Servo motor (60kgcm + 380Kgcm)	2679 + 7000	1	9679
SACH Ankle Adaptor	1358.07	1	1358.07
Tube with Female Pyramid Adapter	4213.87	1	4213.87
Female-Male Tube Adapter	1358.66 + 1285.35	1	2644.01
Socket	15500	1	15500
Li-po Battery	3320	3	9960
CNC Cutting	-	-	6000
Male Socket Adapter	2000	1	2000
Female Socket Adapter	2500	1	2500
Aluminum Molding & Casting	3000	1	3000
PLA Filaments	1700	2	3400
Screw & Nuts	-	54	2500
Bevel Gear	1000	2	1000
Pully Gear	120	7	840
Pully Gear Belt + Bearing	-	-	5500
PCB	2000	-	2000
Bending & Cutting + Lathe Machine	2000 + 3000	-	5000

Spring	50	1	50
Customized Pully Gear	2100	1	2100
Stainless Steel Rod	400	1	400
E-Leg Subtotal			**80722.95**
Miscellaneous Cost			8000
Total Budget			88722.95

Our planned Budget was BDT 57,247 based on the components only. However, our final Budget is inclusive of the workshop adjustment and current price increment. The project has been constructed within around BDT 88,723.95.

8.3 Cost Benefit Analysis

It appears that, the manufacture cost of the project inclusive of miscellaneous cost is around BDT 88722.95 from which a huge portion of miscellaneous cost can be reduced when manufacturing in huge level. The socket price is fixed as it is customized based on the patient leg size, for the socket section we plan to find out more cost effective limb center until we can construct it ourselves.

Considering the miscellaneous cost reduction, it is evident that the project can be constructed within BDT 80722.95. As we know, the non-functional leg as mostly bought within the price range of BDT 45 thousand to BDT 23 Lac based on YouTube research and our subjects used leg, we can manufacture the product within BDT 85 thousand. Hence, understanding the user's demand, we will set the buying price very small with the aim to benefit the patient and make it affordable. As the repairability is easier, we believe the repairability cost will also be affordable.

If we look at the price of C-leg, ranging from BDT 32,00,000 to BDT 42,00,00 where the manufacture cost is not disclosed by the organization, our project can be sold within BDT 1,00,000 – 1,50,000. That shows the total cost can be minimized to a very remarkable range of the following,

Table 16:Prosthetic E-leg (Estimated Cost range) compared to C-leg (Market Price)

Limb	Lowest Range in BDT	Highest Range in BDT
C-leg	32,00,000	42,00,00
Prosthetic E-Leg (Optimal Design)	1,00,000	1,50,000
Cost Different	31,00,000	40,50,000

We can see a very disguised change in the price range as we ensure to provide mid efficient but fully functional prosthetic exoskeleton. Then if we consider the non-functional leg price form high to low range,

Table 17:Prosthetic E-leg (Estimated Cost range) compared to non-functional leg (Market Price)

Limb	Lowest Range in BDT	Highest Range in BDT
Non-functional leg	45,000	23,00,00
Prosthetic E-Leg (Optimal Design)	1,00,000	1,50,000
Cost Different	-55,000	21,50,000

Even though the lower range is higher for our project, we believe having to use a full functional prosthesis is more efficient than a non-functional leg which doesn't provide the patient any single degree freedom of movement.

8.4 Evaluation of Economic and Financial Aspects

As per the above cost evaluation it is transparent that the initiate costing of the development was a bit expensive as we had to collect the components separately. The initial design budget was created when the price was normal. However, current price increase has influenced our total budget. In the meantime, it will affect the actual budget of the project construction. Considering a total manufacture price being around 65,000 to 70,000, it may now increase to 75,000 to 80,000 based on the current situation.

8.5 Conclusion

We have tried to minimize our price range as much as possible in order to make it cost effective as our sustainability plan. As we have used alternate solution to expensive hydraulic based C-leg, we believe this system will save a lot of money and will be affordable for the patient who are unable to buy prosthesis due to its several multiple higher prices of the price we have constructed.

Chapter 9: Ethics and Professional Responsibilities

9.1 Introduction

Ethical consideration is a must take during the research and management of the project. As practicing the ethics under the policy made by certified or verified institutions ensures the project is accepted by the stakeholders. As ethical considerations incorporate and enable people with lower-limb amputee patients to provide their informed consent, being updated of the information and active engagement in beta testing without any harm. Any harm to the stakeholder’s health, resources is considered unethical as per the running policies worldwide. We will now discuss a few necessary ethical considerations we have taken into account for the project.

9.2 Identification of Ethical Issues and Professional Responsibility

- **Approval from Institutional Review Board (IRB):** Any trial of prosthetic, orthotic which requires any device to be worn by a human subject/participant need to gain approval from an IRB at both the clinical trial site and institution of the principal investigator. Our project requires approval from Biomedical Research Foundation Bangladesh (BRF) and we have proposed our project to IRB as the design is ready.

- **Presence of Qualified and Experienced Researchers:** Human testing of prosthetics and orthotics should be done in the presence of qualified, experienced, trained practitioners who have had training in this field, worked in this field and ha excel in research processes and methodologies.

- **Participants’ Agreement, Reimbursement issue, and Trial Exit Arrangement:** The participant should know, understand, and be well-aware of the ongoing clinical project, risk, safety concern, and procedure. If they decline, we cannot proceed with the trial. Besides, the Reimbursement issue will be addressed as per the request of the participants. In the social milieu, the onsite research related everyone should be certain that the participants have given enlightened and risk-aware permission (in writing) and expressed their desire to participate in the research. The participants should also be well aware of how to exit the research trial and to whom they should seek help regarding this matter.

- **Report Writing, Preparing Slides:** There are major ethical factors during report writing and preparing presentation slides as they can be subject to copywrite and plagiarism. The writing may also be subject to usage of bias and offensive language.
- **Safety Measures:** The use of cheap, faulty, and used products degrade the quality of the product and will decrease the efficiency as well as pose threats to the user. According to the "Standards for Prosthetic & Orthotics" by WHO, standard no. 49 implies that "the safety of service providers and users should be ensured by the establishment of documented health and safety regulations."

9.3 Application of Ethical Issues and Professional Responsibility

I. **Approval from Institutional Review Board (IRB):** We have proposed our project to IRB as the design is ready. This process was done in group with the assistance of our ATC panel.

II. **Safety Measures:** We agreed on scheduled testing of the components and systems to identify every possible issue we may face and resolve them. We have individually tested the products in Science lab and collected most of them from Dynamic Limb Center and Brac Limb and Brace Center.

III. **Presence of Qualified and Experienced Researchers: A**s per the project specification, we have taken assistance from the Brac Limb and Brace Center and Dynamic Limb Center. We also customized the socket design in Brac Limb and Brace Center for user's comfort and safety.

IV. **Participants' Agreement, Reimbursement issue, and Trial Exit Arrangement:** We have taken all the measures to make them well aware of the research. In addition, if the participants use any device before the trial, we will be ethical about setting it back like before or we can consider compensation for this issue.

V. **Report Writing, Preparing Slides:** Since, this project is fully innovative we have done the data collection, report writing ourselves and the background research based data has been collected from sources that has been cited in APA citation. Any type of use of bias and offensive language has been taken accounted of while writing the report or preparing the slides.

VI. **Safety Measures:** Hence, while ensuring the availability of the project for the people with physical impairments we must follow the safety considerations. We have pointed out a few safety considerations such as,

- **Water-resistant System:** The continuous change of weather in Bangladesh requires us to construct a well water splash-proof system. Users' purpose to use the prosthetic due to their disabilities, impairment incorporates a wide range of uses that may be open to water bodies. Waterproof automated and manual systems are being inquired from our end to identify the most suited waterproof system.
- **Measure against Slippery areas:** It is mentionable that, fall damage is quite common for prosthesis users. We have considered using extra traction under the feet using anti-slip components in slippery places. However, there is a limitation that such components may be problematic to use in a dry area due to the fraction created by the anti-slip materials. If the problem persists, we plan on controlling the appearance of the tread during necessity either manually after pre-training amputees or automated if possible.
- **Monitoring Voltage:** As the system is constructed with a rechargeable DC battery, it requires in time charging for proper usefulness. The charging will require a monitoring method to initiate necessary charging. Hence, we are to consider adding a voltage checker for the amputee to charge it when needed.
- **Use of Kill switch:** To avoid unwanted malfunction of the leg due to various arbitrary reasons commonly known as loose connections, we have considered using a kill switch. The kill switch will immediately cut off the power in such a situation to ensure the user's safety.
- **Electric Conductivity:** There is no risk as we will be using DC which will have very low voltage. So, it is a safe electrical device to use. Besides material, we will be using PLA filament which is nonconductive and noncorrosive and also has lightweight attributes maintaining its sturdiness. So, we believe it will not be able to distress the wearer in any way or proof to be threatening.

9.4 Conclusion

As an emerging and innovating project, it is our sole responsibility to ensure the fulfilment of ethical consideration, safety consideration during the project implementation. As per the identification and application, we have taken account of all possible code of conduct one must follow as an Engineer. The ethical aspect of the project is required to motivate engineers to develop projects in this field and stakeholder's to be motivated to take interest to the project.

Chapter 10: Conclusion and Future Work.

10.1 Project Summary

We are primarily focusing on enabling the limb amputee or patients having monoplegia or those unforeseen people who have been affected by fatal accidents to have the ability to walk again by providing them with a functional walking aid at a reasonable cost. Which is safe to wear, comfortable and adjustable. After our rigorous data collection and analysis, we considered two approaches. In our 1st approach, the hydraulic actuation method has been used to control the stance and swing phase of the C-Leg. On the other hand, in our design approach 2, we are using the Rotary Actuator method to make it functional. We simulated both the designs and investigated market analysis from various other standpoints such as cost, efficiency, usability, manufacturability, impact, maintainability etc. in order to find out which approach is optimal for our design goal. And after a proper investigation of cost and other variables, we have come to an understanding that the 2nd approach is the optimal design choice for our project objective which is to make an efficient economic and functional prosthetic that can be widely available for the general people and have a meaningful impact over their lives. To make sure of that, we have performed,

- Appropriate market analysis
- Multiple design simulations
- Ethical and safety considerations
- Risk management and contingency planning

We solemnly believe that our decision on approaching the 2nd design: Rotary Actuation method the rotary actuator system will be more impactful than the 1st approach: Hydraulic Actuation.

10.2 Future Work

As the following industry is growing day by day in order to find and develop efficient solution to amputation, stroke, monoplegia, and injury with powered knee systems, we believe there is higher chance that we can upgrade our system to more options such as, division of transtibial amputation, ankle amputation and upgrading the Prosthetic for stroke and monoplegia patients. Our system is not water resistant right now. With the use of high-level material such as e-poxy, Silicon gasket using water resistant external body, we will be able to construct a water resistant system. Moreover, we will finalize the project through injection molding that can help us construct a huge number of covers of product easily in a very short time. We also plan to develop a user based app inclusive of user's training and support system in order to help the user with immediate support in case of any emergency or issue and also a manual training process and support for the amputee. Hence, there are numerous amounts of future work can be done in this project as it is easily upgradable and repairable.

Chapter 11: Identification of Complex Engineering Problems and Activities.

Attributes of Complex Engineering Problems (EP)

Table 18: Attributes of Complex Engineering Problems

		Attributes	Put a tick (√) as appropriate	Analysis
P1		Depth of knowledge required	√	This project includes a variety of areas to be investigated. We investigated the human body to understand transfemoral amputation, biomedical requirements, and policies, mechanical requirements, power distribution to different triggering devices such as sensors we are using and the microcontroller, etc. To inquire about the specific knowledge required for our project we had to go through studies, research papers, and comparative studies incorporating deep knowledge.
P2		Range of conflicting requirements		
P3		Depth of analysis required	√	The depth of analysis has been met for each case.
P4		Familiarity of issues	√	Lower Limb amputation is a worldwide issue, this issue has been addressed as industrialization and modernization are raising further injuries.
P5		The extent of applicable codes		

P6		The extent of stakeholder involvement and needs	√	This project has considered ethical considerations as there is a broad range of stakeholders' involvement such as investors, amputees, relevant institutions, and government.
P7		Interdependence	√	All the systems are interconnected.

Attributes of Complex Engineering Activities (EA)

Table 19: Attributes of Complex Engineering Activities

	Attributes	**Put tick (√) as appropriate**	**Analysis**
A1	Range of resource	√	15+ Various research papers and a wide range of authentic website (Organizations & Academic) has been inquired.
A2	Level of interaction	√	We believe the level of interaction for this project is justified as we have communicated with CRP and other labs regarding users' safety, requirement, and project fund. We are still communicating the organization relevant to our project and trying to interact with the amputees directly to understand their requirements.
A3	Innovation	√	The system has been designed to be upgradable based on its feature, cost, and functionality.
A4	Consequences for society and the environment	√	We identified environmental consequences in our risk management analysis and scope of the mitigation. And social consequences have been discussed in impact as we plan on creating an amputee community and

			learn their feedback on the different prosthesis, they have been using to develop our project.
A5	Familiarity	√	The familiarity of this project is quite a board. Innovators have been trying to identify cost-efficient ways of building a prosthesis that is both dynamic and comfortable. Due to modernization, the number of amputee stakeholders is increasing, and innovators or organizations are emphasizing this topic to carry out comparative/technical study.

To interpret the complex engineering idea, we have inquired throughout several websites, and publications inclusive of necessary data analysis, component analysis, risk, and mitigation to construct the project. Hence, there was a necessary range of sources used for this complex engineering inquiry.

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Appendix

Logbook:

Table 20: Group & ATC information

	Final Year Design Project		
Student Details	**NAME & ID**	**EMAIL ADDRESS**	**PHONE**
Member 1	Fahmida Yasmin Nipa - 18121009	fahmida.yasmin.nipa@g.bracu.ac.bd	01711932435
Member 2	Md. Tahsin Ahmed Abir - 18121017	md.tahsin.ahmed.abir@g.bracu.ac.bd	01989879889
Member 3	Fahin Uddin Enam - 18121008	fahin.uddin.enam@g.bracu.ac.bd	01950700671
Member 4	Musa Ahammed Mahin - 18121019	musa.ahammed.mahin@g.bracu.ac.bd	01725651856
ATC Details:			
ATC 2			
Chair	Chair- Prof. Dr. A. H. M. Abdur Rahim	abu.hamed@bracu.ac.bd	
Member 1	Md. Rakibul Hasan	rakibul.hasan@bracu.ac.bd	

Member 2	Md. Mehedi Hasan Shawon	mehedi.shawon@bracu.ac.bd	

Date/Time/Place	**Attendee**	**Summary of Meeting Minutes**	**Responsible**	**Comment by ATC**
EEE400P				
5.11.2021	1.Fahmida 2.Tahsin 3.Fahin 4.Mahin	1. Chose a few areas of expertise 2. Shortlisted a few research and project area 3. Making Draft Doc on Project ideas	Task 1,2,4: We combinedly contributed to each	N/A as it was a group meeting
6.11.2021	1.Fahmida 2.Tahsin 3.Fahin 4.Mahin	1. Came up with 4 different Projects to preach initially 2. Explored a few research papers on them to understand which one is better for FYDP.	Task 1, 2: Four of us worked in it. Hardware Discussion: Fahin, Mahin Research Paper: Tahsin, Fahmida	N/A as it was a group meeting
7.11.2021	1.Fahmida 2.Tahsin 3.Fahin 4.Mahin	**ATC MEETING** 1. Exoskeleton Leg 2. Bomb Disposal 3. Home energy management Inclusive of a security system 4. Surgical Robot	Task 1: Fahin Task 2. Tahsin Task 3: Fahmida Task 4: Mahin	**ATC2:** Task 1: They suggested this is a sustainable project if we can demonstrate it correctly Task2: They told us to avoid risk since this project is complicated and includes a military system Task3: They told to do either Home energy management or security system as both are complicated individually Task4: Surgical Bot hasn't been preached after we understood the time concern.
9.11.2021	1.Fahmida 2.Tahsin 3.Fahin 4.Mahin	1. Finalizing Project	Task 1: All of us	N/A as it was a group meeting Task 1: Complete
11.11.2021	1.Fahmida 2.Tahsin 3.Fahin 4.Mahin	1. Concept Note Draft	Task 1: Four of us discussed and wrote the topics separately and discussed them	N/A as it was a group meeting Task 1: Incomplete
12.11.2021	1.Fahmida 2.Tahsin	1. Concept Note Draft	Task 1: Four of us discussed and	N/A as it was a group meeting

	3.Fahin 4.Mahin		wrote the topics separately and discussed them	Task 1: Incomplete
13.11.2021	1. Fahin 2. Fahmida 3. Mahin	**ATC MEETING** Task 1: Demonstrating the Draft Concept Note	Task 1: Fahin, Mahin, Fahmida	**ATC 2:** Task 1: They suggested necessary changes in Specifications, requirements, Constraints, and Applicable Standards and codes.
15.11.2021	1. Fahin 2. Abir	Task 1: Multiple Design approach Task 2: EMG Sensor functionality	Task 1: Fahin Task 2: Abir	N/A as it was a group meeting Task 1: Partially Completed Task 2: Completed
16.11.2021	1. Mahin 2. Fahmida	Task 1: Problem Statement and Objectives Task 2: Nonfunctional spec and requirements	Task 1: Fahmida Task 2: Mahin	N/A as it was a group meeting Task 1: Completed Task 2: Completed
17.11.2021	1. Fahin 2. Fahmida 3. Abir 4. Mahin	Task 1. Concept paper and Project Progression Slide Task 2. Code and Standard: Task 3. Flow diagram: Task 4. Specification and Requirements:	Task 1: Fahmida, Tashin, Fahin, Mahin Task 2: Mahin, Fahin Task 3: Tahsin, Fahin Task 4: Fahin, Fahmida.	N/A as it was a group meeting Task 1-4: Completed
18.11.2021	1. Fahin 2. Fahmida 3. Abir 4. Mahin	**Task 1: Progress Presentation 1**	Task 1: Four of us presented our brief idea	**ATC 5:** Had a few issues with the presentation slides. Bullet points were required to add instead of elaborated ideas.
27.11.2021	1. Fahin 2. Abir 3. Mahin	Task 1: Initiating CAD modeling Task 2: CRP Discussion Task 3: lathe Operation Discussion	Task 1: Fahin Task 2: Mahin Task 3: Abir	N/A as it was a group meeting Task 1: Started Task 2: Decided Task 3: Decided
28.11.2021	1.Fahin 2. Mahin 3. Fahmida 4. Abir	**ATC MEETING** Task 1: Discussed our progress with our ATC panel	Task 1: 4 of us	**ATC 2:** Recommended us to focus on our title and think of multiple design structures.
29.11.2021	1.Fahin 2.Mahin 3.Fahmida 4. Abir	Task 1: Mailing CRP Task 2: CRP Information Collection	Task 1: Fahin, Fahmida Task 2: Mahin, Abir	N/A as it was a group meeting Task 1: Completed Task 2: Completed
12.12.2021	1. Fahin, 2. Fahmida, 3. Mahin	**ATC MEETING** Task 1: Project Feedback based on CRP initiation	Task 1: Fahin	**ATC 2:** Suggested us to start the proposal letter
17.12.2021	1. Fahin 2. Abir	Task 1: Work Methodology Task 2: Workflow	Task 1: Fahin Task 2: Abir	N/A as it was a group meeting

				Task 1: Draft Task 2: Draft
18.12.2021	1. Mahin 2. Fahmida	Task 1: Ethical Consideration Task 2: Project Management & Gantt chart	Task 1: Mahin Task 2: Fahmida	N/A as it was a group meeting Task 1: Draft Task 2: Completed
22.12.2021	1.Fahmida 2. Abir	Task 1: Sustainability & Impact Task 2: Safety consideration	Task 1: Abir Task 2: Fahmida	N/A as it was a group meeting Task 1: Draft Task 2: Draft
25.12.2021	1.Fahin 2. Mahin 3. Fahmida 4. Abir	Task 1: Impact & Sustainability Task 2: Applicable standard & Code, Budget Task 3: Risk management and Analysis Task 4: Ethical consideration research	Task 1: Abir Task 2: Fahin Task 3: Fahmida Task 4: Mahin	Task 1: Completed Task 2: Draft Task 3: Draft Task 4: Data collection is done.
29.12.2021	1.Fahin 2. Mahin 3. Fahmida 4. Abir	Task 1: Working methodology, Budget, Applicable standards & Code Task 2: Workflow Task 3: Ethical Consideration, Safety Consideration, Risk Management, and Analysis Task 4: Presentation Slide	Task 1: Fahin, Fahmida Task 2: Abir, Fahin Task 3: Mahin, Fahmida Task 4: Group	Task 1: Completed Task 2: Completed Task 3: Completed Task 4: Completed
30.12.2021	1.Fahin 2. Mahin 3. Fahmida 4. Abir	**Task 1: Progress Presentation 2**	Task 1: Group	**ATC 2:** Suggested us to organize the slide more effectively, modify ethical considerations. **Course Co-Ordinator:** Suggested us to modify multiple design approach & Risk management analysis
30.12.2021	1.Fahin 2. Mahin 3. Fahmida 4. Abir	Task 1: Dividing the Group Task for modification	Task 1: Fahmida	N/A, Short Group Meeting
1.1.2022	1.Fahin 2. Mahin 3. Fahmida 4. Abir	Task 1: Impact & Sustainability Task 2: Applicable Standard and Code Task 3: Ethical & Safety Consideration Task 4: Risk Management and Analysis Task 5: Workflow for multiple Design	Task 1: Abir Task 2: Fahin Task 3: Mahin Task 4: Fahmida Task 5: Fahin & Abir	N/A, Group Meeting Task 1: Draft Task 2: Completed Task 3: Draft Task 4: Research Task 5: Completed
2.1.2021	1.Fahin 2. Mahin 3. Fahmida 4. Abir	**ATC MEETING** Overall suggestion on Mock Presentation	N/A	**ATC 2:** Suggested us the methods to modify our Project Proposal & Slides
3.1.2021	1.Fahin 2. Mahin	Task 1: Impact & Sustainability Task 2: Budget Justification	Task 1: Abir	N/A, Group Meeting

	3. Fahmida 4. Abir	Task 3: Risk Management & Analysis Task 4: Ethical & Safety Consideration As per the modification suggested	Task 2: Fahin & Fahmida Task 3: Fahmida Task 4: Mahin	Task 1: Completed Task 2: Completed Task 3: Completed Task 4: Completed
4.1.2021	1.Fahin 2. Mahin 3. Fahmida 4. Abir	Task 1: Finalizing the Report & Slide Task 2: Referencing, Final Report & Final Slide	Task 1: Group Task 2: Fahmida	Task 1: Completed Task 2: Completed
EEE400D				
15.1.2022	1. Fahin 2. Mahin 3. Fahmida 4. Abir	Task 1: Making a list of nearby prosthetic centers to communicate	Task 1: Group	Task 1: Completed
24.1.2021	1. Fahin 2. Abir	Task 1: Electronic Communication with the limb centre	Task 1: Fahin, Abir	Task 1: Completed
27.1.2022	1. Mahin	Task 1: Visited Patuatoli to confirm the available components	Task 1: Mahin	Task 1: Completed
7.2.2022	1. Fahin 2. Mahin	Task 1: Visited Dynamic Limb Centre and discussed the components price and assistance	Task: Fahin, Mahin	Task 1: Completed
16.2.2022	1. Fahmida 2. Mahin	Task 1: OSUN application discussion Task 2: Application management	Task 1 & 2: Fahmida & Mahin	Task 1: Incomplete
17.2.2022	1. Mahin	Task 1: Gathering necessary document required to submit	Task 1: Mahin	Task 1: Incomplete
20.2.2022	1. Fahmida	Task 1: Finalizing the document to submit	Task 1: Fahmida	Task 1: Complete
26.2.2022	1. Mahin	Task 1: Shared the finalized documents with ATC panel to get confirmation	Task 1: Mahin	Task 1: Completed
27.2.2022	1. Mahin	Task 1: Submission of "OSUN Engaged Senior Project or Capstone Project Application for Funding"	Task 1: Mahin	Task 1: Completed
28.2.2022	1. Fahin 2. Abir 3. Fahmida	Task 1: Draft design planning of Multiple design	Task 1: Group	Task 1: Completed
29.2.2022	1. Fahin	Task 1: Design of rotary actuation system in Solidworks	Task 1: Fahin	Task 1: Incomplete
01.3.2022	1. Fahmida 2. Fahin	Task 1: Gantt Chart Task 2: Design of rotary actuation system in Solidworks	Task 1: Fahmida Task 2: Fahin	Task 1: Completed Task 2: Completed
02.3.2022	1. Abir 2. Fahin 3.Fahmida 4. Mahin	Task 1: Optimal Design Chart Task 2: Finalizing pros and cons of rotary actuation system Task 2: Presentation Slide and Report update	Task 1: Abir and Mahin Task 2: Fahin Task 3: Fahmida	Task 1-3: Completed
03.3.2022	1. Abir 2. Fahin 3.Fahmida 4. Mahin	Task 1: FYDP (D) Progress Presentation	Task 1: Group	**ATC Panel:** No suggestion received considering the progress was complete and satisfactory

08.3.2022	1. Fahin 2. Abir	Task 1: Visited Dynamic Limb Centre again to discuss and negotiate the price of the components	Task 1: Fahin & Abir	Task 1: Completed (However, the cost they have asked for was not within our budget, so we started looking for alternatives)
11.3.2022	1. Fahin	Task 1: Hydraulic Actuation System Solidworks Model Design	Task 1: Fahin	Task 1: Incomplete
15.3.2022	1. Fahmida	Task 1: Market Analysis of non-functional design	Task 1: Fahmida	Task 1: Complete
18.3.2022	1. Fahmida 2. Abir	Task 1: Market Analysis of rotary actuation system Task 2: Market Analysis of hydraulic actuation system	Task 1: Fahmida Task 2: Abir	Task 1: Incomplete Task 2: Incomplete
24.3.2022	1. N/A	Confirmation received from ATC panel regarding assigned faculty	N/A	N/A
28.3.2022	1. Fahin 2. Fahmida 3. Mahin	Task 1: Meeting with ATC and Planned how to demonstrate out multiple design		**ATC** Shahed-E-Zumrat miss suggested as our project is fully mechanical and the multiple designs are expensive to construct, we can consider market analysis and software simulation to demonstrate the motion analysis and emphasize on cost effectivity
30.3.2022	1. Abir 2. Mahin 3. Fahin 4. Fahmida	Task 1: Multiple design discussion & data collection	Task 1: Group	Task 1: Partially Completed
07.4.2022	1. Mahin	Task 1: Meeting with ATC and Planned to submit the progress slide by EOD	Task 1: Mahin	Task 1: Completed
11.4.2022	1. Fahin 2. Fahmida	Task 1: Recommendation letter to Visit Brac Limb Centre	Task 1: Fahin & Fahmida	ATC Chair have written us the recommendation letter to submit to BRAC limb Centre regarding components.
13.4.2022	1. Abir 2. Fahin 3. Fahmida 4. Mahin	Task 1: Meeting with ATC	Task 1: Group	**ATC** Shahed-E-Zumrat miss: We were suggested to complete the draft slide and design
15.4.2022	1. Fahmida 2. Abir	Task 1: Market Analysis of rotary actuation system Task 2: Market Analysis of hydraulic actuation system	Task 1: Fahmida Task 2: Abir	Task 1: Completed Task 2: Completed
16.4.2022	1. Tahsin 2. Fahmida 3. Fahin	Task 1: Visit to Brac Limb Centre to avail components	Task 1: Group	Task 1: Incomplete
17.4.2022	1. Fahin	Task 1: Hydraulic Actuation System Solidworks Model Design	Task 1: Fahin	Task 1: Completed

19.4.2022	1. Fahin 2. Abir	Task 1: Visit to Brac Limb Centre with recommendation letter	Task: Group	Task 1: They agreed upon providing components but asked for time to communicate with us
20.4.2022	1. Fahin	Task 1: Updating the rotary actuation system design in Solidworks	Task 1: Fahin	Task 1: Completed
21.4.2022	1. Fahmida	Task 1: Slide and report update	Task 1: Fahmida	Task 1: Completed
22.4.2022	1. Abir 2. Fahin 3. Fahmida 4. Mahin	Task 1: Meeting with ATC	Task 1: Group	Task 1: ATC Shahed-E- Zumrat miss stated that our progress is satisfactory. Hence, we can sit for a mock presentation with our ATC panel.
25.4.2022	1. Abir 2. Fahin 3. Mahin	Task 1: Mock Presentation to ATC panel	Task 1: Group	Task 1: ATC panel suggested that our time management is alright as we completed within 9 minutes, and we are eventually ready for the final presentation
27.4.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Multiple design information Task 2: Gantt Chart update Task 3: Slide update Task 4: Report Update	Task 1: Abir and Fahin Task 2 & 3: Fahmida Task 4: Mahin	Task 1-4: Completed
28.4.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: FYDP (D) Final Presentation	Task 1: Group	Task 1: Completed and we were asked about the reason behind using Inverse Kinematics in our system. There was no suggestion regarding our update and progress
28.4.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Final Report work distribution	Task 1: Fahmida	Task 1: Completed
30.4.2022	1. Fahmida 2. Fahin	Task 1: Respective part in Report	Task 1: Group	Task 1: Completed
4.5.2022	1. Tashin	Task 1: Respective part in Report	Task 1: Tahsin	Task 1: Completed
5.5.2022	1. Mahin	Task 1: Respective part in Report	Task 1: Mahin	Task 1: Completed
7.5.2022	1. Fahmida	Task 1: Finalizing the logbook & Reference based on everyone’s respective part	Task 1: Fahmida	Task 1: Incomplete

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11.5.2022	1. Abir 2. Fahin	Task 1: Visiting Brac Limb Center for Components	Task 1: Fahin and Abir	Task 1: Incomplete
14.5.2022	1. Abir 2. Fahmida	Task 1: Fund application to university	Task 1:	Task 1: Incomplete
16.5.2022	1. Mahin 2. Fahin	Task 1: Buying available components for local market and shops	Task 1: Fahin & Mahin	Task 1: Partially Completed
19.5.2022	1. Fahin 2. Fahmida 3. Abir	Task 1: 3D design of the final design Task 2: Listing down the components not found in local market & Requesting Programme head of Brac Limb Center for component assistance	Task 1: Fahin Task 2: Abir and Fahmida	Task 1: Incomplete Task 2: Complete
26.5.2022	1. Abir 2. Fahin 3. Mahin 4. Fahmida	Task 1: Taking permission and approval mail from Chairperson Mossadeq Sir for an appointment with the Programme Head of Brac Limb Center	Task 1: Fahin and Nipa Task 2: Abir and Mahin	Task 1: Completed
28.5.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Met Programme Head of Brac Limb Center and collected component and price list they willing to sell	Task 1: Fahin and Nipa Task 2: Abir and Mahin	Task 1: Completed
2.6.2022	1. Abir 3. Fahmida	Task 1: University fund request to Chairperson Mossadeq Sir and going to Sir Arshad M. Chowdhury as per his approval	Task 1: Fahmida & Abir	Task 1: In Progres
10.6.2022	1. Abir 2. Fahmida	Task 2: Fund Request Made to accounts	Task 1: Fahmida & Abir	Task 1: Completed
12.6.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Component collection from Local shops Task 2: Component Collection from Dynamic Limb Center	Task 1: Fahin and Nipa Task 2: Abir and Mahin	Task 1 & 2: Completed
20.6.2022	1. Fahin	Task 1: Collection of the fund from university	Task 1: Fahin	Task 1: Completed
23.6.2022	1. Abir 2. Fahin	Task 1: Buying the component from Brac Limb Center Task 2: Ordering Socket Design based on patient size.	Task 1: Abir and Fahin Task 2: Abir and Fahin	Task 1: Completed Task 2: In progress
27.6.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Beginning of the Knee design	Task 1: All	Task 1: In progress
29.6.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Knee design	Task 1: All	Task 1: In progress
4.7.2022	1. Abir 2. Mahin 3. Fahmida	Task 1: Knee Design	Task 1: All	Task 1: In Progress

	4. Fahin			
6.7.2022	1. Fahmida	Task 1: Working on the report	Task 1: Fahmida	Task 1: Started
10.7.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Knee design	Task 1: All	Task1: Partially Completed
12.7.2022	1. Fahin 2. Fahmida	Task 1: CNC Cutting	Task 1: Fahin & Fahmida	Task 1: Completed
16.7.2022	1. Abir 2. Mahin	Task 1: Lathe Cutting	Task 1: Abir & Mahin	Task 1: Completed
18.7.2022	1. Abir 2. Fahmida	Task 1: Bending and molding	Task 1: Fahmida & Abir	Task 1: Completed
20.7.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Ankle Design	Task 1: All	Task 1: Started
23.7.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Ankle Design	Task 1: All	Task 1: In progress
25.7.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Ankle Design	Task 1: Completed
28.7.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Progress presentation	Task 1: All	Mohsin Sir: Suggested to take IRB Permission, Mohaiminul Sir: Suggested to do power analysis
2.8.2022	1. Fahin	Task 1: Knee design	Task 1: Fahin	Task 1: Completed
3.8.2022	1. Fahin	Task 1: Collection of customized Socket from brac limb Center	Task 1: Fahin	Task 1: Completed
6.8.2022	1. Fahin	Task 1: 3D printing of the external body	Task 1: Fahin	Task 1: Started
7.8.2022	1. Fahin	Task 1: 3D printing of the external body	Task 1: Fahin	Task 1: Completed
8.8.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Combining the design	Task 1: All	Task 1: Started
9.8.2022	1. Fahin 2. Fahmida	Task 1: Report	Task 1: Fahin and Fahmida	Task 1: In Progress
10.8.2022	1. Abir 2. Mahin 3. Fahmida	Task 1: Report	Task 1: Abir, Fahmida and Mahin	Task1: In Progress
12.8.2022	1. Abir 2. Mahin 3. Fahmida	Task 1: Combining the design	Task 1: All	Task 1: Partially Completed

	4. Fahin			
13.8.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Theorical Data Collection	Task 1: All	Task 1: Completed
14.8.2022	1. Mahin	Task 1: Theorical Power Analysis	Task 1: Mahin	Task 1: Completed
15.8.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Combining the Project	Task 1: All	Task 1: Completed
18.8.2022	1. Abir 2. Fahin	Task 1: Managing testing lab and thread mill	Task 1: Abir & Fahin	Task 1: Completed
19.8.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Part by part data testing	Task 1: All	Task 1: Completed
20.8.2022	1. Fahmida	Task 1: Presentation Slide for Final presentation	Task 1: Fahmida	Task 1: In Progress
23.8.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Lab testing	Task 1: All	Task 1: In Progress
24.8.2022	1. Abir 2. Fahin 3. Mahin	Task 1: Lab testing	Task 1: Fahin, Abir and Mahin	Task 1: In Progress
25.8.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Lab testing	Task 1: All	Task 1: In Progress
26.8.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Lab testing	Task 1: All	Task 1: In Progress
27.8.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Lab testing	Task 1: Fahin, Abir and Mahin	Task 1: In Progress
28.8.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Lab testing Task 2: Task 3:	Task 1: Fahin and Nipa Task 2: Abir and Mahin	N/A as it was a group meeting
29.8.2022	1. Fahmida	Task 1: Presentation Slide	Task 1:	Task 1: Partially Completed
30.8.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Lab testing Task 2: Report	Task 1: Fahin, Abir and Mahin Task 2: Fahmida	Task 1: In Progress Task 2: In Progress
31.8.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: Lab testing Task 2: Presentation Slide Task 3: Report	Task 1: Fahin, Abir & Mahin Task 2: Fahmida Task 3: Fahmida	Task 1: Completed Task 2: Completed Task 3: In Progress

1.9.2022	1. Abir 2. Mahin 3. Fahmida 4. Fahin	Task 1: FYDP (C) Final Presentation	Task 1: Group	Mohsin sir suggested us to get more accurate date that will match the normal human movement
2.9.2022	1. Fahmida 2. Fahin 3. Abir	Task 1: Report Task 2: Performance analysis report	Task 1: Fahmida Task 2: Fahin & Abir	Task 1: In Progress Task 2: In Progress
3.9.2022	1. Fahmida	Task 1: Report writing	Task 1: Fahmida	Task 1: In Progress
4.9.2022	1. Fahmida 2. Fahin 3. Abir 4. Mahin	Task 1: Report writing chapter wise	Task 1: All	Task 1: In progress
5.9.2022	1. Fahmida 2. Fahin 3. Abir	Task 1: Report Writing	Task 1: Fahmida, Fahin, Abir	Task 1: Completed

Related code/theory
Arduino IDE Code:

1. **Primary Code based on which the leg is functioning**

```
#include <ESP32Servo.h>
#include <Wire.h>  // Wire library - used for I2C communication
#include <Adafruit_Sensor.h>    // Adafruit  sensor library
#include <Adafruit_ADXL345_U.h>  // ADXL345 library
Adafruit_ADXL345_Unified accel = Adafruit_ADXL345_Unified();   // ADXL345 Object
Servo Myservo1;
Servo Myservo2;
int pos1, pos2;
int servopin1 = 15;
int servopin2 = 2;
int anglelimit = 170;
int certainangle = 140;
int defaultposition = 0;
void setup()
{
  Myservo1.attach(servopin1);
  Myservo2.attach(servopin2);
  Serial.begin(9600);
  pinMode(12, INPUT);//Button pin
  pinMode(14, INPUT);//Hall sensor
  pinMode(5, OUTPUT);//Address pin  SDO>>>> High for 0x1D.............LOW for 0x53
  pinMode(2, OUTPUT);//Address pin  SDO>>>> High for 0x1D.............LOW for 0x53
  Serial.begin(9600);
  if (!accel.begin())  // if ASXL345 sensor not found
```

```
  {
    Serial.println("ADXL345 not detected");
    while (1);
  }
}
void loop()
{
  digitalWrite(5, HIGH);
  digitalWrite(2, LOW);
  delay(100);
  sensors_event_t event;
  accel.getEvent(&event);
  Serial.print("X1: ");
  Serial.print(event.acceleration.x);
  Serial.print("  ");
  Serial.print("Y1: ");
  Serial.print(event.acceleration.y);
  Serial.print("  ");
  Serial.println("m/s^2 ");
  if (digitalRead(12) == LOW && digitalRead(14) == LOW)//motion of servo by ADXL when no hall signal and button is unpressed
  {
    float xaxis = event.acceleration.x;
    float servopos1 = map(xaxis, -10, 10, 0, 180);
    Myservo1.write(servopos1);
    Myservo2.write(0);
    if (servopos1 >= anglelimit)
    {
      Myservo2.write(certainangle);
      delay(1000);
      Myservo2.write(defaultposition);
    }
  }
  if (digitalRead(12) == LOW && digitalRead(14) == HIGH)//when hall signal dected and button is unpressed
  {
    Myservo1.write(anglelimit);
    Myservo2.write(defaultposition);
    if (anglelimit >= certainangle)
    {
      Myservo2.write(certainangle);
      delay(1000);
      Myservo2.write(defaultposition);
    }
```

```
  }
  if (digitalRead(12) == HIGH)//botton pressed
  {

    Myservo1.write(certainangle);
    Myservo2.write(certainangle);

  }
  digitalWrite(2, HIGH);
  digitalWrite(5, LOW);
  delay(100);
  accel.getEvent(&event);
  Serial.print("X2: ");
  Serial.print(event.acceleration.x);
  Serial.print("  ");
  Serial.print("Y2: ");
  Serial.print(event.acceleration.y);
  Serial.print("  ");
  Serial.println("m/s^2 ");

  delay(500);
}
```

2. **Gait detection code**

```
#include <Wire.h>
#include <Servo.h>
#include <Adafruit_Sensor.h>

#include <Adafruit_ADXL345_U.h>
Servo Myservo1;
Adafruit_ADXL345_Unified accel = Adafruit_ADXL345_Unified();

void setup(void)

{

   Serial.begin(9600);

   if(!accel.begin())

   {

      Serial.println("No valid sensor found");
```

```
      while(1);

   }
Myservo1.attach(9);
}

void loop(void)

{

   sensors_event_t event;
float xaxis = event.acceleration.x;
    float servopos1 = map(xaxis, -10, 10, 0, 180);
    Myservo1.write(servopos1);
   accel.getEvent(&event);

   Serial.print("X: "); Serial.print(event.acceleration.x); Serial.print("  ");

   Serial.print("Y: "); Serial.print(event.acceleration.y); Serial.print("  ");

   Serial.print("Z: "); Serial.print(event.acceleration.z); Serial.print("  ");


   Serial.println("m/s^2 ");

  delay(15);

}
```