Design and Structural Analysis of a Passive Ankle-Foot Prosthesis with Manually Adjustable Stiffness and having Two Degrees of Freedom

A Project Report

submitted in partial fulfilment of the requirements for the award of degree of

Bachelor of Technology in Mechatronics Engineering
(ME-Mechatronics)
(Robotics and Mechatronics)

Submitted to

LOVELY PROFESSIONAL UNIVERSITY

Phagwara, Punjab

Transforming Education Transforming India

From 01/13/22 to 04/25/22

Submitted By

Name of Student:
Sankeerth Pradeep
Registration Number:
11806060

Name of Supervisor:
Dr. Jai Inder Preet Singh

UID of Supervisor:
14740

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Declaration by Student

To whom so ever it may concern

I, **Sankeerth Pradeep, Reg. No. 11806060,** hereby declare that the work done by me on "**Design and Structural Analysis of a Passive Ankle-Foot Prosthesis with Manually Adjustable Stiffness and having Two Degrees of Freedom**" under the supervision of **Dr. Jai Inder Preet Singh**, **Associate Professor,** Lovely professional University, Phagwara, Punjab, is a record of original work for the partial fulfilment of the requirements for the award of the degree, **Bachelor of Technology in Mechatronics Engineering (ME-Mechatronics).**

Name of Student: **Sankeerth Pradeep**
Reg. No.: **11806060**

Signature:
Dated: 30/04/2022

Declaration by the Supervisor

To whom so ever it may concern

This is to certify that **Sankeerth Pradeep, Reg. No. 11806060** from Lovely Professional University, Phagwara, Punjab, has worked on "**Design and Structural Analysis of a Passive Ankle-Foot Prosthesis with Manually Adjustable Stiffness and having Two Degrees of Freedom**" under my supervision from **01/13/22** to **04/25/22**. It is further stated that the work carried out by the student is a record of original work to the best of my knowledge for the partial fulfilment of the requirements for the award of the degree**, Bachelor of Technology in Mechatronics Engineering (ME- Mechatronics)**.

Name of Supervisor: **Dr. Jai Inder Preet Singh**
UID of Supervisor: **14740**

Signature:
Dated: 02/05/2022

Lovely Professional University, Phagwara, Punjab

CERTIFICATE

I hereby certify that the work which is being presented in the capstone entitled **“Design and Structural Analysis of a Passive Ankle-Foot Prosthesis with Manually Adjustable Stiffness and having Two Degrees of Freedom”** in partial fulfilment of the requirement for the award of degree of **Bachelor of Technology** and submitted in Department of Mechanical Engineering, Lovely Professional University, Punjab is an authentic record of my own work carried out during period of Capstone under the supervision of **Dr. Jai Inder Preet Singh**, **Associate Professor**, Department of Mechanical Engineering, Lovely Professional University, Punjab.

The matter presented in this capstone has not been submitted by me anywhere for the award of any other degree or to any other institute.

Date: 30/04/2022 **Sankeerth Pradeep (11806060)**

This is to certify that the above statement made by the candidate is correct to best of my knowledge.

Date: 02/05/2022 **Dr. Jai Inder Preet Singh**

Supervisor

The B-Tech capstone examination has been held on _____________

Signature of Examiner

Topic Approval Performa

TOPIC APPROVAL PERFORMA

School of Mechanical Engineering (SME)

Program : P138::B.Tech. (Mechanical Engineering)

COURSE CODE : MEC494A **REGULAR/BACKLOG :** Regular **GROUP NUMBER :** MERGC0009

Supervisor Name : Dr. Jaiinder Preet Singh **UID :** 14740 **Designation :** Associate Professor

Qualification : PhD **Research Experience :** 6 years

SR.NO.	NAME OF STUDENT	Prov. Regd. No.	BATCH	SECTION	CONTACT NUMBER
1	Sumit Kumar Jayswal	11816188	2018	M1801	6283349471
2	Manish Bais	11813777	2018	M1801	8057107638
3	Tenzin Thinlay	11811138	2018	M1801	6260214746
4	Sankeerth Pradeep	11806060	2018	M1861	7012494401
5	Vinay B S	11801704	2018	M1801	8547575866
6	Kovvuri Durga Prasad	11717663	2017		8919193868

SPECIALIZATION AREA : CAD/CAM & Mechatronics **Supervisor Signature:**

PROPOSED TOPIC : Design and Structural Analysis of Passive Ankle- Foot Prosthesis with manually adjustable ankle stiffness having 2 degrees of freedom.

Qualitative Assessment of Proposed Topic by PAC		
Sr.No.	**Parameter**	**Rating (out of 10)**
1	Project Novelty: Potential of the project to create new knowledge	7.16
2	Project Feasibility: Project can be timely carried out in-house with low-cost and available resources in the University by the students.	7.16
3	Project Academic Inputs: Project topic is relevant and makes extensive use of academic inputs in UG program and serves as a culminating effort for core study area of the degree program.	7.44
4	Project Supervision: Project supervisor's is technically competent to guide students, resolve any issues, and impart necessary skills.	9.56
5	Social Applicability: Project work intends to solve a practical problem.	8.00
6	Future Scope: Project has potential to become basis of future research work, publication or patent.	8.00

PAC Committee Members		
PAC Member (HOD/Chairperson) Name: Dr. Manpreet Singh	UID: 20360	Recommended (Y/N): Yes
PAC Member (Allied) Name: Dr. Manjeet Singh	UID: 21545	Recommended (Y/N): Yes
PAC Member 3 Name: Dr. Vishal Francis	UID: 24813	Recommended (Y/N): Yes

Final Topic Approved by PAC: **Design and Structural Analysis of Passive Ankle- Foot Prosthesis with manually adjustable ankle stiffness having 2 degrees of freedom.**

Overall Remarks: Approved

PAC CHAIRPERSON Name: 24694::Dr. Vijay Kumar Singh **Approval Date:** 03 Mar 2022

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It gives me immense gratification to place on records my profound gratitude and sincere appreciation to each and every one of those who have helped me in this endeavour. I express my sincere thanks to the **Lovely Professional University** for giving me an opportunity to work with Teachers, Fellow Students and Lab Assistants and also, for their encouragements and constant guidance, which has energized me to successfully complete my capstone project and heartfelt gratitude to my project mentor **Dr. Jai Inder Preet Singh**, Associate Professor and Head- Design Department, School of Mechanical Engineering , for selecting me as his mentee and for his constant guidance and help and also, for understanding various challenges and delays that we faced throughout this project. This project was a very challenging but from his strategy and mindset to think out of the box, we experienced and learned a lot about the dedication required to get this kind of project accomplishment and the level of numerical approach required to produce any realistic results out of any project. This project was not possible without his guidance and understanding.

Finally, I also express my sincere thanks to all those who have helped me directly or indirectly throughout this project work. I would like to offer a special thanks to members of team whose timely support and assistance made my experience truly pleasant and memorable.

Name of Student: **Sankeerth Pradeep**

Reg. No.: **11806060**

Abstract

Every year, more than one million limbs are amputated throughout the world. Many nations have so conducted theoretical and experimental investigations to produce prostheses to assist ease the pain of people with severed limbs. When it comes to the Below Knee Prosthetics (BKP), even the most modern commercial transtibial prosthesis on the market today, only passively alter the ankle position during the swing phase of gait and return a fraction of the user's own gravitational input. To significantly enhance a transtibial amputee's quality of life, new technologies and methodologies must be applied to develop a cutting-edge ankle prosthesis that can function on par with, if not surpass, the corresponding able-bodied human ankle. The majority of commercial BKP in the market today are Passive Prosthetics because they are lightweight, inexpensive, durable, and need little care. Because the human ankle is a complex collection of joints, ankle design is the most important part of the Below Knee (transtibial) prosthesis design procedure. The talocrural joint (which permits dorsiflexion-plantarflexion) and the subtalar joint (which allows inversion-eversion) are important joints in the ankle. The aforementioned two joints give the amputee with the necessary two degrees of flexibility (2 DOF). This study focuses on building and analysing a Passive Ankle-Foot Prosthesis with 2 DOF to replicate the behaviour of a natural missing limb. Furthermore, this work highlights the incorporation of manual ankle stiffness modulation into the design for dorsiflexion-plantarflexion, which may be changed by the amputee to a chosen stiffness for different ambulation requirements. The design offered in this study also incorporates key aspects of an ESR and a SACH foot; moreover, a keel design with greater terrain adaptation is recommended. As the weight of the individual user controls the engagement and disengagement of the artificial ankle joint during the gait cycle, the same consideration has been made throughout the analysis of the model. The effects of the location of fulcrum on the stiffness of the prosthesis is also analysed in this study under deflection analysis. The analysis shows that the stiffness of the leaf spring increases linearly for up to 70% of its length as the fulcrum moves towards the free end, however, the stiffness starts increasing exponentially as the fulcrum moves closer to the free end. Primarily, this research work offers a novel design of a passive ankle-foot prosthesis with adjustable ankle stiffness and 2 DOF; moreover, structural analysis demonstrates that the device can sustain a load of 800N with a FOS of 1.5, providing amputees with optimum safety and comfort.

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List of Abbreviations

BKA	Below Knee Amputation
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
COT	Cost of Transport
DOF	Degree of Freedom
ESR	Energy Storage and Return
FDM	Finite Difference Method
FEA	Finite Element Analysis
FEM	Finite Element Method
FOS	Factor of Safety
FVM	Finite Volume Method
PDE	Partial Differential Equation
SACH	Solid Ankle Cushion Heel
SEA	Series Elastic Actuator
VSF	Variable Stiffness Foot

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Chapter-1
Introduction

It is a well-known fact that no artificial systems, things, or functions can compete with their natural counterparts in a wholesome manner; however, if there is any deficiency, absence, or defect in natural systems, and it is impractical to continue with the default system, then there is a need to create their man-made substitute for the means. Humans are emulating natural processes in order to find the best feasible answer and substitute for them; this process is known as "Biomimicry." A prosthesis is a man-made item or solution that substitutes and functions in place of a missing bodily component. In this study, a completely new design of ankle-foot prosthesis for transtibial amputation is offered, with certain beneficial characteristics that consider natural human movement. The term 'prosthesis' in this context refers to a prosthetic substitute for a missing bodily component, either internal or external. Among the numerous forms of amputations, Transtibial Amputation or Below Knee Amputation (BKA) is a surgical operation used to completely remove a diseased lower leg.

According to studies, the number of amputees throughout the world is rapidly growing[1]. When it comes to the causes of transtibial amputation, the most common are injury, accident, illnesses, congenital deformities or diseases, natural disasters, and wars. Prior to the amputation, patients with similar difficulties wore metallic or wooden constructions or simply used walking sticks, which, of course, were not pleasant for the amputee and required extra effort[2], and they also did not resemble the normal leg in terms of functioning. Prosthesis also assists amputees in resuming a fulfilling social and career life, as well as improving aesthetics. A prosthetic leg is a device meant to replace a lost limb, allowing the amputee to walk comfortably and without distractions. Many sophisticated researches have been undertaken in recent years, and prostheses have changed greatly[3], but there are still obstacles in terms of convenience, price, and comfort. It is believed that the design and analysis suggested in this study effort would address such concerns to a large extent if the same principles are implemented in the manufacturing process of the prosthesis.

A leg prosthesis at the transtibial level (below the knee, between the knee joint and the ankle joint) is made up of three major components: an ankle-foot, a pylon, and a socket[4]. Amputations at this level account for more than half of all lower limb amputees[5]. The prosthetic leg or foot comes in a variety of styles. All of these variants may be generally classified into three groups[6]: (a) Conventional or Passive Foot: It lacks active mobility and only provides basic functioning; (b) Powered or Active Foot: it receives external power via motors and, as a result, has the ability to operate; and (c) Bionic Foot: sensors are employed in this form of foot to sense signals from the user's muscles and acts virtually like a natural foot. Furthermore, conventional or passive prosthesis may be divided into two types[6]: Solid Ankle Cushion Heel (SACH) Foot Prosthesis, Figure 1.1 (a) and (b), and Energy Store and Return (ESR) Foot Prosthesis, Figure 1. 2 (a) and (b). SACH feet were created in the 1950s and have a collapsible heel, aids to reduce the impact when it contacts on the ground during a plantarflexion action. This form of prosthesis is inexpensive and lightweight[7]. The heel absorbs shock in the SACH foot, while the forefoot simulates dorsiflexion. They have a

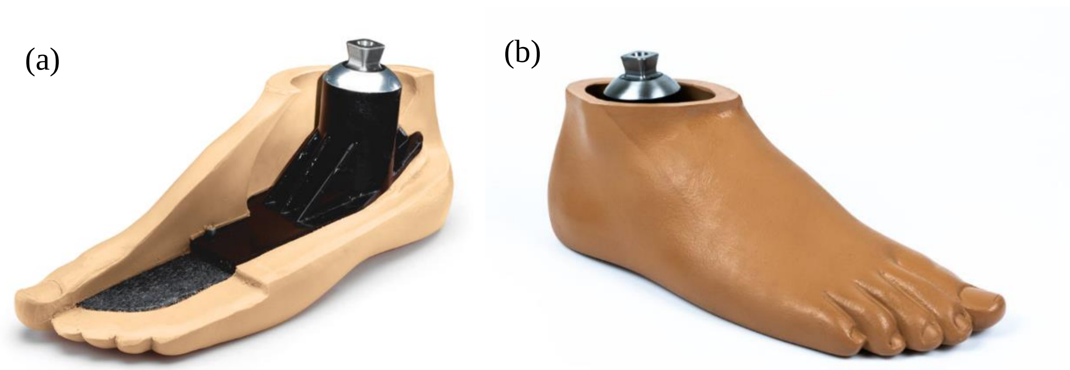

Figure 1.1. (a) SACH Foot (without cosmetic shell), (b) Typical SACH Foot[9]

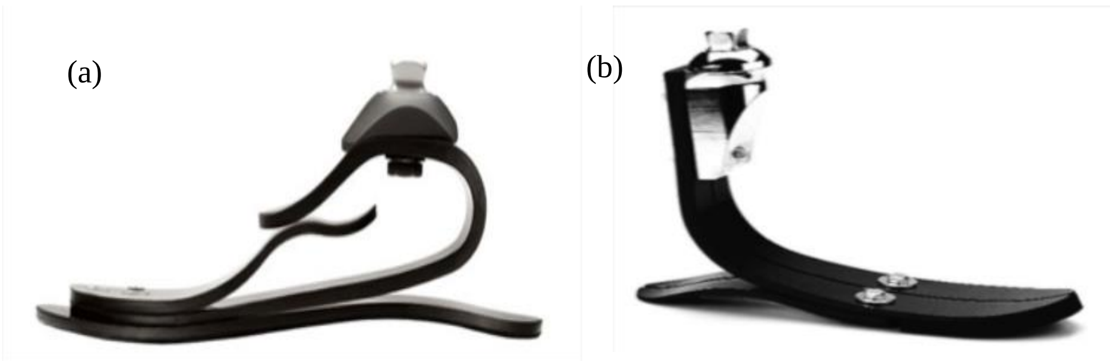

Figure 1.2. Typical ESR Feet (without cosmetic cover)[10]

simplistic look and offer minimal functionality. In the 1980s, the ESR foot was invented. This prosthesis consists of a foot-shaped plate (often composed of carbon fiber) that stores elastic potential energy and gradually releases it as kinetic energy[8]. The Keel of an ESR foot is built in such a way that it serves to attenuate shocks. This foot can be effective for the majority of amputees, particularly those with an intermediate activity level, which means they vary their walking speed, travel longer distances, and change their directions fast. Some ESR shoes additionally contain a toe component that aids in the imitation of inversion and eversion movement. Although there are other research fields in various aspects of the foot prosthesis, this research activity focuses solely on the design and structural analysis of the ankle-foot.

Passive Prosthetic foot designs currently available have either one degree of mobility[11] or adjustable ankle stiffness[12], but not both. Particular designs even omit both characteristics and focus solely on lowering the weight utilizing 3D printed feet and topology optimization techniques for some stiff types of prostheses[13], as the weight of the prosthesis directly impacts both the movement and expense of the amputees. This study effort has applied the comparable topology optimization approach to optimize the weight, and some particular materials for components have been recommended to achieve the same. Even in passive prosthetic feet, plantarflexion-dorsiflexion, Figure 1.3, is accessible in some designs, but it is based on just one degree of freedom (1 DOF)[14], i.e., inversion-eversion is not available. This causes pain while walking across tough or uneven terrain

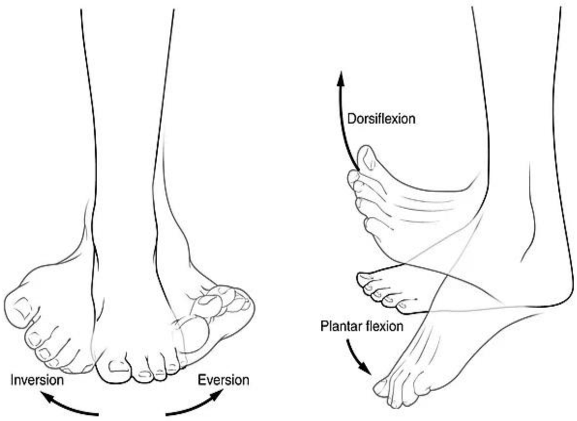

Figure 1.3. Foot Motions: (a) Inversion-eversion, (b) Dorsiflexion-plantarflexion[10]

with only one degree of freedom. As a result, in the design provided in this study effort, an extra second degree of freedom for inversion-eversion is offered in order to improve the amputee's walking experience and stability under tough terrain circumstances. Furthermore, the stiffness for dorsiflexion and plantarflexion is usually set or not addressed at all in most passive foot designs[14,15]. It has been established that the degree of stiffness required differs from amputee to amputee[16]. Researchers created the adjustable ankle stiffness concept for passive foot prosthesis to address these shortcomings[12]. Though active prosthetic leg designs with two degrees of freedom and adjustable stiffness are available[14,18], this research work focuses on a passive prosthetic ankle foot, because the according to the World Health Organization (WHO), there are over 30 million amputees in developing countries, with 95% of them without access to prosthetic devices, and current prosthetic foot development does not target the majority of end users (about 80%)[19]. As a result, in the poor world, the most prevalent and commercially accessible foot prosthesis are passive. Because of the expense, as well as the needed maintenance from qualified technicians, poor adaptability to unfavorable circumstances, and the difficulties to secure and maintain a continuous power supply, advanced prosthetic technologies are not practical for the developing world[20]. As a result, in this study's design, the passive ankle-foot may achieve 2 DOF for enhanced terrain adaptation and amputee comfort with manually adjustable ankle stiffness.

Because the suggested design is a hybrid of a SACH and an ESR foot, the desirable characteristics of both an ESR and a SACH foot are incorporated into the design presented in this study effort. Several studies have been undertaken to examine the properties of various types of foot, as well as their benefits and drawbacks[21]. It has been demonstrated that an ESR foot improves gait during heel-off [22], but a SACH foot improves stability during heel-strike[23], as seen in Figure 1.4. A specific blade profile was chosen in a research

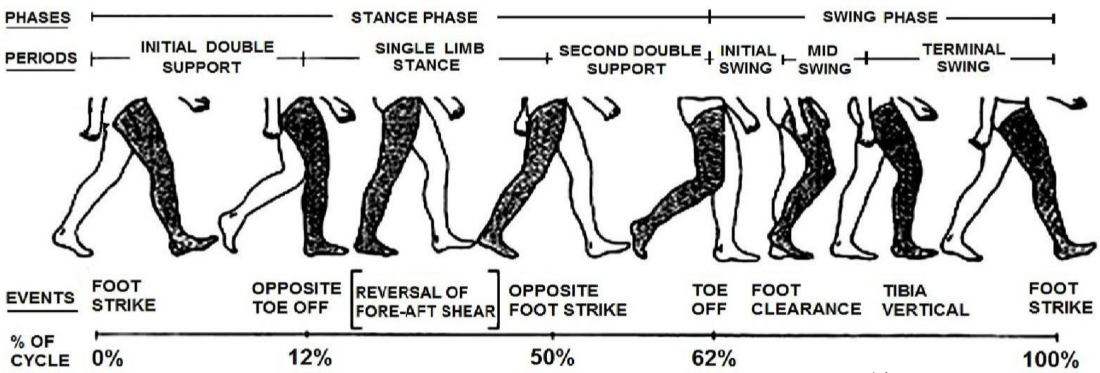

Figure 1.4. Human Gait during Normal Walking[14]

to include the features of an ESR foot that simultaneously serves as the keel[21]. However, rather of employing the same blade for both the keel and the ESR, a separate blade has been proposed in this paper's design, which is effectively an inclined plank as represented in Figure 4.3 and is screwed to the keel. The residual musculature of an amputee must adjust for the absence of propulsive ankle torques in passive prosthetic feet. The passive feet are superior in terms of weight, which is critical for minimizing the stress on an amputee's residual muscle. There are primarily two approaches for reducing the weight of prosthetics: structural optimization of the prosthesis and selection of lightweight materials for the prosthesis. To obtain the ideal weight, both procedures were used. Topology optimization is conducted on several critical components of the prosthetic foot, and numerous materials are offered for various prosthetic components (described further in this report). Hence, this research work presents a passive foot design that not only incorporates features such as 2 DOF and manually adjustable ankle stiffness in a novel design, but also provides the amputee with an affordable and comfortable passive ankle-foot that has been thoroughly tested and analyzed for safety and ergonomics.

Chapter-2
Literature Review

2.1 Study of Previous Research Works

There has been an increase in the number of lower limb amputees worldwide in recent years., which includes both transfemoral and transtibial amputations depending on the amputation location. Many recent researches have looked into whether a well-designed prosthetic ankle-foot has enough characteristics to increase the user's comfort, affordability and safety. This study will analyze the features of several lower limb prosthetics through an examination of numerous mechanisms and trials that will decide which features to include the design. Moreover, these findings will add context to the design and help to better understand the capabilities and requirements of the various prostheses which are available. The summary and statistical analysis of data on prosthetic ankle-foot, based on researches carried out between the years 2009 and 2022, are discussed below:

- N. P. Fey et al. (2009)[24] presented a system for creating novel prosthetic feet by combining topology optimization with selective laser sintering (SLS). As an example of use, the framework was used to construct a prosthetic foot that used the least amount of material while attempting to imitate the stiffness attributes of a carbon fiber foot which was available for commercial purposes. The result was a one-of-a-kind foot design that has the potential to enhance the stride of the amputee by providing energy storage and return while also decreasing the weight of prosthetic with future design changes.

- H. Masum et al. (2014)[14]: This ankle-foot design introduced an additional degree of motion (inversion-eversion). The rotation occurred in the frontal plane. The subtalar joint aided in this movement. This second level of flexibility was helped with terrain adaption and allowed the user to walk over difficult terrain. The foot has been designed in the way that the ankle joint can only move to a limited amount. The flexible connection and damper arrangement helped in energy storage and return. In this design, passive plantarflexion-dorsiflexion was controlled by a series of parallel torsion springs.

- R. C. Martinez et al. (2014)[11]: This study presented a low-cost powered knee and ankle prosthesis, in which the knee and ankle were produced as two modules and can be used by persons who had undergone a transfemoral or transtibial amputation. Series Elastic Actuators (SEA) and unidirectional springs were utilized for energy force adjustment and storage. In the proposed model, the ankle foot movement had just one degree of freedom (plantarflexion-dorsiflexion). When the two modules work together, the user was more comfortable and performed better when walking on flat ground, reducing human effort.

- J. Gardiner et al. (2015)[21]: Comparison of Solid Ankle Cushioned Heel (SACH) and Energy Storage and Return (ESR) feet has been discussed in this study. When compared to SACH, the ESR foot only significantly ameliorated the Cost of Transport (COT) in persons with traumatic transtibial amputation. This was modest but significantly different in a statistical manner. It did not represent a significant improvement in a functional manner in COT for the amputees and was most likely because of the low push-off power produced by the ESR foot.

- E. M. Ficanha et al. (2015)[25]: The control of an ankle-foot prosthesis with 2 Degrees of Freedom in the sagittal and frontal planes was described in this work using a finite state machine. Impedance and admittance controllers were employed at heel strike and push-off, respectively, with ground reaction torque feedback provided by strain gauges implanted in the foot. Active control was used to quantify the ankle's quasi-static stiffness, finding a nearly linear relationship between torque feedback gain and ankle stiffness. According to the findings, the impedance/admittance controller was able to follow the right input trajectory while lowering the required torque at the ankle joint.

- E. Ficanha et al. (2016)[26]: This study described an ankle-foot prosthesis which was cable driven with 2 DOF. Bowden cables allow motors and gearboxes to be positioned closer to the user's centre of gravity and away from the distal regions of the limb, minimizing the metabolic cost of an ankle–foot prosthesis. It also gave the amputee additional possibilities for customizing the prosthesis, which was especially useful if the amputee had a long residual limb that restricted space availability for active elements.

- M. K. Shepherd and E. J. Rouse (2017)[27]: A semi-passive foot prosthesis for ankle with a configurable torque-angle curve and the ability to swiftly modify ankle stiffness between jobs has been described in this research. The specific torque-angle curve for the analysis was created using a transmission (cam- based) and fibreglass leaf spring. The research suggested that a tiny motor could be used to achieve variable stiffness by actively controlling the leaf spring's support conditions, affecting the torque and the angle of rotation which made the foot more or less stiff.

- D. Dong et al. (2017)[28]: This study described a mechanical design, development, and experimentation of a new motorized ankle-foot prosthesis based on a geared five-bar spring mechanism. The geared five-bar spring mechanism provided more flexibility than the usual single axis with elastic unit construction. The optimization and experimental findings of the geared five-bar spring mechanism indicated that it could give better impedance torque performance in the controlled dorsiflexion phase. A powered ankle-foot prosthesis with a geared five-bar spring mechanism provided patients with better security during the controlled dorsiflexion phase as compared to a regular powered ankle-foot prosthesis.

- W. L. Childers and K. Z. Takahashi (2018)[22]: This research focused at how adjusting the energy return of a prosthetic foot influenced walking mechanics on different slopes. The suggested foot had a greater movement range and returned more energy than the typical foot. Greater energy was related with an increase in Centre of Mass energy during prosthetic limb propulsion, whereas greater energy was associated with a decrease in Centre of Mass energy change on the sound limb. Such findings showed that proposed foot can return more energy than a normal prosthetic foot, that could be used to improve whole-body propulsion.

- E. M. Glanzer and P. G Adamczyk (2018)[29]: This research described the development and testing of the Variable-Stiffness Foot (VSF), a lower-limb prosthesis that adjusted its forefoot stiffness in response to user movement. To save size, mass, and power consumption, the variable- Stiffness Foot was designed as a semi-active prosthetics that modifies stiffness during swing phases, once per stride. The forefoot keel was a composite overhang beam that can be stiffened by changing the length of the overhang which was achieved by adjusting a support fulcrum.

- C. Elley and C. A. Nelson (2018)[30]: This study presented the design of a passive ankle-foot prosthesis with 2 DOF, with the objective of enhancing overall performance over previous devices. Proposed prosthetics were able to give enough lateral stability to the ankle while normal walking. This passive ankle prosthesis weighed 539 gm when it was discovered. The device's total weight, with the pyramid connector on top and a composite keel at the bottom, was roughly 840 gm, which was less than the previously indicated 1.5 kg weight restriction and it was less than the claimed weight of functionally equivalent devices. With a build height of less than 90mm, the new gadget was likewise more compact than previous models.

- T. Dongo et al. (2019)[12]: A manually adjustable ankle stiffness model was constructed in this proposed study, and structural analysis of components was done. A slider attached to the lead screw slid and assisted in stiffness adjustment. The user could vary the stiffness of the lead screw using a manually adjustable knob at one end. This design also included energy storage in the forefoot section to help the foot during walking.

- W. S. Jang et al. (2021)[31]: A two-degree-of-freedom ankle-foot prosthesis with a compact footprint and low inertia was described in this work. It has 2 active Degrees of Freedom in the sagittal and coronal planes thanks to a parallel connection mechanism. A new spring technology enhanced walking propulsion without increasing the weight of the foot prosthesis. Heavy materials like as actuators, springs, batteries, and controller circuits were also placed towards the proximal region to reduce patient inertia and metabolic expenditure. The use of capacitive force sensors at the shank frame enabled for precise ground force measurement without adding foot mass.

- C. Lecomte et al. (2021)[18]: This study described a novel prosthetic foot design in which stiffness could be regulated in the sagittal plane. This Variable Stiffness Ankle device was fitted on a prosthetic foot that was available commercially. The hardness of the foot was maintained using a wirelessly controlled lightweight servo motor. Adjusting the support points on the glass fibre leaf spring changed the stiffness of the Variable Stiffness Ankle unit.

- S. Negi (2022)[15]: This work designed and tested a magnetorheological damper. The magnetorheological actuator assisted in impact absorption when walking. The prototype was controlled by two parts: the first one controlled the magnetorheological actuator, which absorbed impacts while walking, and the second one controlled the magnetorheological actuator. The second component controlled the electric actuator that created the dorsiflexion and plantar-flexion motions.

- H. Xiu et al. (2022)[32] presented a compliant passive ankle– foot prosthesis with 2 Degrees of Freedom rotation during locomotion. The compliant passive ankle–foot featured a compliant component to assist and produce torque to accommodate to rough terrains, as well as a 2 Degrees of Freedom parallel mechanism was used to support the bodyweight and provide restricted rotation during movement. During level-ground walking, the compliant passive ankle– foot delivered good gait motion and created appropriate ankle torque according to the results obtained from the analysis.

2.2 Problem Formulation

In this section, a problem is stated in a fashion that can be researched. This includes the process of shaping a study topic so that it is ready for scientific examination. The research topic is simply referred to as a research problem. A researcher must refine the issue and specify explicitly what will be investigated about it. This is referred to as the formulation of the research problem, and it entails narrowing down a larger study field into a single research topic and setting goals. Once the research challenge is defined, the topic is ready for scientific investigation, or research. The same methodology has been used in this study and the work is narrowed down to just ankle-foot because it is a most critical and complex joint; moreover, it directly affects the comfort of the amputees as seen from the literature reviews. The aim of this study is to answer the following two major questions:

1. How does ankle foot aids more to the user’s comfort?
2. How both 2 DOF and adjustable ankle stiffness can be achieved in an ankle foot?

These research questions have been transformed into the objectives of the study which are elaborated in chapter- 3.

2.3 Research Gap

Current Passive Prosthetic foot designs consist of either one degree of freedom or with adjustable ankle stiffness, but not both. In some designs, plantarflexion-dorsiflexion, is available even in passive prosthetic feet but they are based on only one degree of freedom (1 DOF), i.e., inversion-eversion is not available. This creates discomfort while walking through difficult or uneven terrains with one degree of freedom. Therefore, in the design presented in this research work, an additional second degree of freedom for inversion-eversion is proposed so that walking experience and stability of the amputee, through difficult terrain conditions, could be improved. Moreover, in most of the passive foot designs, the stiffness for dorsiflexion and plantarflexion are either fixed or not considered at all. It is proven that the required amount of stiffness varies from one amputee to another based on the activities performed. To rectify these drawbacks, researchers invented the adjustable ankle stiffness design for passive foot prosthesis. Though Active Prosthetic leg designs with two degrees of freedom and adjustable stiffness are available, they are very costly and hence are not affordable by most of the amputees, especially in the developing world; moreover, their handling and maintenance is also very critical.

Chapter-3
Research Methodology

This chapter discusses the material selection and methodology of the research work adapted in this study. To allow the in-depth discussion of the research, this part has been split into four sub-sections. The first section discusses the purpose of the study, the second section displays the research methods used for this work, the third section explains the stiffness adjustment mechanism, and the final section focuses on the elaboration of the 2 DOF mechanism suggested for the proposed prosthetic ankle- foot.

3.1 Objectives of the Study

Human walking is a cyclical pattern of body movement in which one gait cycle begins with a heel strike and finishes with another heel strike of the same foot. A gait cycle is broken into two major phases, i.e., stance phase and swing phase. The stance phase for a foot starts with the Heel Strike and finishes with the Toe Off, while the swing phase starts with the Toe Off and concludes with the following Heel Strike, as seen in Figure 1.4. The more quickly the entire sole of the prosthetic foot makes contact with the ground, the more stable it becomes. During walking, a decent prosthetic foot can reduce the impact and stress on the leg. The proposed design is tested for a person weighing 80 kg.

The proposed design of prosthesis comprises two degrees of freedom (2 DOF) and a manual stiffness adjustment mechanism that regulates the stiffness of the ankle. The objectives of the design are mentioned below:

- Resemble the dimensions and structure of a natural ankle-foot.
- Provide a completely mechanical adjustment system to adjust the stiffness of the ankle manually as per the amputee's requirements.
- Incorporate a 2 DOF i.e., plantarflexion-dorsiflexion and inversion-eversion motions, Figure 1.3.
- Implement the salient features of both a SACH and an ESR foot.
- Develop an affordable, durable, safe, lightweight, and ergonomically suitable ankle-foot prosthesis.

3.2 Flow Chart for Research Methodology

The following flow-chart shows the research methodology:

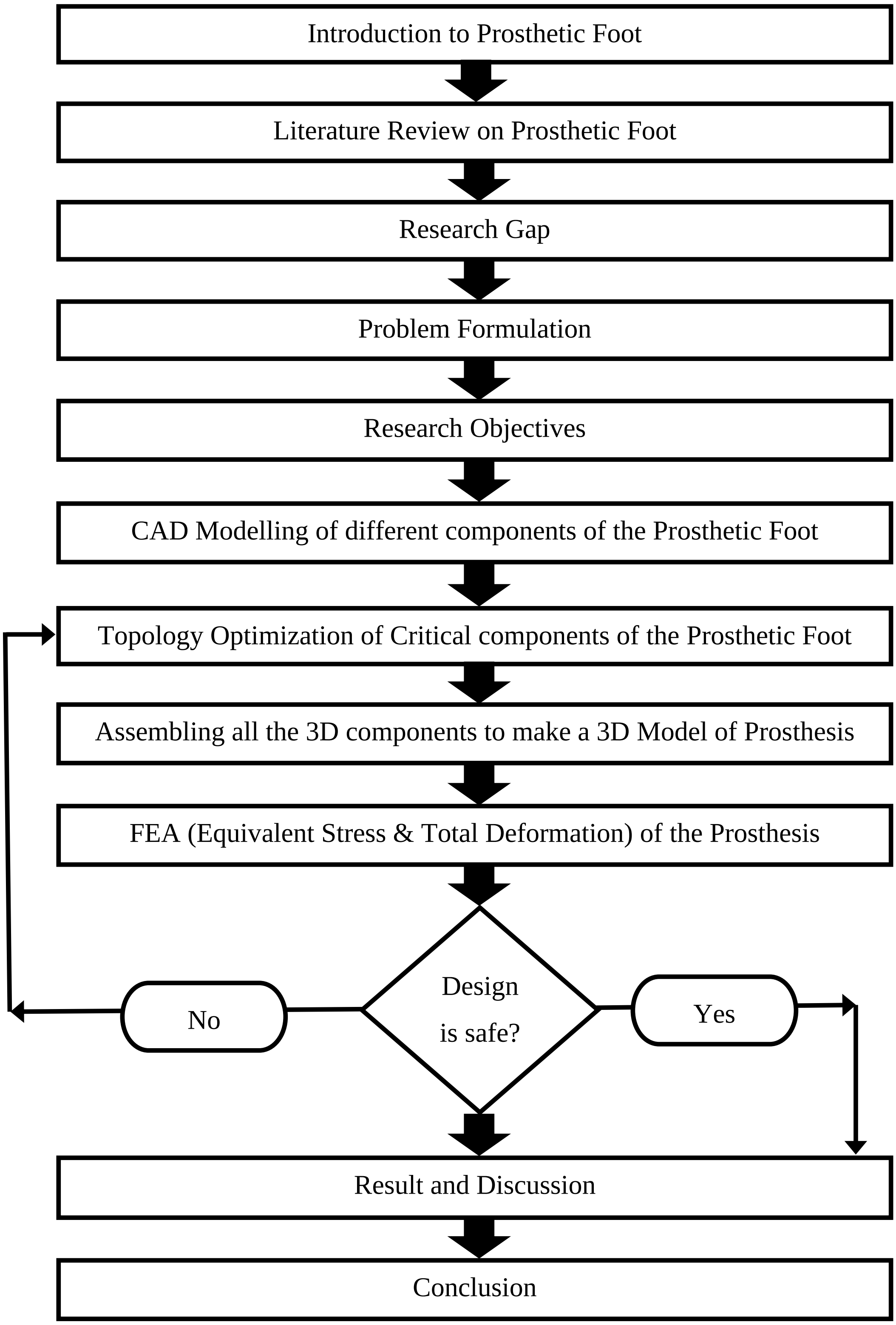

Figure 3.1. Flow Chart for Research Methodology

3.3 Adjustable Stiffness Mechanism

Previous research has shown that matching amputees with the appropriate stiffness is crucial for their overall mobility and may be their long-term health[16]. However, there are just a few prostheses available with adjustable stiffness for plantarflexion and dorsiflexion. To solve this problem, a study proposed an ankle-foot that could be stiffened by adjusting the spring support along the leaf spring's longitudinal axis with a DC motor[27]. A semi-active foot with a flexible keel whose fulcrum could be modified using a DC motor to obtain the desired stiffness was proposed in another study in the same field[29]. In one version, adjustable leaf springs are arranged vertically, and the fulcrum point is controlled by a servomotor[18]. Another research proposed a changeable toe-joint to address the aforementioned problem[33]. The concept of an adjustable stiffness powered ankle-foot prosthesis using a standard Series Elastic Actuator and a length changeable lever arm is given in a research paper[34]. All of these prostheses are active or semi-active in some way. A system similar to the previous study[27] with minor modifications has been proposed, in which the action is entirely manual[12]. The concept given by the latter was modified in this study such that the slider moved on an inclined plane rather than a horizontal plane. This slanted plane, with the help of the same leaf spring, contributes to the characteristics of an ESR foot[24].

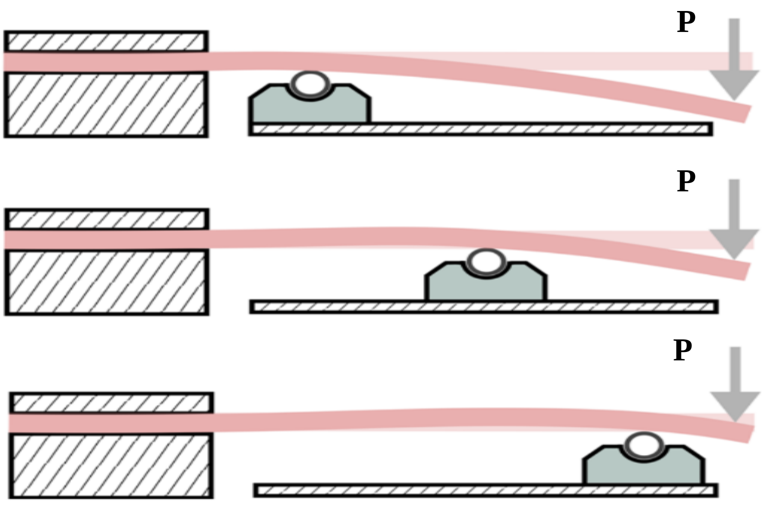

Figure 3.2 Adjustable Stiffness Mechanism[28]

The stiffness of the proposed design can be increased by rotating the lead screw using the knob in clockwise direction. For a low activity level higher stiffness can be useful while lowering the stiffness will help in higher activity level. Figure 3.2 depicts the stiffness adjustment procedure schematically. The lead screw (not shown in the illustration) is set up such that when it is turned, the link (called the slider) attached to it moves translationally, similar to a nut and bolt mechanism. The force 'P' created by the cam transmission owing to the amputee's weight deflects the leaf spring, which is fastened at one end and free at the other, as depicted in the same figure. When the support slider moves, the spring's stiffness varies. This change in spring stiffness would correspond to a similar change in ankle stiffness. The degree of deflection of the leaf spring is determined by the placement of the support slider, which is adjusted by the amputees using the lead screw knob. The energy held in the leaf spring takes the form of strain energy, which is presented by the following equation:

$$U = F^2 l^3 / 6EI \tag{3.1}$$

Where, the reaction force at the terminal stance is 'F', 'l' denotes the length of the spring, 'I' denotes the moment of inertia and, 'E' is the elasticity modulus of the material. The distance 'x' moved by the slider when the screw with the lead 'l' is rotated through an angle 'θ' can be calculated using the following relation:

$$x = l\theta / 2\Pi \tag{3.2}$$

The mechanism facilitates a maximum travel distance of 110 mm for the support slider. The number of screw rotations for this travel was arbitrarily set as 55, and hence the screw lead was found to be 2 mm. As a result, during a complete screw turn, the slider travels 2 mm, as specified by the relation above. Moreover, in the design proposed, the components of forces play a vital role because the force received at the free end of the leaf spring is not normal unlike what was proposed in previous studies[12,27] and unlike what is shown in the figure above.

3.4 Two Degrees of Freedom (2DOF) Mechanism

The ankle-foot prosthesis must have at least two degrees of flexibility to match the natural human gait cycle[35,36]. The majority of existing Passive Prosthetic foot designs have only one degree of mobility[11,14]. However, research explored the two degrees of freedom mechanism but did not suggest the whole ankle-foot design[30]. In another study, researchers used a cable and pulley mechanism to provide two degrees of freedom in a passive ankle foot prosthesis[26]. Although two degrees of freedom are uncommon in passive ankle foot prostheses, they are widely used in most active foot prostheses[25,28,31,32]. Since one of the key aims of the research reported in this study is to construct a passive foot with two degrees of freedom, the design proposed in earlier studies[14,25] has been used and changed to satisfy the other objectives as mentioned in section 3.1.

The 2 DOF mechanism is obtained mechanically in this suggested design. The ankle joint is primarily responsible for two motions: dorsiflexion-plantarflexion and inversion-eversion. Dorsiflexion occurs from heel strike to heel-off, and plantar flexion occurs from toe-off to pre-swing, as shown in Figure 1.4. As the heel impacts, the ankle plantarflexes and the distance between the tibial component and the toes increases. When the amputee enters the stance phase of the gait cycle, the ankle flexes. The axis around which inversion-eversion movement occurs is the Coronal Axis, which is perpendicular to and intersecting the Sagittal Axis. When landing on rough ground, the foot tends to tilt inward or outward (eversion-inversion) due to the person's self-weight. The motions in the Frontal Plane are inversion and eversion. The frontal plane twisting movement of the prosthetic ankle allows

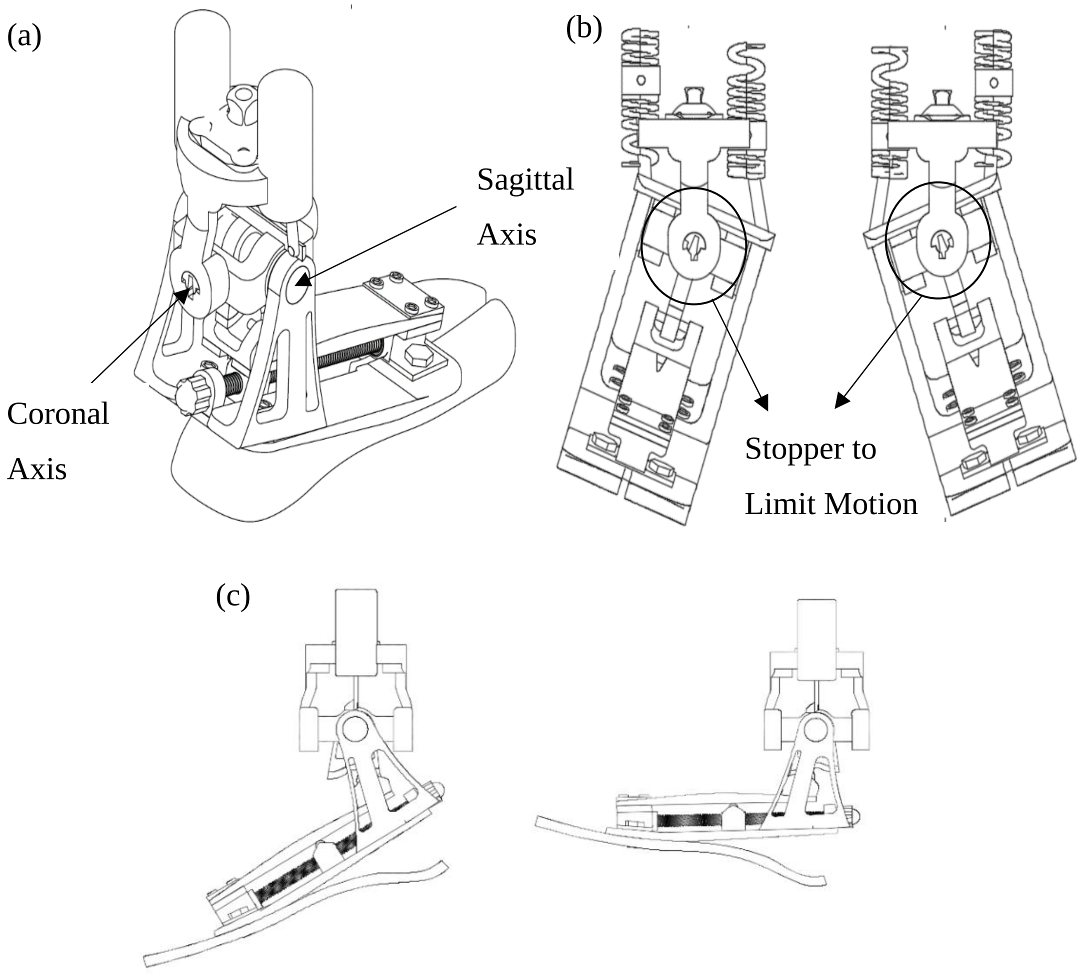

Figure 3.3. Motions of Proposed Ankle Foot: (a) Axes; (b) Inversion-Eversion Motion with Stopper to Limit the Motion; (c) Dorsiflexion-Plantarflexion Motion

amputees to walk in a more natural stride and on difficult terrain. The eversion-inversion movement of the ankle foot is shown in Figure 3.3(b) using a pair of piston-cylinder dampers on the left and right sides of the ankle. The dampers are supported by the ankle-Upper foot's Ankle Block and Connecting Link. For the aforementioned movement, a couple of connecting rods are employed to link the ankle to the dampers. A part of the ground reaction force owing to the amputee's weight is kept in helical springs within the cylinder at the time of the stance phase of strolling over a rough surface and then released during the swing phase for foot neutralization. Furthermore, a split toe design aids with terrain flexibility. The ankle may spin up to 20 degrees in each direction for the amputee's comfort and the safety of the components during eversion-inversion. As recommended in prior study[25], a stopper, as shown in Figure 3.3(b), is used in the front of the shaft at the Coronal Axis to limit the motion to the above-mentioned angle.

During dorsiflexion, the body's centre of mass is immediately above the foot's centre of pressure, and the foot is compressed[11]. The plantarflexion-dorsiflexion movement is provided in the design, Figure 3.3(c), by a cam that is placed on a shaft whose axis is known as the Sagittal Axis. As a result, the plantarflexion-dorsiflexion motions are in the Sagittal plane. The cam is followed by a cylindrical follower, which sends motion to the leaf spring through the roller bracket. As seen in Figure 3.2, the leaf spring bends as it receives force from the cam. The ankle rotates between 15° and 25° during dorsiflexion and plantarflexion, respectively, in the design described in this study effort. Walking is made simpler using a prosthetic foot that rotates between 15° and 25° during dorsiflexion and plantarflexion, respectively[28].

Although movement in the frontal plane is important, it serves a secondary role because 93% of the work done, at the ankle, is done in the Sagittal Plane[38]. Because the bulk of ankle labour is done in the Sagittal Plane, it is appropriate to make all of the components strong and durable without jeopardizing the integrity of the prosthesis, which plays an essential part in the Sagittal motions, namely Plantarflexion and Dorsiflexion.

Chapter-4

CAD Modeling

4.1 Selection of Designing Software

CAD Modelling, abbreviated for Computer Aided Design Modelling, allows designers to bring concepts into reality. Through CAD modeling, it is possible to refine, modify, and test different designs before they are ready for production. There are many software, from basic to advanced, which are available to perform these tasks. One such CAD software is Autodesk Fusion 360 (shortly, Fusion 360), Figure 4.1(a). All the designs created in this research have been created using this software.

Fusion 360 enables users to create 3D models, engineer, simulate, and manufacture - all in one product development software. Although Fusion 360 is a much newer 3D modeling and analysis program, it is quickly gaining popularity among professionals and hobbyists alike. In addition to the CAD, it also has the features of a CAM, and CAE software, Figure 4.1 (b). It takes a more contemporary approach to design and offers a lot of design, simulation, and production capabilities. For engineering tasks, mechanical parts, and product design, Fusion 360 is a better choice.

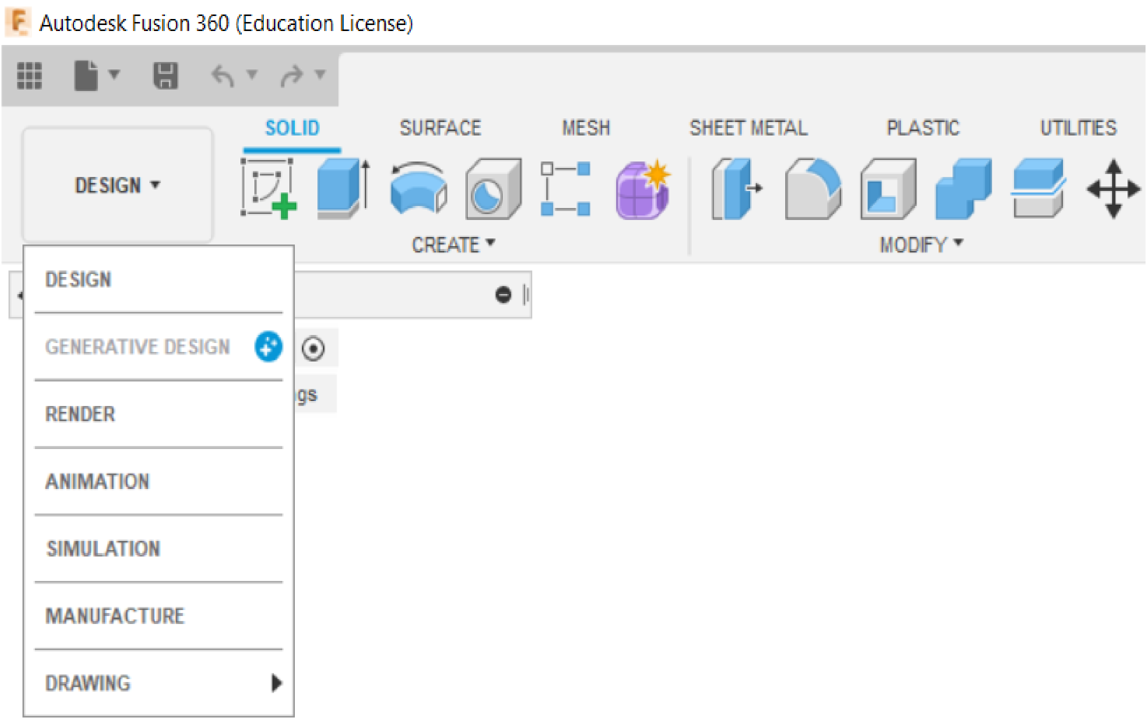

Figure 4.1. Autodesk Fusion 360 Interface showing Different Modules

Since Fusion 360 is a cloud-based software, it allows users to use the software in multiple devices simultaneously. Also, it has a unique feature where a team can be formed, and the members can work on the same design on cloud from anywhere around the world. It enables the users of a tea m to see the progress and can give feedbacks regarding the design that has been developed by the other teammates. The design can be viewed using web browser and feedback can be provided without the need of the software at all on any device. These were the main reasons behind opting Fusion 360 as the designing software for this project.

4.2 Development of the Design

After the intense research regarding various prosthetic foot available in the market and the development of technology in the ankle-foot prosthesis, a novel design for passive ankle-foot prosthesis was conceptualized. This design concept has two degrees of freedom for the ankle-foot, namely Inversion-Eversion and Plantarflexion-Dorsiflexion. The design has a huge influence from Sparky 3[39] and a Passive Ankle-Foot with Adjustable stiffness[12]. The features of both these ankle-foot has been implemented together into one in this project work. Initially a rough sketch of the design was made as shown in Figure 4.2.

The motive of the design concept was based on the fact that the foot should be

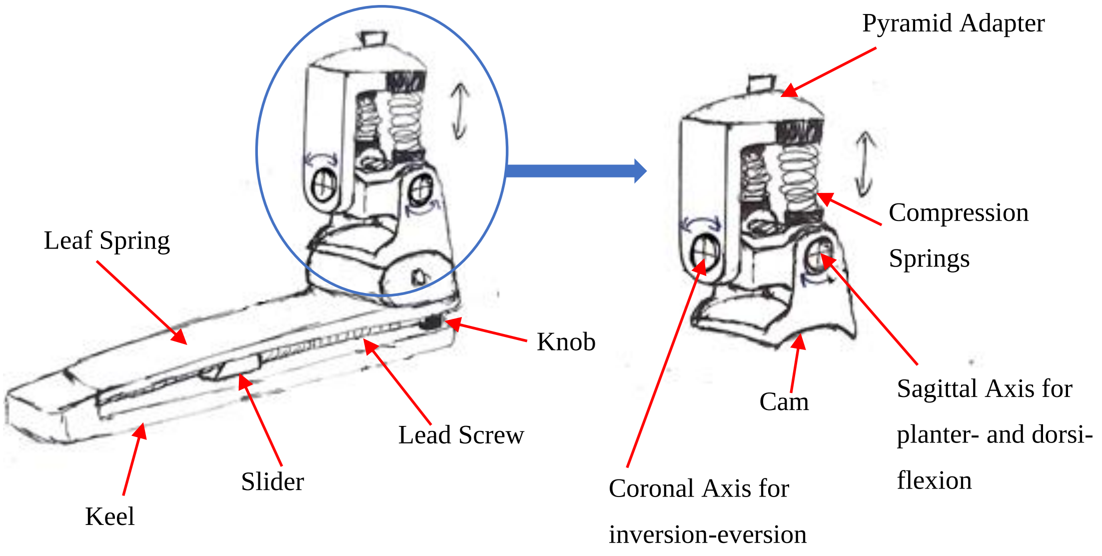

Figure 4.2. Initial Rough Sketches for Proposed Ankle Foot Design

lightweight and must be able to provide the demanded features without compromising the strength and functionality of the foot. The amputee should be able to have much more natural gait and to perform day to activities with ease. This is one of the main reasons behind providing the 2 DOF for the prosthetic foot.

The dampers present here as spring in Figure 4.2 activates the inversion and eversion. Whereas the leaf spring which is supported using a slider which can be moves using the lead screw aids the plantarflexion and dorsiflexion of the foot. A cam roller present on the leaf springs provides motion to the follower cam profile. Since the support of the leaf spring can be adjusted using a lead screw, the stiffness of the leaf spring will also be affected. This is one of the features that is provided in the prosthetic foot. The amputee will be able to adjust manually the stiffness of the leaf spring based on his needs. The dampers are accommodated within the joint axis to make the design much more compact unlike SPARKy 3.

4.3 Final Design and Nomenclature

Mainly, the design consists of the following components: (a) Keel, (b) Slider Support, (c) Housings, (d) Leaf Spring, (e) Slider (f) Cam and Follower (g) Adapter (h)

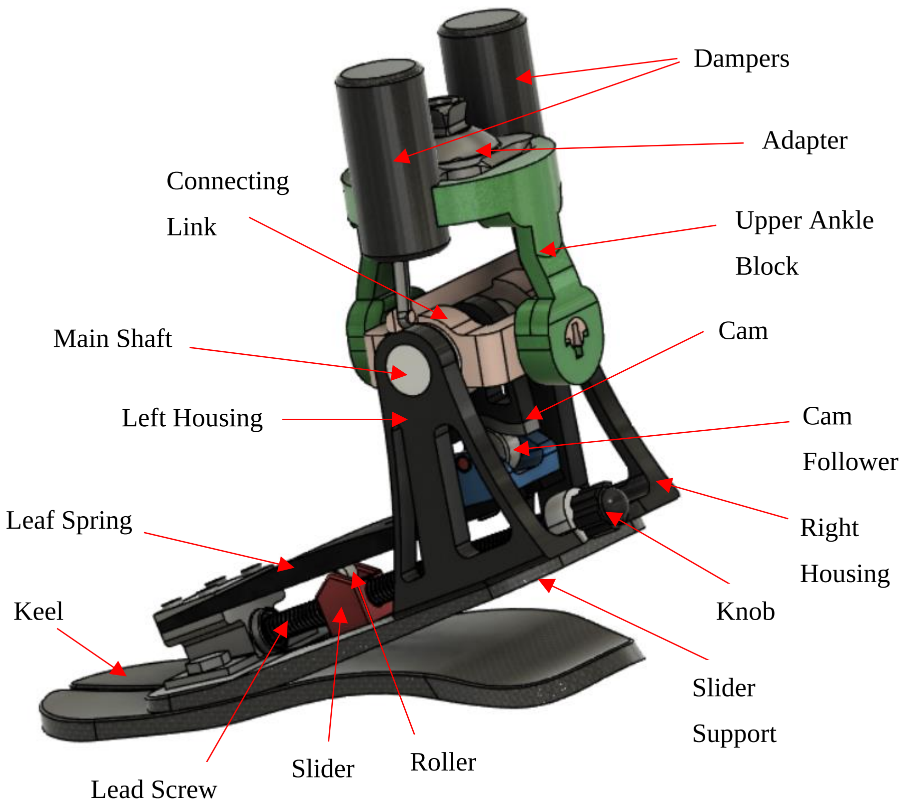

Figure 4.3. Parts of the Prosthetic Ankle Foot

Upper Ankle Block (i) Connecting Link (j) Lead Screw and (k) Dampers. The detailed view and nomenclature of the design are illustrated in Figure 4.3.

The arches, in the Keel design, are created to maintain the body balance. The design is inspired from the previous research[40]. They provide a cushioning effect to the amputee like a SACH foot to prevent the amputee from the unnecessary jerks during heel-strike and work as an elastic component that can store and release energy like an ESR foot; thereby, reducing the metabolic cost of strolling. Due to the design and material of the Keel, it absorbs the energy during the ‘roll over’ phase of walking and releases this energy during the toe- off phase. This creates a push off action that leads to a more symmetric gait. These features are vital for the amputee in terms of comfortability.

The Housing is one of the main components of the design which bears most of the weight of the amputee. Further, Cam, Springs-Dampers and Adapter are supported on it. As the Housing is directly fixed to the slider support, it transfers the forces to the latter. The housing design has been optimized for weight reduction up to 22.3% (from 140.4g to 109.1g) using Topology Optimization method without compromising the safety. Similarly, Upper Ankle Block weight was reduced to 30.5% (from 411.3g to 285.5g) using the same method. The Connecting Link connects the Upper Ankle Block and the Dampers.

Another important component in the design is the inclined Slider Support which not only aids in to achieve the features of an ESR foot but also prevents any mechanical damage to the components of the prosthetic foot. Cam profile has been adopted from the previous research for the required angle of deflection in the leaf spring during dorsiflexion-plantarflexion[12], however, its weight has been optimized to 19.09% (from 31.25g to 25.3g). Piston-Cylinder Dampers with Helical Springs are used to assist in inversion-eversion. The slider consists of a roller on which the leaf spring is supported. The roller rolls in contact with the leaf spring and the slider is moved by rotating the Lead Screw using the Knob provided at extreme right as shown in Figure 4.3. The lead screw is a standard acme-threaded screw with the required lead as discussed in chapter-3.

4.4 Design of Components

The first component of the foot to be designed was the lower keel. It was greatly inspired by the keel design of the PROPRIO FOOT by Ossur[40]. It has a dynamic carbon foot blade with exceptional roll-over characteristics. Carbon fiber stacking enhances forefoot deflection from mid-stance to toe-off, and it's proportional to the user's weight and impact intensity. The full-length keel/toe lever corresponds to the length of the sound foot, resulting in a more symmetrical, smoother gait. The split toe feature allows amputees to walk naturally on uneven ground by allowing the foot to adjust to the surface below. All these are vital features that are required in every prosthetic foot. Prosthetic foots all over the world has opted for similar designs for maximum performance. Moreover, the material used is carbon fiber for the keel blade which gives it high yield and tensile strength. This enables it to absorb more shock during different gait phase. Hence it was the optimal choice to choose over other keel designs. Figure 4.4 depicts the detailed drawing and the design used for the proposed ankle foot design concept.

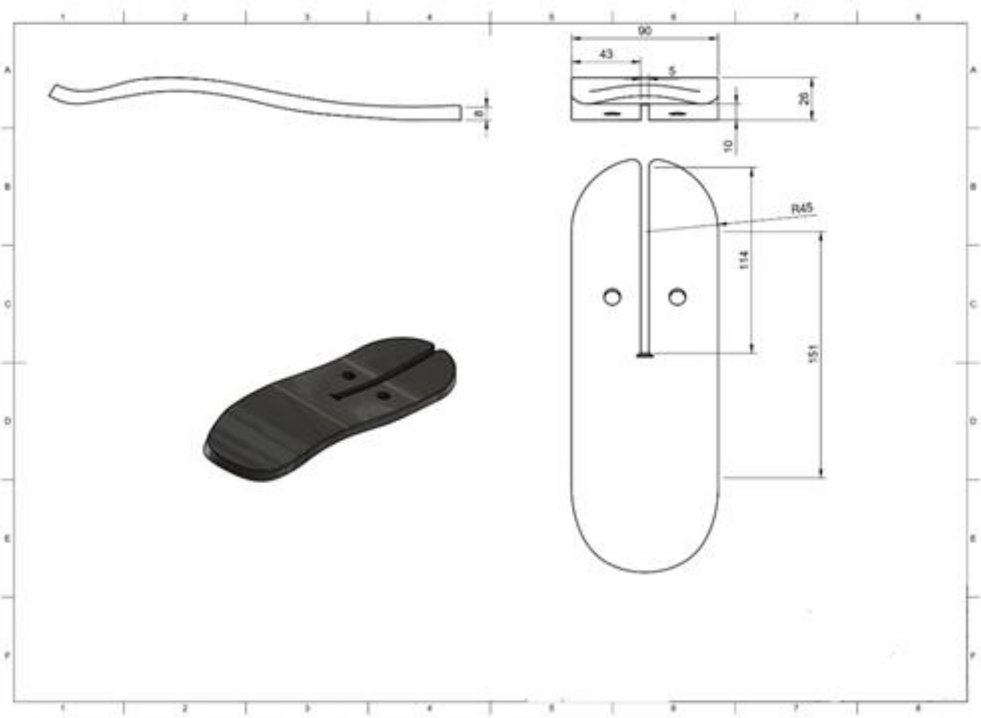

Figure 4.4. Detailed Drawing of Keel

The next component designed was the slider support, Figure 4.5, it is the inclined plane over the keel. It provides the base for the slider to slide over. It provides support for the leaf spring which is used for the adjustable stiffness mechanism. It is made of same material as of the keel and hence is light in weight.

Design of the ankle housing, Figure 4.6, was crucial as it houses the entire ankle assembly and the entire weight of the body acts on the housing. The ankle housing accommodates the sagittal axis joint, coronal axis joint and the cam profile. It is supported on the slider support using screws. Topology Optimization was used to minimize the materials to develop a lightweight component for the ankle housing. Figure 4.7 shows the result of topology optimization under given boundary conditions.

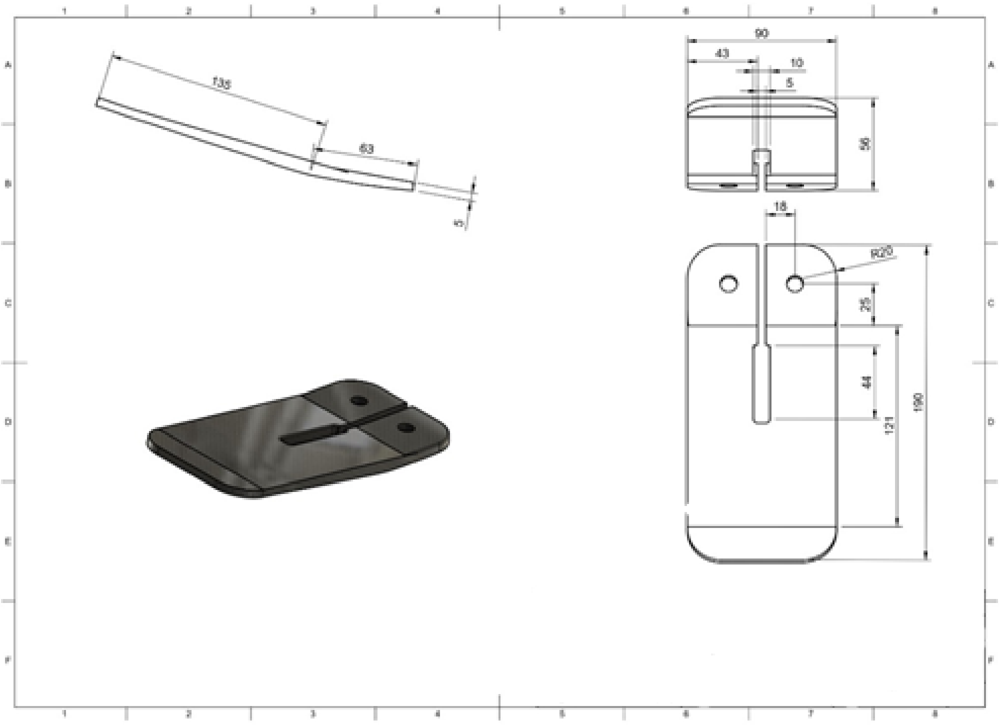

Figure 4.5. Detailed Drawing of Slider Support

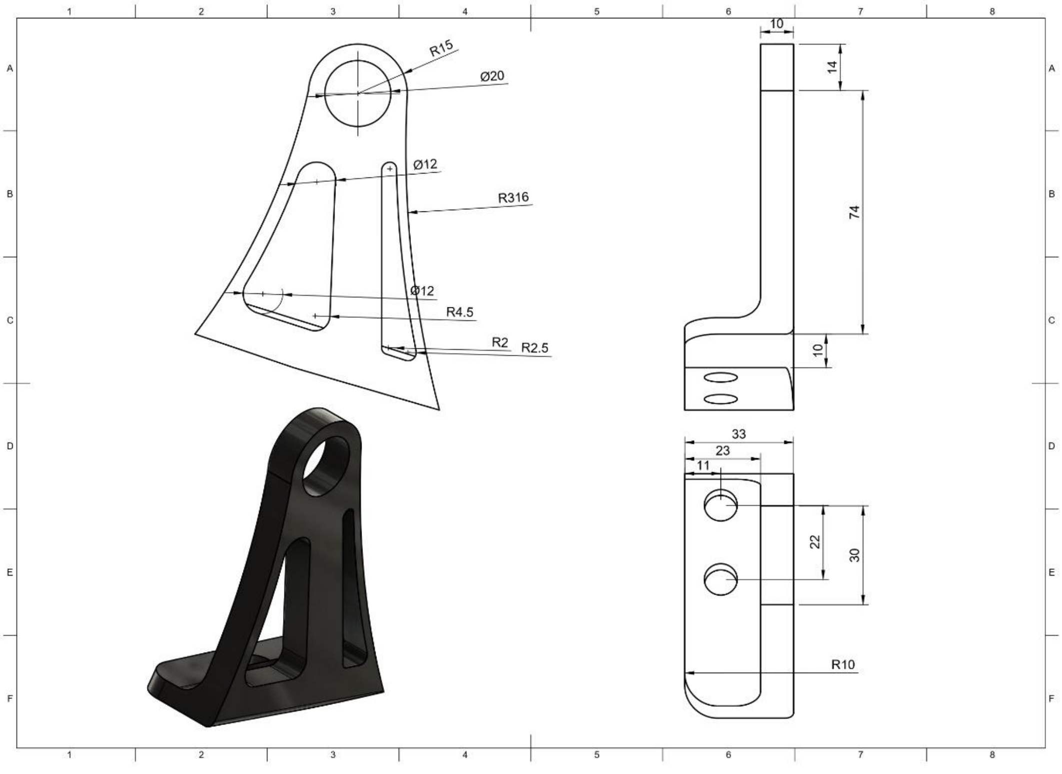

Figure 4.6. Detailed Drawing of Housing

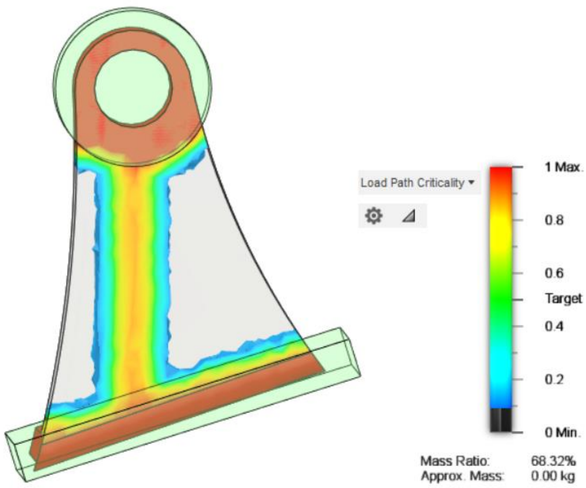

Figure 4.7 Topology Optimization of Housing

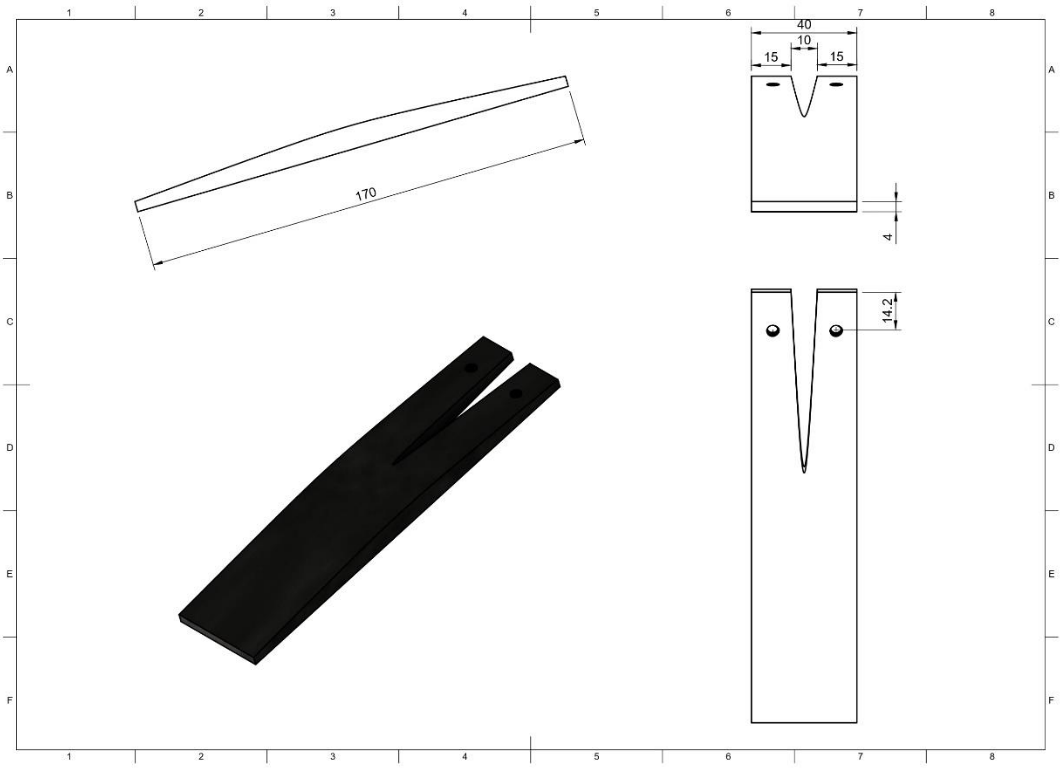

Figure 4.8 Detailed Drawing of Leaf Spring

The base of the ankle housing which is fixed to the slider support using bolts is the fixed end. The hole at the top portion is where the vertical force of 800N will be acting. Moreover, this is where the other components such as coronal axis joint and sagittal axis joint will be connected using a connecting rod, bearings and washers. And these two regions were preserved for the optimisation process. (Target mass 50%, load 800N, Al 7075T6). And the housing design was made based on these results. The Leaf Spring, Figure 4.8, is the main component that comes into play during the adjustable ankle stiffness. The cam roller housing is placed on the leaf spring and the slider acts as a support for the leaf spring beneath it. This slider can be adjusted based on the activities the amputee is performing. And hence the stiffness is adjusted by turning the knob. The material of the leaf spring is the Glass Fibre.

Upper Ankle Block (Figure 4.9) has an axis passing through coronal plane. This axis provides the inversion and eversion feature of the prosthetic foot. The coronal axis joint (upper ankle block) is joined to the sagittal axis joint (connecting link) which is connected to the ankle housing using bearings. The coronal ankle joint has a stopper which limits the motion of the feet to certain ankle of 20 degrees on either direction. This is the angle of movement for inversion and eversion.

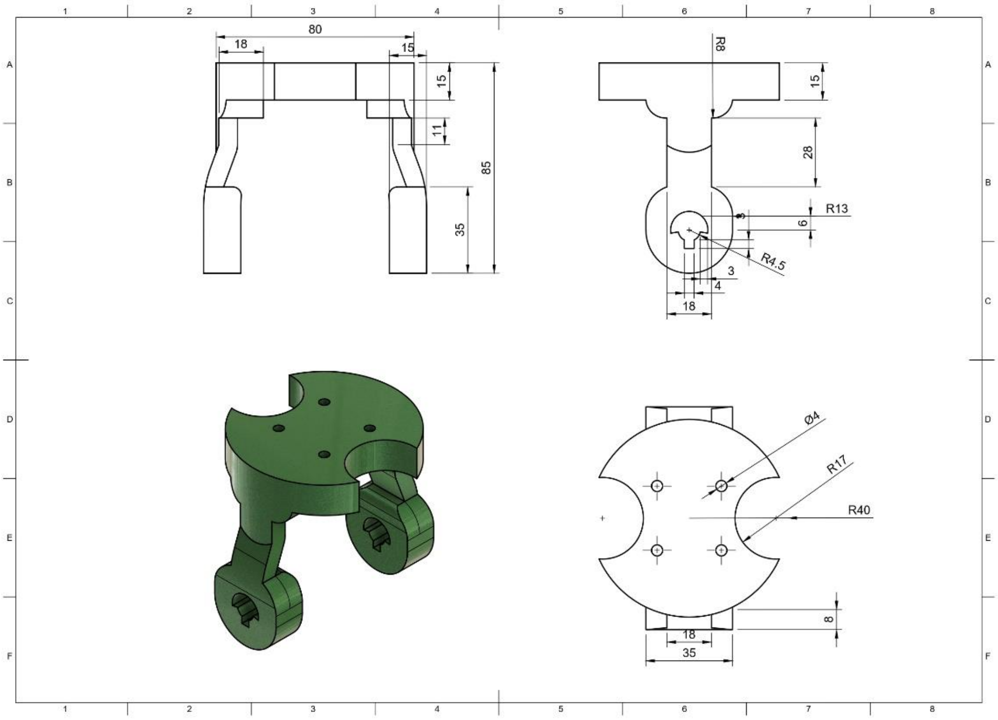

Figure 4.9 Detailed Drawing of Upper Ankle Block

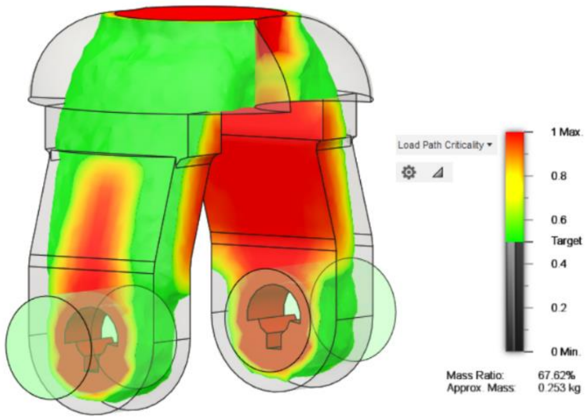

Figure 4.10 Topology Optimization of Upper Ankle Block

The final design of the coronal ankle joint was obtained after topology optimization (Figure 4.10) study with certain boundary condition (target mass 66%, load 800N, Al 7075T6). This uses less materials and gives optimum strength.

The sagittal axis joint or the Connecting Link, Figure 4.11**,** has an axis passing through the sagittal plane. This joint provides the plantarflexion and dorsiflexion to the

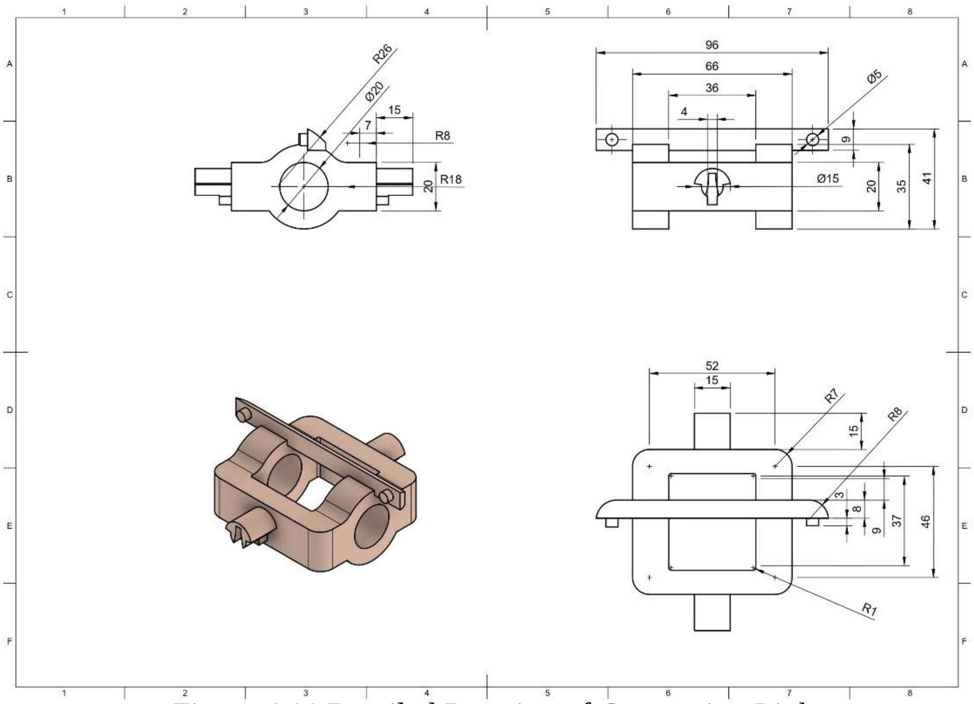

Figure 4.11 Detailed Drawing of Connecting Link

foot. Dorsiflexion is the movement of the top of the foot toward the anterior leg by raising the front of the foot. The lifting of the heel of the foot off the ground or pointing the toes downward is known as plantar flexion. During plantar flexion and dorsiflexion, all the lower muscles and tendons work together to maintain the body balanced and steady. The ankle moves the most in the sagittal plane and much of the plantarflexion and dorsiflexion movements is achieved with the help of tibiotalar joint. Several studies show, the overall rotation of movements (ROM) in the sagittal plane is between 65º and 75º, ranging from 10º to 20º of dorsiflexion to 40– 55º of plantarflexion[41]. For the proposed design of the ankle foot the movement for dorsiflexion is restricted to 15 degrees whereas the plantarflexion has a movement up to 25 degrees. The sagittal joint is joined with the ankle housing using bearings.

It also has an extrusion that is used to connect the connecting link of the dampers used for Inversion and Eversion. These links are connected to the piston rod in the damper cylinder. It is entirely made of Aluminium 7075 T6 which is lightweight and provides optimum strength. It is connected to the ankle housing using washers and bearings.

One of the most important components of the ankle foot design is the Cam Profile (Figure 4.12). It rolls over a roller, and the provides the plantarflexion and dorsiflexion of the foot and regulates the stiffness during the motion by deflecting the

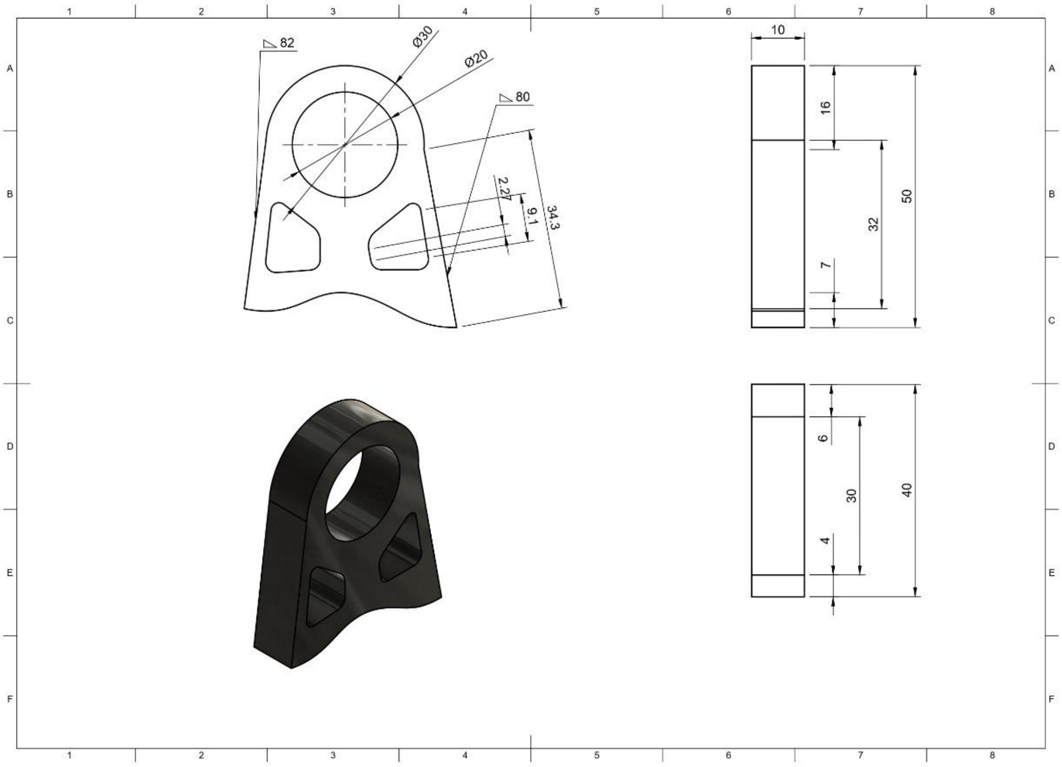

Figure 4.12 Detailed Drawing of Cam

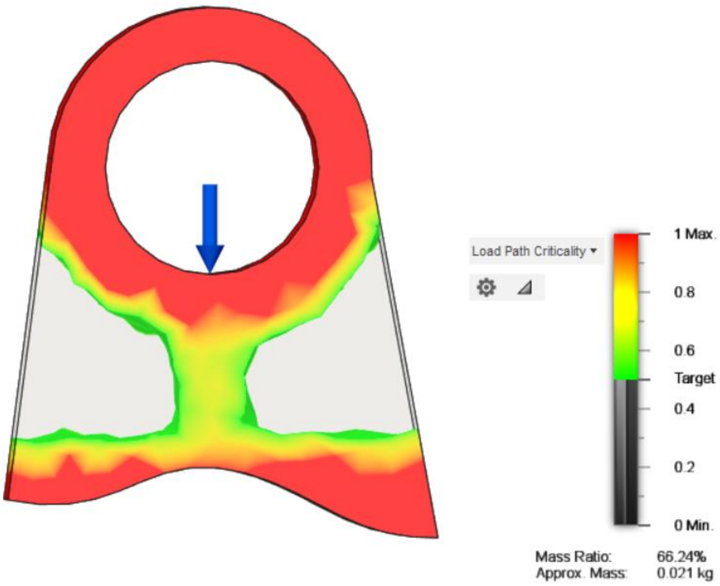

Figure 4.13 Topology Optimization of Cam

leaf spring. The profile is inspired from the design created in the previous research[12] for the required amount of deflection in the spring.

Topology optimization was used for the cam profile, Figure 4.13, to reduce the weight my minimising the material used without compromising the strength. The Blue arrow shows the direction through which the load is acted on the cam. The load of 800N of the amputee acts vertically to the cam. With these boundary conditions (Target mass 65%) the topology optimisation study was carried out. Based on these results the final design of the cam profile was made.

As soon as the ankle joint rotates, the cam follower is displaced by the cam. Since follower is connected to the leaf spring, the leaf spring to deflects downward. This allows a torque-angle relationship which is nonlinear and configurable. When the slider is in the 'main slider position', the cam profile is structured in such a manner to generate the 'principal torque-angle curve'. The manually adjustable simple support slider, adjusted with the help of the lead screw, modifies the leaf spring's stiffness that causes the mechanics to deviate from the principal torque-angle-curve, making them less or more stiff in general. Through a rolling cam transmission, rotation of the ankle joint causes a downward deflection of the free end of the leaf spring. The torque (restoring) at the ankle joint is caused by the deflected leaf spring. The torque- angle curve at the ankle is governed by the cam profile; with the right description of this connection, a cam profile may be generated for practically any arbitrary torque- angle curve.

4.5 Material Selection and Design Specification

The parameters, based on which the design is created, are given in Table 4.1. The parameters of the prosthesis are set and maintained in such a way that they match with the characteristics of a missing natural foot.

The material selection of different parts of prosthetic foot is very important as the foot must withstand the amputee's weight and torque, at the same time, it should not make the prosthetic foot heavier, moreover; the components should not fail during application. Selection of suitable materials for the component plays a significant role in this stage. The materials are assigned to the components very cautiously taking into consideration all those factors. Types of the materials used for different components in the design of the ankle foot prosthesis are presented in Table 4.2. Similarly, Table 4.3 presents the key properties of the materials which are used during Design and Analysis.

Table 4.1. Design Specifications/Parameters

Description	Values	
	Avg. Human Foot[37]	Prosthesis
Length of prosthetic foot (mm)	260	250
Width of prosthetic foot (mm)	94	90
Toe length (mm)	50	59.4
Height of the Foot up to ankle joint (mm)	70	80
Weight of the ankle foot (kg)	2	2.0083
Max. allowable Dorsiflexion (degrees)	20	15
Max. allowable Plantarflexion (degrees)	40	25
Max. Eversion angle (degrees)	20	20
Max. Inversion angle (degrees)	30	20
Max. travel distance of support slider (mm)	-	110
Factor of Safety (Minimum of All Components)	-	1.5

Table 4.2. List of Materials for Components

Component	Material
Helical Springs	Stainless steel, 302, Annealed
Connecting Rods (Damper)	Aluminium Alloy, Wrought, 7075, T6
Slider	Aluminium Alloy, Wrought, 7075, T6
Cam Follower	Low Alloy steel, 4130, Annealed
Slider Support	Composite, Carbon fibre reinforced carbon matrix
Lead Screw	Structure Steel
Keel	Composite, Carbon fibre reinforced carbon matrix
Leaf Spring	Composite, PA12/glass fibre, woven fabric, biaxial
Slider Roller	Low alloy steel, 4130, Annealed
Cam Profile	Carbon steel, 1060, Annealed
Main Shaft	Aluminium Alloy, Wrought, 7075, T6
Housing	Aluminium Alloy, Wrought, 7075, T6
Connecting Link (Sagittal Axis)	Aluminium Alloy, Wrought, 7075, T6
Upper Ankle Block (Coronal Axis)	Aluminium Alloy, Wrought, 7075, T6
Damper Cylinder	Aluminium Alloy, Wrought, 7075, T6
Pyramid Adapter	Aluminium Alloy, Wrought, 7075, T6
Piston (Damper)	Aluminium Alloy, Wrought, 7075, T6

The main motive is to design a prosthetic foot which is lightweight and strong, hence the materials have been chosen accordingly. Such as Aluminium 7075 T6 which has exceptional mechanical qualities, including high ductility, strength, toughness, and fatigue resistance. For the mating surfaces in motion such as cam profile and cam roller Low alloy steel grade 4130 is used. It is a versatile alloy with strong corrosion resistance and a moderate strength. It has a superb overall balance of strength and toughness. and fatigue resistance.

Table 4.3. Properties of Materials

Material	Density (Kg/m^3)	Young’ s Modulus (GPa)	Poisson’ s Ratio	Bulk Modulus (GPa)	Shear Modulus (GPa)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
Aluminium Alloy, wrought, 7075, T6 (at 22.2°C)	2800	71.7	0.33	71.68	26.9	436.2	501.7
Composite, Carbon Fibre Reinforced Carbon matrix	1565	54.65	0.306	46.95	20.923	666.7	666.7
Composite, PA12/glass fibre, woven fabric, biaxial	1857	26.4	0.1543	12.728	11.436	440.1	440.1
Structural Steel	7850	200	0.3	166.7	76.923	250	460
Stainless steel, 302, annealed	8027	193	0.27	139.86	75.984	252.1	562.3
Low alloy steel, 4130, annealed	7850	200	0.27	140	80	357.8	556.8
Carbon steel, 1060, annealed	7850	212	0.29	168.25	82.171	370.1	620.5

The properties of materials stated in the Table 4.3 are at certain standard conditions of temperatures and is subject to vary at different temperature conditions. Aluminum alloy wrought 7075 T6 has been used for the majority of the components due to it exceptional mechanical properties. And the components such as Keel and Inclined plane are made of Composite Carbon Fiber reinforced carbon matrix. Carbon fiber feet are one of the materials used in prosthetic feet to meet shock absorption and energy efficiency requirements. Its mechanical properties have been considered good fit for the majority of the keel available in the market. That is the reason why most of the prosthetic foots available has keel blade made up of carbon fiber. Whereas Glass fiber has been opted for the leaf spring due to its exceptional damping properties. Materials utilized in prosthetic connective componentry include aluminum, stainless steel, carbon, and titanium. Standard adapters are used to connect the socket to a prosthetic joint and/or a terminal device/foot in the construction of the prosthesis.

Chapter-5

Analysis Framework

5.1 Flow Chart for Analysis Framework

The following framework has been adapted during analysis of the design:

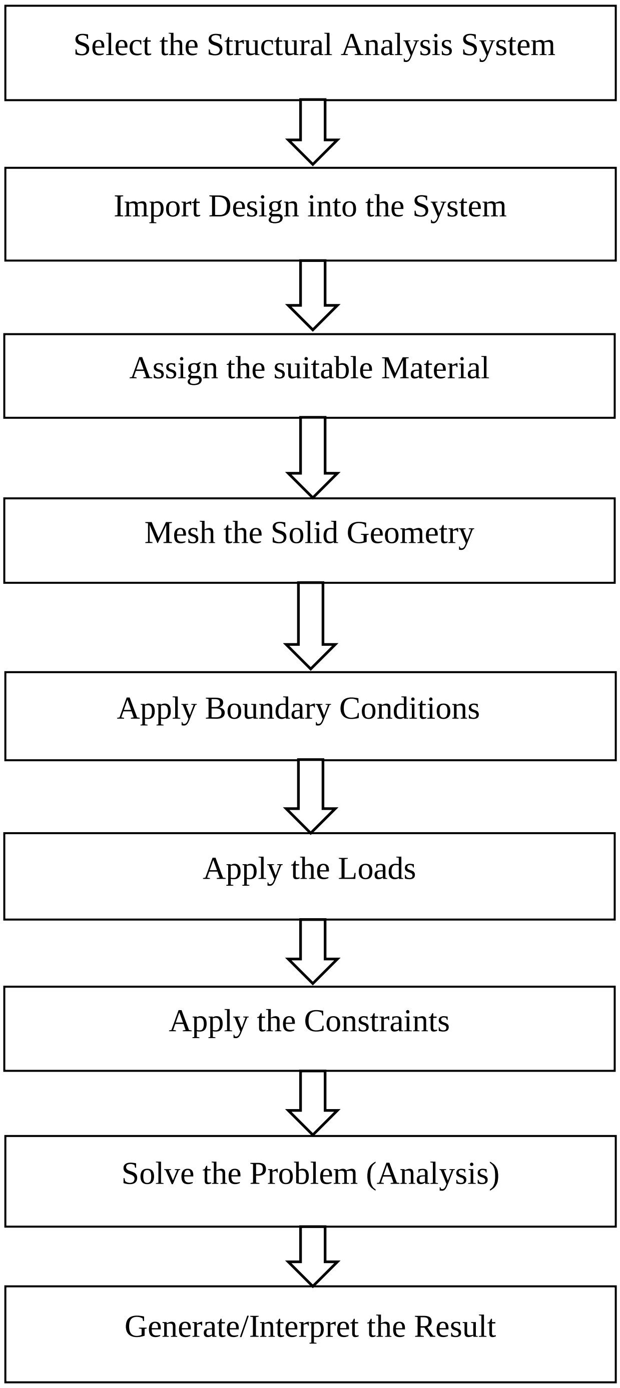

Figure 5.1. Flow Chart showing Analysis Methodology

5.2 Static Structural Analysis

Statics is the study of structures that are in equilibrium. The structure's equilibrium means that all of the forces operating on it must balance, and the net torque must equal zero. The effect of static (or steady) loading conditions on a structure is calculated using static structural analysis, which overlooks inertia and damping effects caused by fluctuating loads. Here, the term 'varying loads' refers to the loads that changes over time. Calculations, from basic to advance and nonlinear, related to material, geometric, and contact are performed using static structural analysis. A static analysis can incorporate constant inertia loads (e.g., rotational velocity, gravity, acceleration etc.) as well as time-varying loads that can be represented as static equivalent loads. A static structural analysis is performed to find out stresses, strains, displacements, and forces in a structure or component induced because of the loads; then finding out the values of these quantities to determine the safety of the structure by identifying weak spots with poor strength and durability. However, the analysis has some underlying assumptions such as loading, and response conditions are assumed stable. Because of such assumptions, the results of the analysis may differ from the actual, hence due considerations should be made while designing the components of a structure to achieve the desired level of safety.

Static structural analysis can be performed using computer software such as Abaqus FEA, ANSYS, STAAD Pro, ETABS, SAFE etc. Although methods of calculation (e.g.

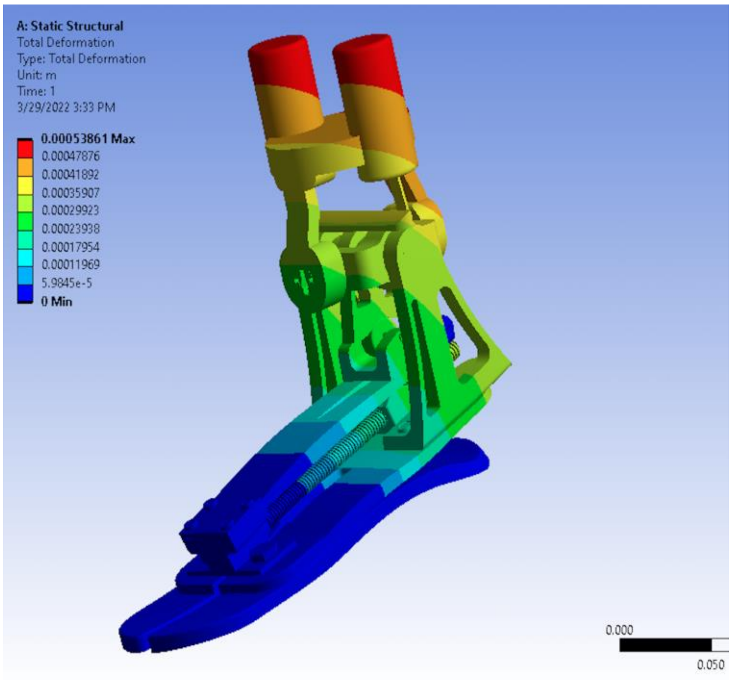

Figure 5.2. Structural Analysis being Performed on the Model in ANSYS

FEM, FDM, FVM, Matrix Analysis or Direct Stiffness Method etc.) vary from one software to another, FEM is the most popular. In this study, the structural analysis of the proposed ankle-foot has been performed on ANSYS.

5.3 Finite Element Method (FEM)

The FEM is a generic numerical approach for resolving Partial Differential Equations (PDEs) with 2 or 3 variables in space that includes some boundary value problems. In order to resolve a problem, the Finite Element Method breaks a big system into significantly smaller ones. Those smaller sections are known as finite elements. This is achieved through creating an object mesh and performing a specified space discretization in the space dimensions. The numerical domain for the solution is termed a mesh, and it has a finite number of points called nodes. An FEA mesh solver cannot operate efficiently with irregular surfaces and shapes, but it is much easier with standard shapes such as cylinders, cubes, cuboids, and so on. Meshing is the process of transforming irregular forms into more distinct volumes, called 'elements'. Before starting meshing, a Geometry or CAD model should be first uploaded to the Model workspace. There are two main types of meshing methods namely Tetrahedral element meshing and Hexahedral element meshing. Mesh is a vital component of the model that must be carefully handled to achieve the best results. Usually, the more elements in a mesh there are, the more exact the discretized issue solution becomes. However, there comes a point where the values converge and further mesh refinement has minimal impact on accuracy.

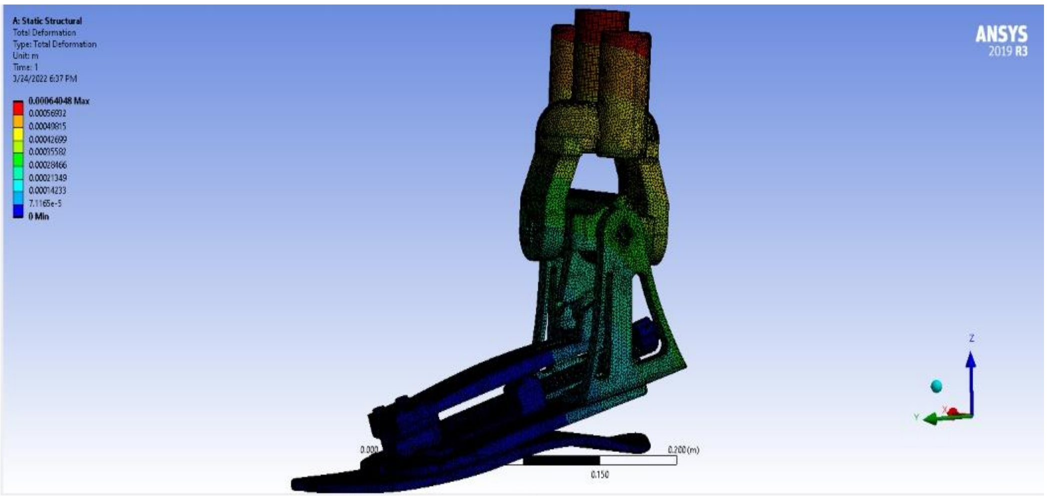

Figure 5.3. An initial 3D Model of Prosthesis after Generating Mesh in ANSYS

The finite element approach formulation of a boundary value issue results in a system of algebraic equations. The approach approximates the unknown function over the domain. The basic equations that represent these finite elements are then merged to form a larger system of equations that reflects the entire problem. The Finite Element Method then approximates a solution with the help of the calculus of variations to minimize an associated error function.

A range of specialties within mechanical engineering typically employ integrated Finite Element Method in the design and development of their products. Electromagnetic, thermal, fluid, and structural working conditions are all included in several recent FEM programs. FEM is extremely useful in structural simulations for providing stiffness and strength visualizations as well as decreasing weight, materials, and prices.

Finite Element Method allows for detailed depiction of where structures bend or twist, as well as load and displacement distribution. This software provides a number of simulation choices for adjusting the level of complexity of modeling and analysis of a system. The desired level of precision and associated computing time requirements can be modified simultaneously to accommodate most engineering applications. FEM technology allows for the development, refinement, and optimization of the entire designs before are actually manufactured. The term “Finite Element Analysis” (FEA) refers to the process of investigating or analyzing a phenomenon using finite element methods (FEM). This study has adapted the FEM to analyze the components with the help of ANSYS.

5.4 Boundary Conditions

A location on a structure where the external force or displacement is known before the analysis begins is called as a boundary condition. In this sense, boundary conditions are places where the system interacts with the environment, either by applying an external force or by imposing a displacement through some restriction. A general boundary condition must be applied to every site on the structure's border, either a known force or a known displacement, for a structural analysis task to be solved. In this design, the Keel was fixed, the force was taken as -800N along Z axis and applied to the Upper Ankle Block and was acting normal to the coronal and sagittal axis. This can be considered as boundary conditions for the analysis. A boundary condition with zero displacement is comparable to the system being kept in place at that location.

Along with the boundary conditions, other related operations such as selecting the right type of load and its direction, defining the contacts and applying the correct constraints for the motion of components were also performed cautiously as these factors affect the accuracy and reliability of the results.

5.5 Selection of Analysis System

In this research work, the structural analysis has been performed on ANSYS. The name ANSYS can be viewed as the acronym for ‘Analysis System’ which is a computer software based on FEM. The main package under which the analysis has been done is called ANSYS Workbench. This package provides the user with the flow of operations to be performed for the selected type of analysis to be performed. This makes it easy to use the software. ANSYS has all other modules present which might be required during the analysis of the model. For example, a Design Modeler can be used to edit or create a design from the scratch. The actual structural analysis is performed in the module called ANSYS Mechanical.

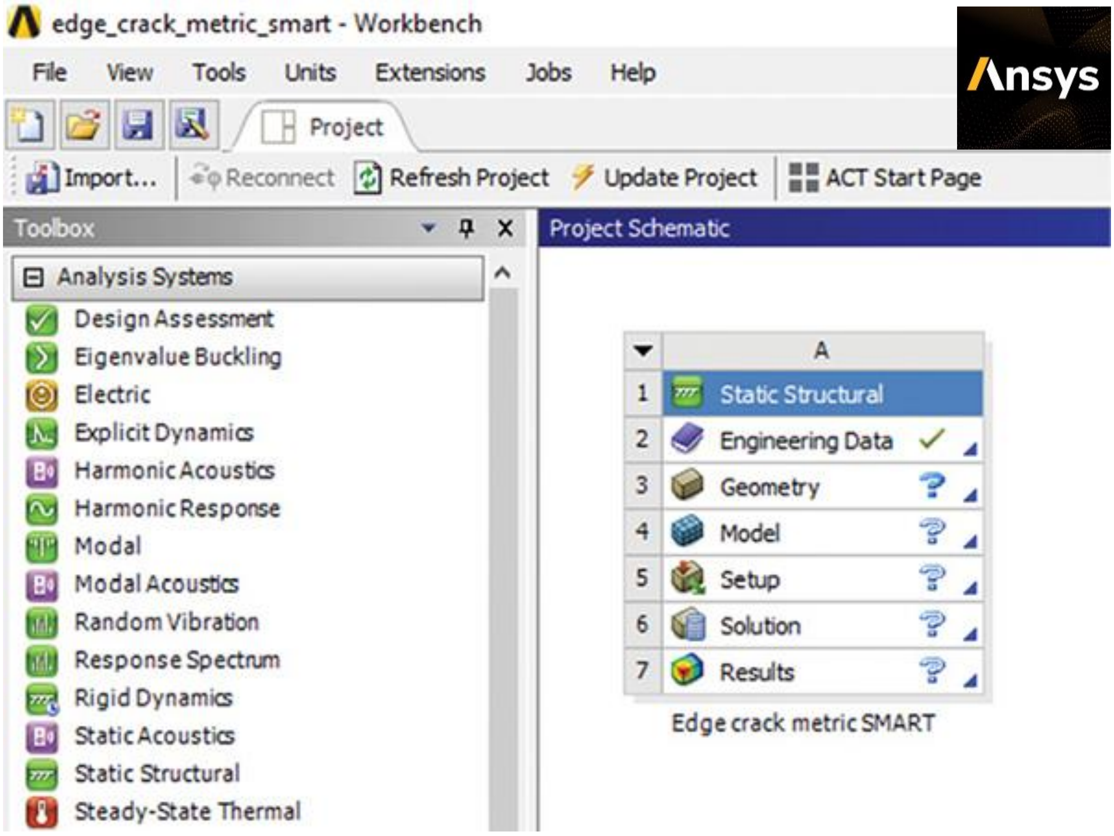

Figure 5.4. ANSYS Workbench Interface with ANSYS Logo in the inset

Ansys Mechanical is one of the optimum user-friendly finite elements- based simulation tool and it is highly resilient and strongly linked with Ansys’ extensive array of Multiphysics solvers. Users may take their mechanical design from the geometry phase through early proof of concept simulations, optimization, and validation using a variety of analytical techniques. If physics coupling is necessary to provide robust results for a certain product or process, the Mechanical interface communicates directly with extra ANSYS physics solvers in the Workbench environment. This best-in-class, user-friendly, and completely customizable application enables engineers of all skill levels to receive meaningful results quickly and confidently. For over 50 years, ANSYS Mechanical has been extensively recognized and employed in high- tech sectors i.e., power, aerospace, military, automotive, and electronics. It delivers a dynamic environment based on a highly polished, intuitive, and customizable graphical user interface, with robust meshing and in-built postprocessing capabilities, as well as numerous contact and connection choices. This enables engineers to acquire results fast and precisely, allowing the project to continue schedule. Moreover, in most of the cases, the results obtained on ANSYS Mechanical are found to be very close to the actual. These were the reasons behind selecting ANSYS as the analysis software for this project.

The detailed results obtained from the structural analysis of the various components of the proposed prosthesis has been discussed in the following chapter.

Chapter-6

Results and Discussion

6.1 Topology Optimization

Topology optimization is a mathematical approach for carefully optimizing the distribution of the mass of the material within a defined region by satisfying boundary conditions and thereby reducing the cost. Topology Optimization was used to reduce the quantity of material utilized and the strain energy of constructions while preserving mechanical strength. The housing design, Figure 6.1**,** has been optimized for weight reduction up to 22.3% i.e., from 140.4g to 109.1g. Upper Ankle Block, Figure 6.2, weight was reduced to 30.5% i.e., from 411.3g to 285.5g. Similarly, Cam Profile, Figure 6.3, design has been optimized from 31.25g to 25.3g which accounts for around 19% weight reduction. These optimizations were performed with the help of the popular design and analysis software from Autodesk called Fusion 360.

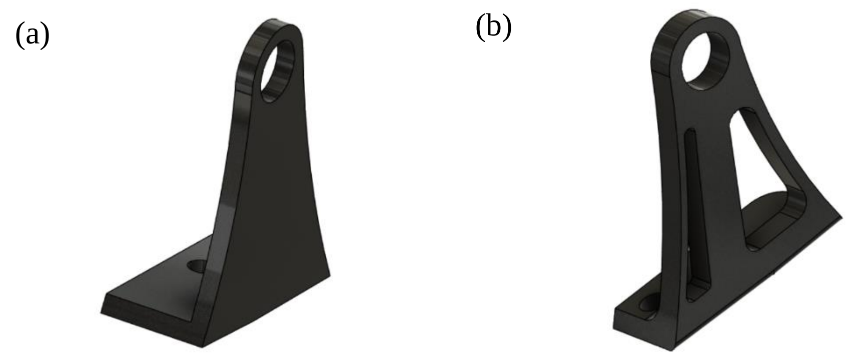

Figure 6.1. Topology Optimization of Housing: (a) Before (b) After

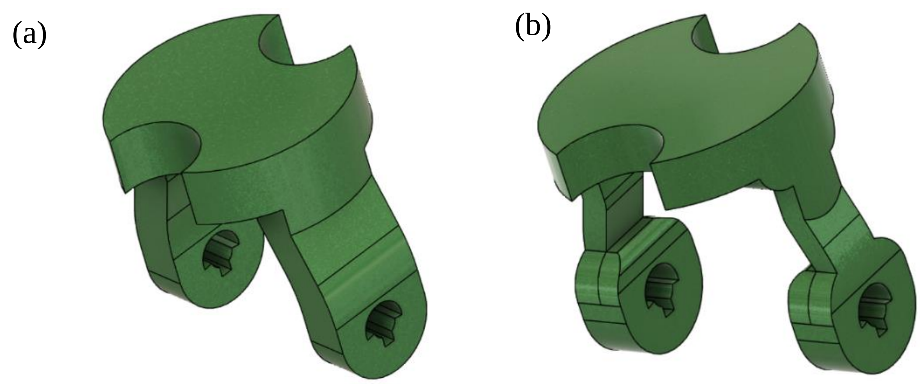

Figure 6.2. Topology Optimization of Upper Ankle Block: (a) Before (b) After

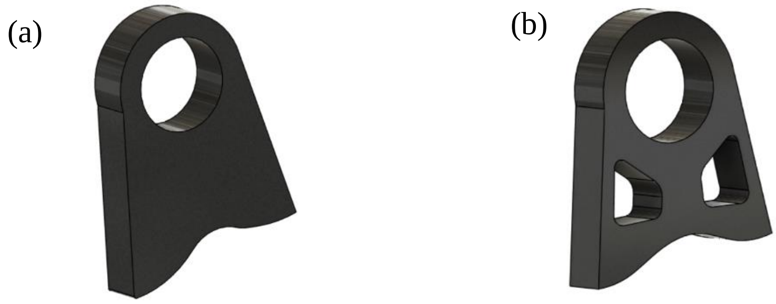

Figure 6.3. Topology Optimization of Cam Base: (a) Before (b) After

6.2 Structural Analysis of Critical Components

The process of calculating and identifying the effects of loads such as stress produced, deformation etc. on a structure, building, object or components under the specified boundary conditions is known as structural analysis. A structural study of the prosthetic foot was undertaken on ANSYS to assess the structure's strength and to verify that the design of the prosthetic foot is strong enough to support the amputee's weight. The structural study of the critical components of the proposed model of the ankle- foot prosthesis was completed. The following relation was used to calculate the Vertical Ground Reaction Force for the suggested design:

$$W = mg \tag{6.1}$$

In the above equation, 'W' is the ground reaction force, 'm' is the amputee's body mass, and 'g' is the acceleration due to gravity. For the purposes of the analysis, the Vertical Ground Reaction Force was determined to be 800N based on the amputee's body mass of 80 kg. To analyze the suggested design, the Von Mises Yield Stress method was used. The yield stress data, as well as the deformation, are shown in Figure 6.4-6.9.

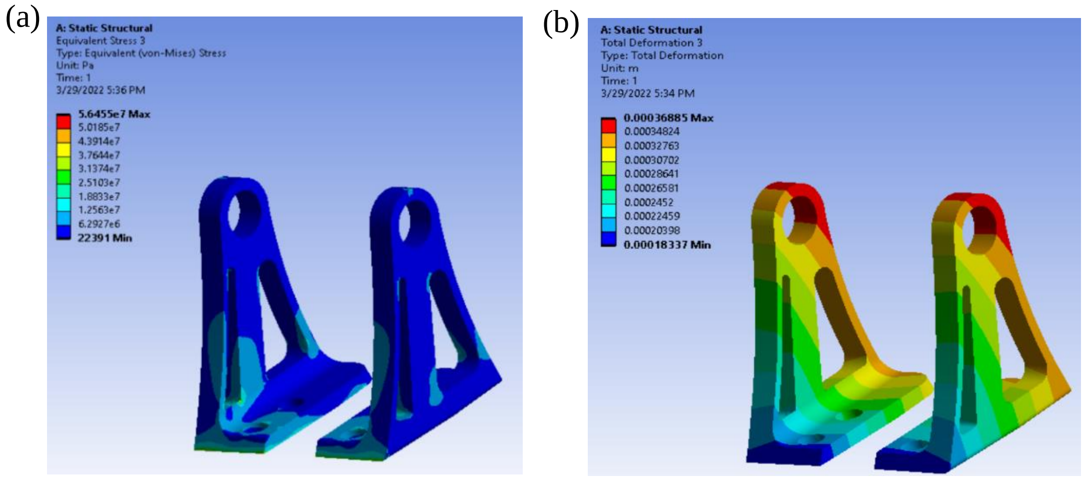

Figure 6.4. Analysis of Housing: (a) Stress Distribution (b) Deformation

Figure 6.4(a) shows the stresses in the Housings, whereas Figure 6.4(b) shows the consequent deformation under static load conditions. The greatest stress achieved within this component is 56.455 MPa. Because the yield strength of the material utilized is 436.2 MPa, the factor of safety is roughly 8. The largest amount of deformation found in the element is 368.85 µm.

(a) (b)

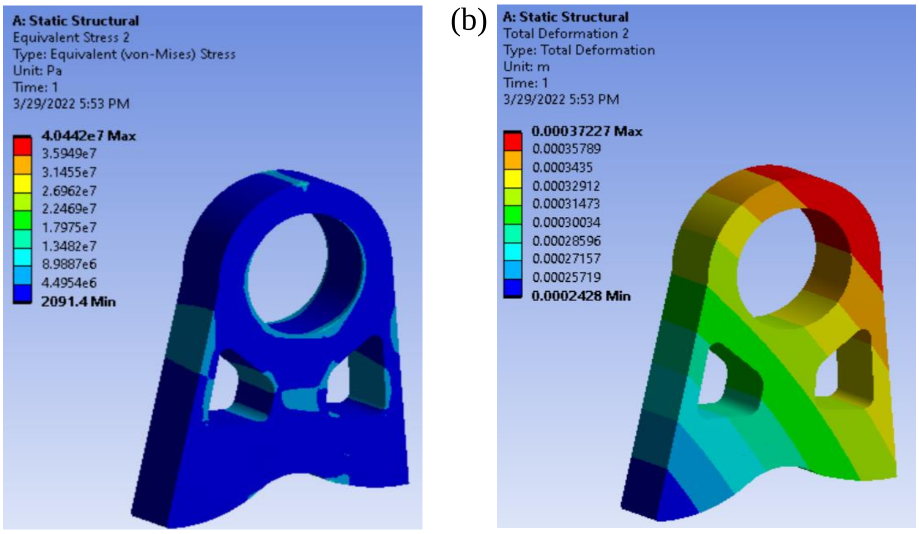

Figure 6.5. Analysis of Cam Base: (a) Stress Distribution (b) Deformation

Similarly, Figure 6.5(a) shows the stress in the Cam base, and Figure 6.5(b) illustrates the displacement during static loading. This component's maximum stress is 40.422 MPa. Because the material's yield strength is 436.2 MPa, it has a factor of safety of roughly 11. The greatest distortion of the component is determined to be 372.27 µm, which may be ignored for practical reasons.

(a) (b)

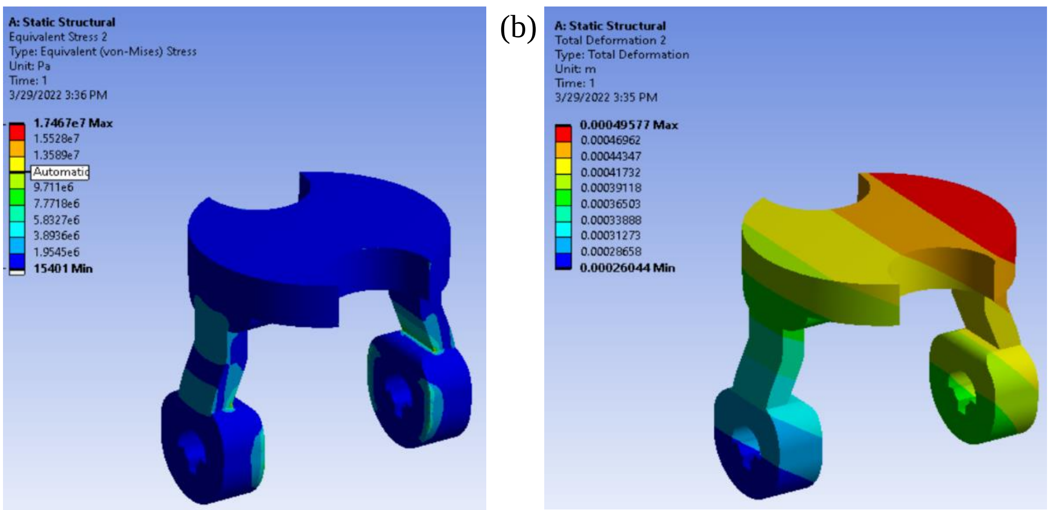

Figure 6.6. Analysis of Upper Ankle Block: (a) Stress Distribution (b) Deformation

The highest stress created in the Upper Ankle Block, as shown in Figure 6.6, is 17.467 MPa, and the related displacement under static loading is 495.77 µm. The material utilized in this element has a yield strength of 436.2 MPa, giving the component a factor of safety of roughly 25. This indicates that the component is safe to use.

As indicated in Figure 6.7(a), the maximum stress within the Leaf Spring is 324.41 MPa. In respect to the yield strength of the material, 440.1 MPa, a FOS of about 1.5 is attained, which might be enhanced in future investigations. Furthermore, as indicated in Figure 6.7(b), the maximum deformation of this element is 313.71 µm, which may be ignored for practical reasons.

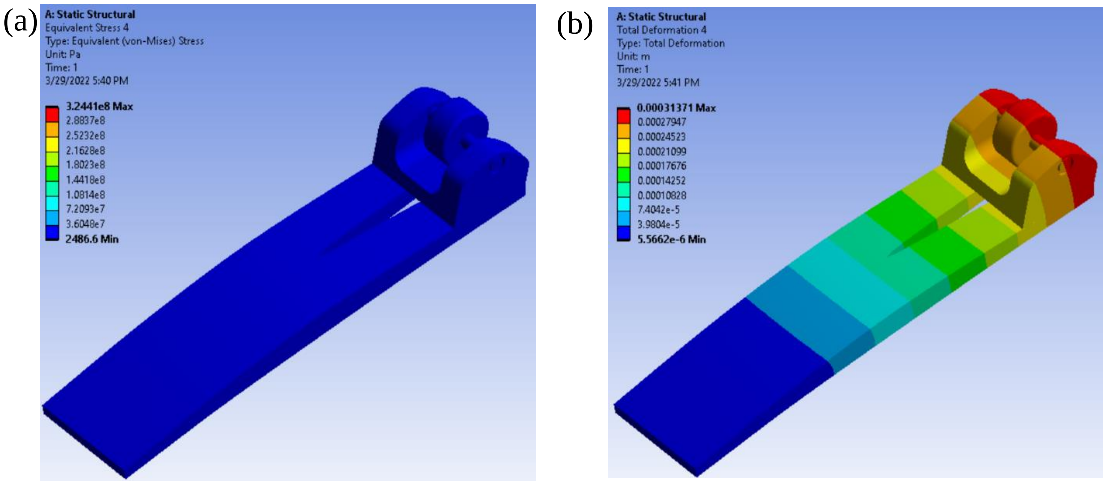

Figure 6.7. Analysis of Leaf Spring: (a) Stress Distribution (b) Deformation

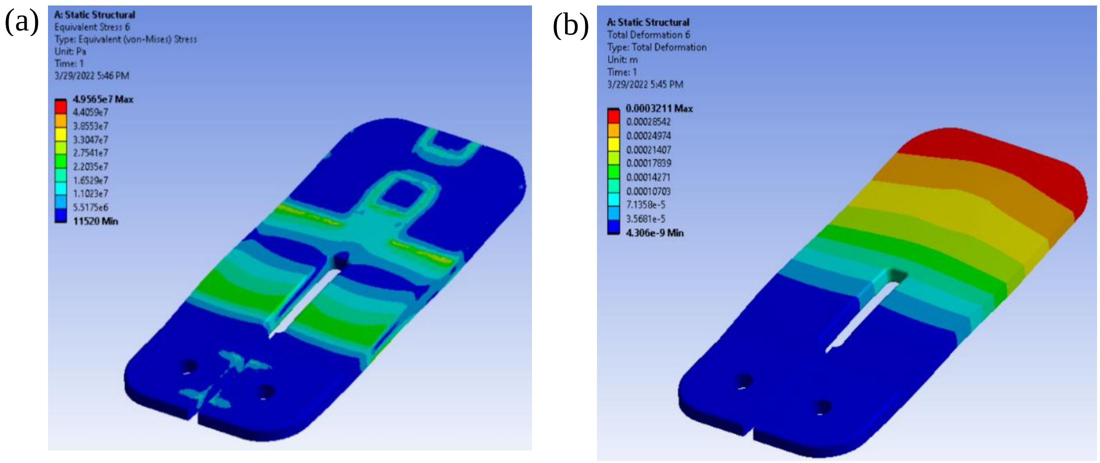

Figure 6.8. Analysis of Slider Support: (a) Stress Distribution (b) Deformation

Slider Support's structural analysis was also completed. Figure 6.8 depicts the tension and displacement caused by this element. The material utilized has a yield strength of 666.7 MPa. According to the study, the maximum stress within the Slider Support is

49.567 MPa. This results in a factor of safety of about 13. The maximum deformation of the Slider Support is 321.1 μm. Finally, Figure 6.9 depicts the structural analysis of the Connecting Link. Figure 6.6(a) depicts the stress, whereas Figure 6.9(b) depicts the displacement caused by the stress during loading. The

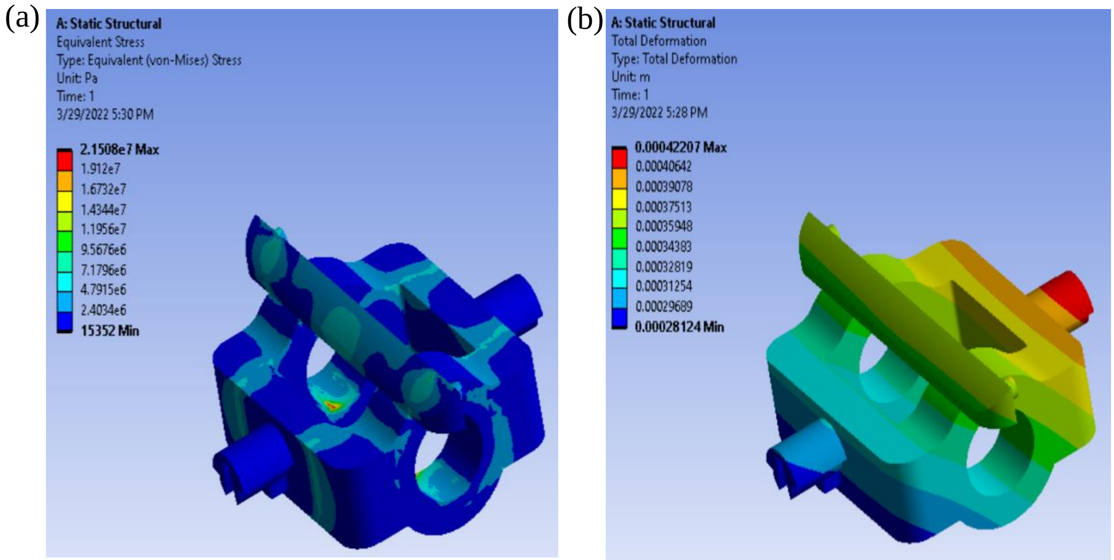

Figure 6.9. Analysis of Connecting Link: (a) Stress Distribution (b) Deformation

largest value of stress found within it is 21.508 MPa. Using the material's yield strength of 436.2 MPa, we get a FOS of roughly 20. The maximum distortion of the Connecting Link was likewise discovered to be 422.07 μm.

6.3 Deflection Analysis of Leaf Spring

The relationship between stiffness and slider position was established using MATLAB. The slider position was set at 50 mm from the fixed end and gradually increased, in the multiple of 10 mm, to 150 mm towards the free end. For the computation, the following equation was employed:

$$F = kx \tag{6.2}$$

Here, 'F' is the force received at the free end of the spring, 'k' denotes the stiffness of the Leaf Spring material, and 'x' is the amount of deflection in the Leaf Spring. The amount of deflection at the intervals observed in this investigation was derived from the leaf spring's structural analysis which was done prior to this. The acquired result is represented in the graph shown in Figure 6.7. It is clearly seen in the graph that initially, the stiffness increases linearly for up to 70% of length of the spring, however, as the slider approaches the free end of the leaf spring, the stiffness increases exponentially.

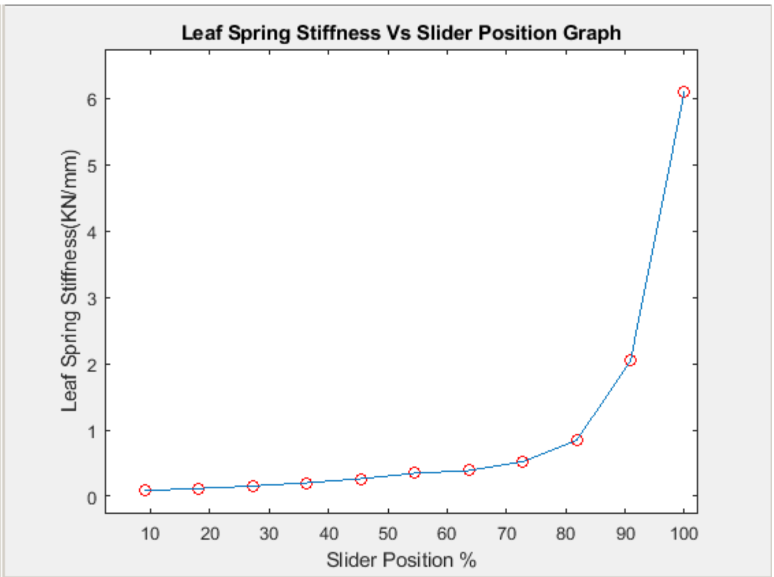

Figure 6.10. Stiffness Vs Slider Position Graph

6.4 Properties of the Prosthesis

As indicated in Table 1, the dimensions of the created prosthesis nearly resemble those of the biological ankle-foot. This is required and desirable since the prosthesis would be an exact replica of the missing limb. Another vital characteristic of the prosthesis is the adjustable stiffness. The right stiffness is determined mostly by a patient's body weight, the activities he or she chooses, and the intensity degree of those activities. An incorrect stiffness selection can result in higher metabolic expenditures, irregular activation patterns of muscles, poor gait symmetry, tissue damage from abnormal residual- limb and intact-limb loads, and discomfort. The proposed prosthesis provides amputees with the adjustable mechanism for it. Similarly, 2DOF aids in to achieve different natural-foot-like motions. The proposed ankle foot, when fitted with a suitable length and type of pylon and the socket, can be worn very comfortably by the amputees. The design also incorporates the features of a SACH foot and an ESR foot. Structural analysis tests of components show that the prosthesis is safe to use for the amputees of body weight 80 kg. The acquired weight of the prosthesis was determined to be roughly 2 kg with all of the materials utilized in the 3D model of the prosthetic foot. Since the weight of a typical foot is believed to be 2.5% of body weight[37], considering 80 kg as body weight as mentioned before, the weight of a whole ankle-foot structure would be roughly 2 kg. As a result, the weight of the prosthesis is approximately identical to that of the natural ankle.

Chapter- 7
Conclusion and Future Work

7.1 Conclusion

This research work presents a new design and structural analysis of a passive ankle-foot prosthesis with two Degrees of Freedom and manually adjustable ankle stiffness. The prosthesis has a leaf spring with adjustable stiffness for plantarflexion and dorsiflexion movements. For inversion-eversion motion, an extra degree of flexibility is recommended in this passive prosthesis. Furthermore, the design incorporates several distinguishing traits of an ESR and a SACH foot. Although all these properties of the prosthesis are highly desirable to closely resemble an entire human ankle-foot complex, these are not integrated in one design in the existing passive ankle-foot. This research work has successfully filled that gap. Further, the structural analysis of crucial parts of the prosthesis revealed that the prosthesis can sustain ground reaction forces because of the amputee's weight during application with significant value of factor of safety. Finally, the effect of slider position on the stiffness of the prosthesis' leaf spring was examined to validate the range of stiffness that can be obtained during the usage.

7.2 Future Work

Even though the suggested prosthesis nearly mimics the functioning of the normal ankle-foot, more research is needed to refine the design for different terrain conditions. Moreover, future studies may include a more detailed assessment of the impacts of stiffness and links movements during various mobility activities, as well as the implications of stiffness on the metabolic cost of transportation (COT) or walking with the help of mathematical modeling. The work may also be required to validate the selection of materials based on parameters such as availability, affordability, and load requirements during various foot activities. Furthermore, a prototype of the same can be developed to verify the results obtained from the FEA. Finally, to end the methodological development loop, future work is needed to link the prototypes to user experiences.

List of Publications/Conference Papers

1.

Name of the Conference	International Conference on Materials Science and Sustainable Manufacturing Technology 2022 (ICMSSMT 2022)
Date of Conference	20/05/2022 to 21/05/2022
Venue of Conference	Coimbatore, Tamilnadu, India
Organizer	Sri Eshwar College of Engineering, Coimbatore, Tamilnadu, India
Name of the Publisher	Materials Today: Proceedings
Research Title	Design and Structural Analysis of a Passive Ankle-Foot Prosthesis with Manually Adjustable Stiffness and having Two Degrees of Freedom
Status of the Research Paper	Reviewers' comments received

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Abstract

Every year, more than one million limbs are amputated throughout the world. Many nations have so conducted theoretical and experimental investigations to produce prostheses to assist ease the pain of people with severed limbs. When it comes to the Below Knee Prosthetics (BKP), even the most modern commercial transtibial prosthesis on the market today, only passively alter the ankle position during the swing phase of gait and return a fraction of the user's own gravitational input. To significantly enhance a transtibial amputee's quality of life, new technologies and methodologies must be applied to develop a cutting-edge ankle prosthesis that can function on par with, if not surpass, the corresponding able-bodied human ankle. The majority of commercial BKP in the market today are Passive Prosthetics because they are lightweight, inexpensive, durable, and need little care. Because the human ankle is a complex collection of joints, ankle design is the most important part of the Below Knee (transtibial) prosthesis design procedure. The talocrural joint (which permits dorsiflexion-plantarflexion) and the subtalar joint (which allows inversion-eversion) are important joints in the ankle. The aforementioned two joints give the amputee with the necessary two degrees of flexibility (2 DOF). This study focuses on building and analysing a Passive Ankle-Foot Prosthesis with 2 DOF to replicate the behaviour of a natural missing limb. Furthermore, this work highlights the incorporation of manual ankle stiffness modulation into the design for dorsiflexion-plantarflexion, which may be changed by the amputee to a chosen stiffness for different ambulation requirements. The design offered in this study also incorporates key aspects of an ESR and a SACH foot; moreover, a keel design with greater terrain adaptation is recommended. As the weight of the individual user controls the engagement and disengagement of the artificial ankle joint during the gait cycle, the same consideration has been made throughout the analysis of the model. The effects of the location of fulcrum on the stiffness of the prosthesis is also analysed in this study under deflection analysis. The analysis shows that the stiffness of the leaf spring increases linearly for up to 70% of its length as the fulcrum moves towards the free end, however, the stiffness starts increasing exponentially as the fulcrum moves closer to the free end. Primarily, this research work offers a novel design of a passive ankle-foot prosthesis with adjustable ankle stiffness and 2 DOF; moreover, structural analysis demonstrates that the device can sustain a load of 800N with a FOS of 1.5, providing amputees with optimum safety and comfort.

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