DESIGN AND STATIC STRUCTURAL ANALYSIS OF LOWER LIMB ORTHOSIS FOR POSTURAL PROBLEMS

A Project report submitted in partial fulfilment of the requirements
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Submitted by

V. PRATHYUSHA	**319126520057**
G. MURARI	**319126520013**
M.P. SANDEEP	**319126520027**
P. RAM KUMAR	**319126520036**
G. NIKHIL	**319126520012**

Under the Esteemed Guidance of

Dr. M. PRASANTH KUMAR MTech., Ph.D.
Associate Professor

DEPARTMENT OF MECHANICAL ENGINEERING
ANIL NEERUKONDA INSTITUTE OF TECHNOLOGY & SCIENCES (A)
(Permanently Affiliated to Andhra University, Approved by AICTE, Accredited by NBA Tier-I, NAAC)
Sangivalasa, Visakhapatnam (District) Andhra Pradesh -India– 531162.

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DEPARTMENT OF MECHANICAL ENGINEERING
ANIL NEERUKONDA INSTITUTE OF TECHNOGY & SCIENCES
(UGC Autonomous & Permanently Affiliated to Andhra University)

CERTIFICATE

This is to certify that the Project Report entitled **"Design and Static Structural Analysis of a Lower Limb Orthosis for Postural Problems"** being submitted by **V.Prathyusha (319126520057), G.Murari (319126520013), M.P.Sandeep (319126520027), P.Ram Kumar (319126520036), G.Nikhil (319126520012)** to the Department of Mechanical Engineering, ANITS is a record of the bonafide work carried out by them under the esteemed guidance of **Dr. Prasanth Kumar.** The results embodied in the report have not been submitted to any other University or Institute for the award of any degree or diploma.

Project Guide	**Head of the Department**
	17.4.23
Dr. PRASANTH KUMAR Associate Professor Dept. of Mechanical Engineering, ANITS	**Dr. B. NAGA RAJU** Professor Dept. of Mechanical Engineering ANITS

THIS PROJECT IS APPROVED BY THE BOARD OF EXAMINERS

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V. PRATHYUSHA	**319126520057**
G. MURARI	**319126520013**
M.P. SANDEEP	**319126520027**
P. RAM KUMAR	**319126520036**
G. NIKHIL	**319126520012**

ABSTRACT

An exoskeleton is an external skeleton that provides strength and support to human body. A powered exoskeleton known as powered suit is a wearable mobile machine that is energized by approach of hydraulics, pneumatics, electric motors, or a combination of systems that allow for limb movement with increased strength and tolerance. An exoskeleton works on the principle of mechanical gear and motor system which provides an increasing amount of support as the user lifts his or her arm. Its design aims to provide back support, sense the user's motion, and send a signal to motors which manage the gears.

Lower Limb exoskeletons are those that help users to accomplish the tasks of everyday life that they are unable to do. A lower limb Exoskeleton is manufactured by the combination of actuators, sensors, materials, batteries and computer processors. Even though there are many exoskeletons manufactured all around the world, they are not enhanced in India as these are too expensive. Hence our main intention is to deduct the cost as much as possible and made it available to the people at low cost.

Lower Limb Exoskeletons plays a major role in helping the elderly people. Not only in completing the daily activities but also, they are very much useful in medical purposes where functionality is limited or lost and these can also be used by the people who met with accidents like amputees. Hence, we are designing a lower limb orthosis for postural problems in elderly people.

Keywords: *Exoskeleton, Postural Phases, Strength, Static Structural Analysis, Modal Analysis.*

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CHAPTER-1

INTRODUCTION

A lower limb exoskeleton, also known as a lower limb orthosis, is a wearable device that is designed to provide support and assistance to individuals with lower limb weakness or paralysis. Exoskeletons typically consist of a frame that attaches to the user's legs and feet, as well as motors or other mechanisms that provide powered assistance to walking and standing. Some exoskeletons are controlled by the user through sensors or other input methods, while others are controlled by a physical therapist or other trained professional. Lower limb exoskeletons can be used for a variety of purposes, from allowing individuals with spinal cord injuries to walk again to providing support and assistance to people with muscular dystrophy. They can also be used in rehabilitation settings to help individuals regain strength and function in their lower limbs.

In the field of lower limb exoskeletons, structural static characteristic analysis using finite element modelling is a useful method for evaluating the performance and design of exoskeletons. Finite element modelling is a computational method used to analyse the stresses, strains, and forces that act on a structure under various loads and conditions. This method involves dividing a complex structure into smaller, simpler elements that can be analysed individually. Each element has certain properties, such as stiffness and strength, that are used to calculate its response to different loads. In the context of lower limb exoskeletons, finite element modelling can be used to assess the structural integrity and load-bearing capacity of key components such as the frame, joints, and actuators. This analysis can help designers optimize the design of the exoskeleton to ensure it can withstand the loads and forces it will experience during its use ,while minimizing its weight and bulk.

By using finite element modelling to analyse the structural static characteristics of lower limb exoskeletons, researchers and engineers can make informed decisions about the design and construction of these devices. This can help to improve the performance, safety, and comfort of lower limb exoskeletons, making them more effective for individuals with lower limb weakness or paralysis.

The use of finite element analysis tools like ANSYS is an effective way to perform statics analysis of lower limb exoskeletons. This type of analysis provides valuable insights for optimizing the design and performance of exoskeletons.

One of the key benefits of using ANSYS for this type of analysis is that it allows for the simulation of the exoskeleton under different loading conditions. Different loading scenarios like walking, running, climbing stairs, and standing can be simulated to determine the maximum stresses and strains that the exoskeleton will experience.

The software also allows for the creation of detailed 3D models of the exoskeleton components using CAD software. These models can then be imported into ANSYS for simulation. ANSYS can compute various quantities of interest like the displacements, stresses, and strains on the components of the exoskeleton.

Furthermore, ANSYS provides an efficient and effective way to optimize the design of the exoskeleton by analysing multiple design configurations. This can be done by creating a parametric model that allows for the automatic generation of many different design variations. The software can then simulate each design variation and automatically choose the optimal design based on a specific set of criteria like weight, comfort, and strength.

In summary, using finite element analysis tools like ANSYS can help engineers and researchers to analyse the statics characteristics of lower limb exoskeletons. This analysis can help to optimize the design and ensure that the exoskeleton is safe and effective for its intended use.

Modal analysis is an important technique for designing and analysing lower limb exoskeletons, particularly with regards to understanding how the exoskeleton will respond to vibrations and other dynamic loads.

When designing a lower limb exoskeleton, it is critical to ensure that the device will not cause unnecessary vibrations or resonance. Modal analysis can help determine the natural frequencies, mode shapes, and damping ratios of the exoskeleton, which will provide insights into how the device will behave when subjected to dynamic loads.

Modal analysis involves applying an external force or displacement to the exoskeleton and measuring the resulting vibrational response. By applying various frequency sweeps and analysing the amplitude and phase of the response, engineers can determine the natural frequencies and mode shapes of the exoskeleton.

One of the key benefits of modal analysis is that it can be used to identify problematic areas in the exoskeleton and suggest design changes to improve the device's vibrational behaviour. For example, by identifying areas of high stress or strain during vibration, engineers can modify the design to reduce these stress or strain levels, improving the device's overall performance and reducing its susceptibility to damage.

Overall, modal analysis is an essential tool for designing and analysing lower limb exoskeletons. It provides valuable insights into the dynamic behaviour of the device and helps to ensure that the exoskeleton is safe, effective, and capable of meeting the requirements of its intended application.

1.1 Functions of Exoskeleton

The exoskeleton is an external skeleton that provides support, protection, and structure for many invertebrate and some vertebrate organisms. Here are some functions of exoskeletons:

A. **Protection:** The exoskeleton provides a tough outer layer that helps protect the organism from physical damage, predators, and environmental stressors.

B. **Support:** The exoskeleton also provides structural support, giving the organism a rigid framework that can support its weight and movement.
C. **Movement:** Muscles are attached to the exoskeleton, allowing the organism to move its limbs and body segments.
D. **Sensory input:** The exoskeleton can also serve as a sensory receptor, detecting touch, pressure, and temperature changes in the environment.
E. **Water retention:** Some organisms, such as insects, use their exoskeletons to retain water, preventing dehydration in dry environments.
F. **Moult:** The exoskeleton is shed and replaced periodically during the growth and development of many organisms, allowing for continued growth and development.

Overall, the exoskeleton plays a critical role in the survival and success of many organisms, providing protection, support, and mobility while also serving as a sensory receptor and allowing for continued growth and development.

Fig. 1.1 Exoskeleton

1.2 Applications of Exoskeleton

Exoskeletons are wearable devices that can augment or enhance human physical abilities, providing support, strength, and endurance. Some of the applications of exoskeletons include:

A. **Medical Rehabilitation:** Exoskeletons can be used for rehabilitation of patients with neurological and orthopaedic injuries. They can provide support and assistance to patients during walking, standing, and other movements, allowing them to regain their mobility and strength.
B. **Industrial Manufacturing:** Exoskeletons can help reduce fatigue and injury in workers who perform repetitive tasks, such as lifting heavy objects or working in awkward positions. They can also improve productivity and reduce the risk of workplace injuries.
C. **Military and Law Enforcement:** Exoskeletons can enhance the physical capabilities of soldiers and law enforcement personnel, improving their endurance, strength, and agility. They can also provide protection against injuries and improve their mobility in difficult terrain.
D. **Sports and Fitness:** Exoskeletons can be used to improve athletic performance, providing additional support and strength to athletes during training and competition. They can also help people with disabilities participate in sports and other physical activities.
E. **Personal Mobility:** Exoskeletons can be used to assist people with mobility impairments, such as those with spinal cord injuries, allowing them to stand, walk, and move independently.

1.3 Types of Exoskeletons

Exoskeletons can be classified into several types based on their design, materials used, and application. Here are some common types:

A. **Soft exoskeleton**: soft exoskeletons are made of flexible materials such as fabric, foam, or elastomers. They are typically worn like a garment and provide support and assistance to the wearer's muscles and joints.
B. **Rigid exoskeleton:** Rigid exoskeletons are made of hard materials such as metals or composites. They provide structural support to the body and are often used in applications such as rehabilitation or industrial settings.

C. **Powered exoskeleton:** Powered exoskeletons use electric motors or hydraulic systems to augment the wearer's strength and mobility. They are often used in military, industrial, or medical applications.
D. **Hybrid exoskeleton:** Hybrid exoskeletons combine elements of both soft and rigid exoskeletons. They provide a balance between flexibility and support, and are often used in rehabilitation or athletic training.
E. **Bio-inspired exoskeleton:** Bio-inspired exoskeletons are designed to mimic the movements and mechanics of natural organisms. They often use advanced sensors and control systems to adapt to the wearer's movements and environment.

1.4 Actuators systems used in Exoskeleton

Exoskeletons use various types of actuator systems to provide mobility and support to the wearer. Here are some common types of actuator systems used in exoskeletons:

A. **Electric motors:** Electric motors are commonly used in powered exoskeletons to provide torque to the joints. They can be either DC motors or brushless motors, depending on the application.
B. **Pneumatic systems:** Pneumatic systems use compressed air to power the exoskeleton's actuators. They are often used in industrial exoskeletons for heavy lifting tasks.
C. **Hydraulic systems:** Hydraulic systems use pressurized fluid to power the exoskeleton's actuators. They are often used in powered exoskeletons for medical rehabilitation or military applications.
D. **Shape memory alloys:** Shape memory alloys (SMAs) are materials that can change shape when exposed to heat. They are often used in soft exoskeletons to provide shape-changing properties to the material.
E. **Springs:** Springs can be used to store and release energy in the exoskeleton's joints. They are often used in passive exoskeletons that provide support and assistance to the wearer's movements.

CHAPTER-2

LITERATURE REVIEW

Before going with the project, a brief study on papers related to exoskeleton design and analysis done. Many authors presented different views related to their works on the analysis and design of exoskeleton.

Shubham S. Kawale *et.al* (2018), [1] described that wearable lower-body exoskeletons are used by shipbuilding workers to lessen lower-body stress while they execute lower-body fatigue-oriented tasks including welding, sandblasting, grinding, and painting, among others. This design's goal is to lessen physical exhaustion while carrying a heavy load without experiencing too much difficulties.
In this study, the concept design, kinematic analysis, and dynamic studies are presented. The Lagrangian energy approach is used to derive the equations of motion, and design factors are optimised based on the findings of the kinematic and dynamic analysis to produce an exoskeleton system that is both energy-efficient and small. To achieve the needed gait patterns, an appropriate control system will be created, and after that, a functional prototype will be built and tested.

Hoda Mahmoud Saleh Samir *et.al* (2020), [2] described that in order to design an active upper-body exoskeleton for industrial applications, specifically load handling, this thesis will employ a human-centred approach. The exercise involves moving a 25 kg load 30 mm up from a certain height while walking a predetermined distance (800 mm). This was accomplished by investigating and adhering to the most recent and pertinent engineering standards, followed by a biomechanical analysis of the human upper body and a number of loads lifting techniques, with an assessment of their effects on various body parts and parameters, and using this information as an additional guideline to develop a computer-aided design that can achieve the required range of motion.

Gao, Moyao *et.al* (2021), [3] described that the article presents a knee exoskeleton design that focuses on human comfort to aid knee joint recovery. The design is based on a bionic knee exoskeleton structure using a cross four-bar linkage component to mimic the movement of the human knee joint. An engine drives the adjustable pole to reproduce the movement of the thigh muscle, and a locking structure prevents hyperextension of the knee joint. The particle swarm-based algorithm is used to optimize the size and position of the connecting bar of the cross four-bar linkage to better mimic the human knee joint movement. The results show that the improved cross four-bar linkage component can better imitate the human movement characteristics of the knee joint and improve coordination and flexibility with human joint movement. The wearer test showed that the design has a variable quick focus of turn direction, which can achieve consistency with the human knee joint movement and improve wear comfort during the rehabilitation process.

Deepak Kumar S *et.al* (2017), [4] described that working on the strength, speed, and perseverance through wearable assistive gadgets has been the fantasy of people for a considerable length of time. A few innovations have been created towards that fantasy. A significant objective of the field of robot-helped development preparing is to foster a light and strong mechanical arm exoskeleton. Numerous exoskeleton plans exist however none have coordinated or surpassed the capacities of the human arm as far as inactivity, strength, force-control capacity, and scope of movement. Mechanical exoskeleton is getting essential to human in numerous perspectives, for example, power help, muscle preparing, recapture engine capability and restoration. The innovative work towards these capabilities is supposed to be consolidated and incorporated with the human canny and machine power, in the end turning into one more age of robot which will improve the machine astute and human power. The objective of this task is to plan and manufacture a mechanical exoskeleton for work expansion. The exoskeleton should be made compact and as light as conceivable to give solace to the individual. The sort of exoskeleton picked is a furthest point exoskeleton.

Akash Gupta *et.al* (2019), [5] described that the kinematics and joint position analysis of a 3 DOF upper-appendage mechanical exoskeleton, as well as the feasibility of using computed torque control for the exoskeleton. The goal of the development of the exoskeleton is to improve the quality of life for individuals with stroke or spinal cord injuries. The exoskeleton is designed to mimic the three most important movements of the human arm for activities of daily living, with design parameters taken from a typical individual's upper limb. The computed torque control is applied to the system to move the exoskeleton to desired joint positions. Results show that the computed torque control successfully reduces errors in the exoskeleton joint positions.

Luis I. Minchala *et.al* (2017), [6] described that a lower appendage exoskeleton mechatronic plan for patients suffering from lower body paralysis due to spine injuries or stroke. The mechanical design is presented and validated through dynamical simulations. A communication network design is proposed for a secure and fast data interface between sensors, actuators, and microchips. The patient-exoskeleton system interaction is also presented and detailed. Development is done through digital signal processing methods applied to EMG and EEG signals. The communication system design is tested and evaluated in MATLAB, and a proposal for real-time regulatory control is also presented as part of the integration of each component of the exoskeleton.

Qiang Yan *et.al* (2018), [7] described that a proposed unpowered exoskeleton that aims to enhance the load-bearing capacity of the wearer. The design of the exoskeleton is explained, along with an analysis of the number of connections and kinematic joints. The forward position analysis of the exoskeleton for the swing leg is obtained using MATLAB. The static force analysis of the supporting leg for the exoskeleton is also obtained. The text further discusses the genetic algorithm used to obtain the optimal stiffness of the spring for the energy-restoring device. Finally, the changes in power and force for the supporting leg of an individual wearing and not wearing the exoskeleton are compared, leading to some conclusions.

Lalchand Kumawat *et.al* (2021), [8] described that the design and development of a full-body, rigid, dynamic, performance-type exoskeleton model for use in the business, defence, and civil sectors. The paper focuses on the design philosophy, mechanical construction, and selection of the actuation system for the prototype, which was validated using Ansys Workbench and Altair Transition Engine. The "walk" cycle and its phases were also analysed using Opensim to guide the actuation of the model using strain gauge belts attached to the user's muscles. The exoskeleton uses four different control drivers for actuation, with a customized control drive for the thigh joint. The battery system uses high-performance Lithium-ion cells, and a common aluminium heat sink is used for cooling. The article also considers factors such as cost-effectiveness, minimal maintenance, ergonomics, efficiency, and safety in the design process. The final prototype had a weight of 79 kg and was able to lift and move at 1.36 m/s with a payload of 258 kg.

V. Mohan Srikanth *et.al* (2017), [9] described that lower body Exoskeleton is only seat less seat utilized in Businesses. Individuals who are working in Industry can wear it on legs like Exoskeleton. A mechanical ergonomics gadget is planned by the shape and capability of the human body. It's anything but a seat yet it behaves like a seat. The idea of this seat less seat is the point at which it initiates you can walk. And afterward assuming that it is inert, it gets into place from a point of 900, 1200 and 1500 and you can plunk down on it. It is primarily utilized for modern specialists, representing a significant stretch of time prompts inconvenience and diminish efficiency. In this way, Plan and Examination is a significant boundary to realize the powers prompted in every component and actuators.

Fangzheng Wang *et.al* (2019), [10] described that the wearable lower appendage power mechanical exoskeleton is a device designed to improve human walking ability. The paper describes a new exoskeleton for the knee joint, which includes improvements to the mechanical structure and hydraulic chamber. To test the effectiveness of the hydraulic chamber, experiments were conducted. The new design includes a length adjustment device and a cut-off device for the knee joint to improve safety and comfort. The model's dynamics were calculated using Lagrange and laid out for ADAMS motion simulation. The hydraulic chamber's power was compared with the power of the previous version, and a significant improvement of 8% was achieved. The simulation was validated through wear tests, which showed that the exoskeleton device could effectively follow human motion. The study provides useful parameters for production and a theoretical basis for future control theory.

Swapnil Manyar *et.al* (2021), [11] described that the mechanical exoskeleton frameworks are grown fundamentally to be utilized for human power help and haptic cooperation with human Movement. The planned pneumatic arm comprises of two sets of chambers both the sides, a shaft exertion with lead screw component capable of switching a development of cylinder over completely to rotational development of arm by using the packed air from pneumatic framework. The planned cycles of the suit are completed in view of some coordinated data of kinematic, elements and underlying examination of the ideal exoskeleton design in general. The very unique pneumatic arm rendition can be basically place up at not many transitional spots by controlling the strain utilizing the stream control valve. This exoskeleton frameworks can be utilized for truly difficult work (pick and spot) of articles in industry, can be utilized along mechanical production system in different processing plants (e.g., For example, vehicle painting robots), salvage missions to clear the fallen designs. Since, such exoskeleton straightforwardly collaborates with a human body there are a few mechanical constraints to its plan. While planning such exoskeleton portable scope of arms, wellbeing and solace Wearing, low dormancy, versatility is thought of. This paper momentarily surveys the usefulness and plan of pneumatic framework-based water driven arms exoskeleton frameworks.

Philippe Malcolm *et.al* (2013),[12] described that the use of exoskeletons to reduce the metabolic cost of walking. The researchers aimed to determine if adjusting the activation timing of a pneumatic exoskeleton could result in a higher reduction in metabolic cost. They measured the metabolic cost of walking with and without the exoskeleton and found that the exoskeleton can reduce metabolic cost by 6.62% below the cost of walking without the exoskeleton, assuming activation starts just before opposite leg heel contact. This timing aligns with a mathematical model of walking. While the current exoskeleton is not ambulatory, the researchers suggest that future ambulatory exoskeletons could be built to reduce metabolic cost without power supply limitations by reusing energy from knee expansion deceleration work.

Andrew Chu *et.al* (2005), [13] described that many spots on the planet are excessively rough or encased for vehicles to get to. Indeed, even today, material vehicle to such regions is restricted to difficult work and pack animals. Present day headways in wearable mechanical technology might make those strategies outdated. Lower furthest point exoskeletons look to enhance the insight and tactile frameworks of a human with the critical strength and perseverance of a couple of wearable mechanical legs that help a payload. This paper frames the utilization of Clinical Step Examination information as the structure for the plan of such a framework at UC Berkeley.

Manoj M. Jadhav *et.al* (2021), [14] described that exoskeleton is fundamentally a wearable mechanical component in which the gadget works in worry with the client's development. Need of which emerge because of wounds to works through weight and weight powers of different works. The reason to utilize this system is to diminish the anxieties created due to lifting, conveying the weighty parts, and so forth, and to keep away from outer muscle problems. This study is to foster a lower body exoskeleton for strolling reason in industry. Plan of gadget is made appropriately thinking about following focuses: Idea plan, Parts required, Estimations in plan, actually looking at plan security. Examination of configuration is done on ANSYS and it were breaking down: Burden applied, Stresses at different places, most extreme and least anxieties, Misshapen Ings at different areas, meeting of plan prerequisites with real plan to follow boundaries. This is the means by which the end is made considering the work that the arrangement of exoskeleton to reinforce and satisfy necessities of 80kg human by giving adequate tension and incitation to the movement to be done.

Shaik Mubarak Basha *et.al* (2018), [15] described that the exoskeleton is a wearable mechanical component designed to provide human prosthetic lower limb support and help reduce fatigue and increase productivity in workplaces that require standing for extended periods of time. Unlike machines, humans have limitations and require comfort and convenience, which is why the Exoskeleton was developed to meet these needs. It is compact, lightweight, and designed using modern manufacturing techniques such as Solid Works, DELCAM, CNC-VMC, and simulation analysis. To reduce weight, it is constructed using high-strength, low-density materials such as Aluminium Composite 6082. Overall, the Exoskeleton is a unique and innovative solution to improve the working conditions of individuals in physically demanding jobs.

Ionut Daniel Geonea *et.al* (2017), [16] described that the article describes a new exoskeleton solution designed to provide assistance for human leg movement and rehabilitation. The exoskeleton is human-friendly, structurally simple, low-cost, and easy to adapt to the human body. The article focuses on the mechatronic structure of the exoskeleton, which was designed using SolidWorks, and the mathematical simulation performed using MSC.ADAMS. The simulation results were compared to the results obtained from the walking of a healthy subject. The feasibility of the exoskeleton model was analysed from both design and operation perspectives.

Brian Flynn *et.al* (2016), [17] described that the use of rehabilitative exoskeletons in aiding stroke patients to re-learn how to walk. Over 795,000 individuals in the US suffer from strokes each year, leading to neurological damage that affects their ability to walk without assistance or rehabilitation. Rehabilitative overground stride training, often performed using portable exoskeletons such as the Hybrid Assistive Limb (HAL) and ReWalk, can help with body weight compensation support and modified sound walk movements. Clinical trials are performed to determine the efficacy of these exoskeletons, focusing on patient feedback and improvement in walking speed or ease. However, the article argues that it is important to also analyze the kinematic and dynamic data of the exoskeletons, and various methods such as forward and reverse kinematics, dynamics procedures, and the bond diagram method are being applied to the design of lower-limb exoskeletons for clinical stride restoration. The article emphasizes the importance of evaluating the effects of a device affected by internal and external forces and capable of adjusting its aspects.

Kai Yang *et.al* (2018), [18] described that the development of a recovery exoskeleton robot for leg recovery after knee joint replacement surgery. The design is based on the genuine necessities of restoration preparing after the surgery and considers ergonomics and the possibility of representation plan. The robot is intended to recognize the development pattern of the human body, decide the movement goal being used, and advance the development of the rear leg for knee joint recovery. The passage additionally mentions the modular investigation of the lower appendage recovery exoskeleton robot, which has led to the acquisition of the initial six order normal frequencies and vibration modes.

Scope of the work:

From the above works, it is observed that all researchers' work contributes towards the use of power assisted, automatic control exoskeleton system. This type of exoskeletons uses actuator system of motors that is electrically powered to obtain locomotion. To develop such systems, the initial step carried out is to obtain human gait analysis. The human gait analysis represents a cyclic motion between heel strike on ground and next ground contact of same heel. These exoskeleton systems are developed to increase consistency among patients, as well as reduce the workload of, or increase the effectiveness of professional rehabilitative workers.

CHAPTER-3

OBJECTIVES AND METHODLOGY

3.1 Objectives

- To study human gait cycle analysis and obtain the extension/flexion angles of hip, knee and ankle joints.
- To design a lower limb orthosis structure using SolidWorks for dimensions required.
- To determine the forces acting on the thigh and shank links of the lower limb orthosis using theoretical calculations.
- To determine the stresses acting on the lower limb orthosis caused due to human body weight and buckling load using theoretical calculations.
- To perform static structural analysis and determine the maximum deformation, maximum equivalent stress, maximum equivalent strain using Ansys Workbench.
- To perform modal analysis and determine the maximum deformation of the lower limb exoskeleton for five different modes.

3.2 Methodology

The Fig. 3.1 shows the approach taken to adequately address the breadth and depth of the research objectives involved conducting a detailed literature review. The literature review focused on collecting information about lower limb exoskeletons and their functions, which are relevant to the research project. The scope of the literature review is not specified in the statement. However, the outcomes of the literature review were used to refine the research gap for the surveys.

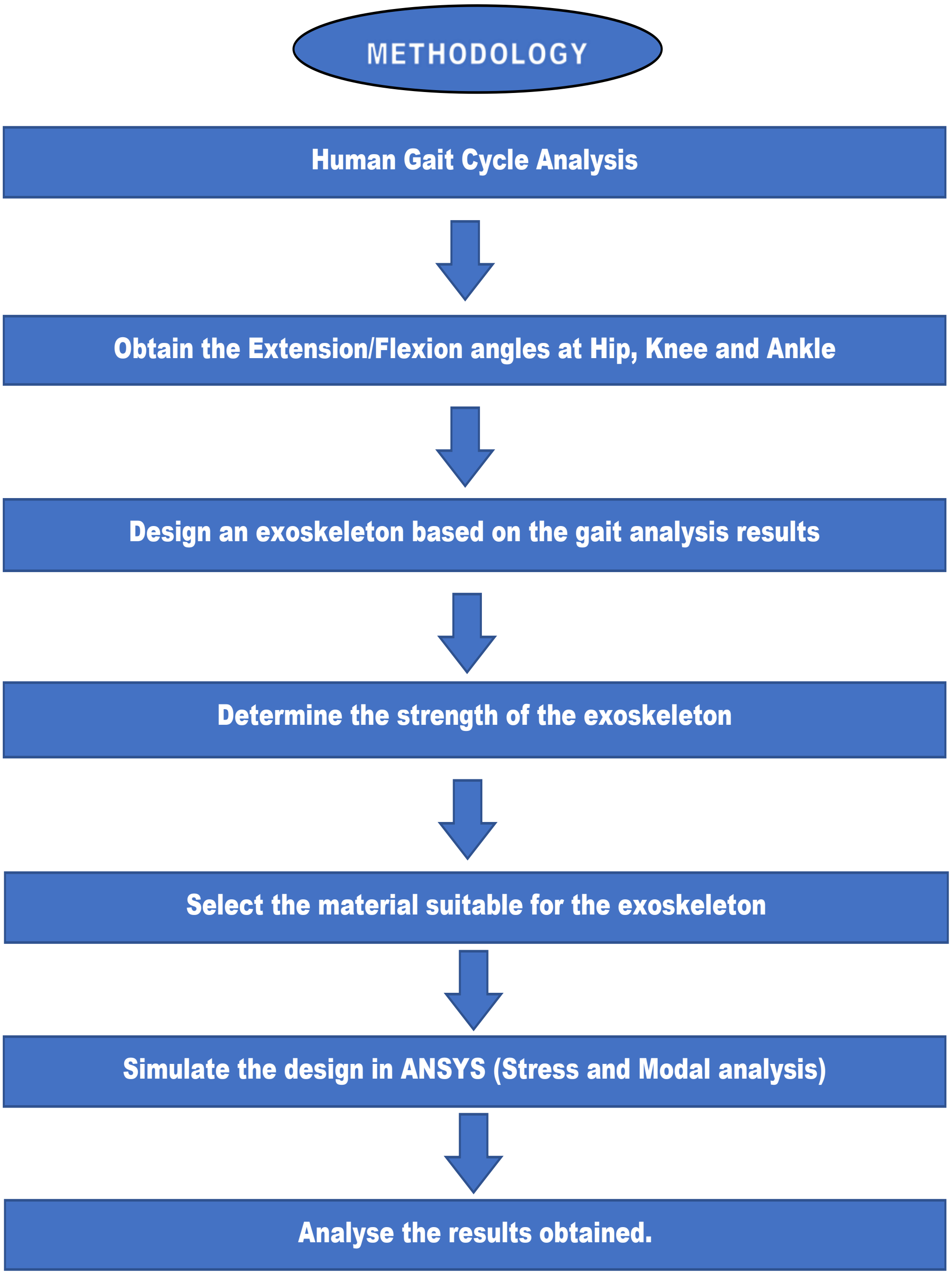


Fig. 3.1 Methodology of the Project

CHAPTER-4

MODELLING AND ANALYSIS

4.1 Biomechanical Analysis

Biomechanical analysis of the human joints related to the movement assisted by the exoskeleton is arguably one of the most important aspects related to the development process of exoskeletons. This chapter contains an analysis of lower body biomechanics, an analysis of different walking phases and sit-to-stand cycle, subsequent recommendation for the users to incorporate during usage of exoskeleton.

4.1.1 Planes of motion

The movement of limbs in different directions can be described using three anatomical planes: the sagittal (lateral) plane, the coronal (frontal) plane, and the transverse (axial) plane. The sagittal plane divides the body into left and right halves, the coronal plane divides it into front and back, and the transverse plane divides it into upper and lower parts. These planes are illustrated in fig. 4.1.

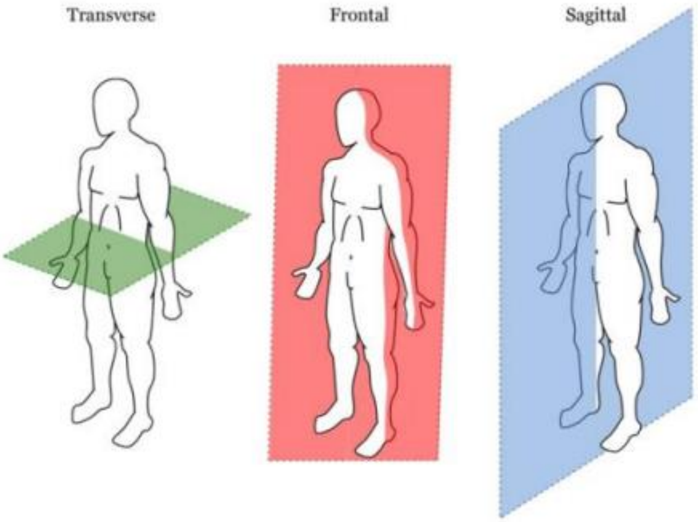


Fig. 4.1 Anatomy Planes of Motion

4.1.2 Human Gait Analysis (HGA)

The gait cycle refers to the sequence of events involved in human locomotion, which is separated into the stance and swing phase. A lower limb exoskeleton with similar mass and inertia to a human requires joint torques and power approximated to those required by a human of similar size. Joint angles for the exoskeleton are determined by analysing the walking cycle, with HGA angle data typically collected via motion capture.

Average data of range of motion is obtained from literature survey, with the hip angle designed to have 10° extension and 115° flexion, walking knee flexion limited to approximately 70˚, and ankle flexion ranging from -38° to +35° for an average person.

4.2. Modelling

The modelling of lower limb orthosis is carried using SolidWorks software. It is set to focus on different phases of sit-to-stand and walking cycle.

4.2.1 Phases during Sit-to-Stand cycle

Sit-to-Stand cycle involves three postural phases of human. These phases involve human subject to stand (extension phase), sit-to-stand transition (momentum transfer phase) and sit (flexion phase).

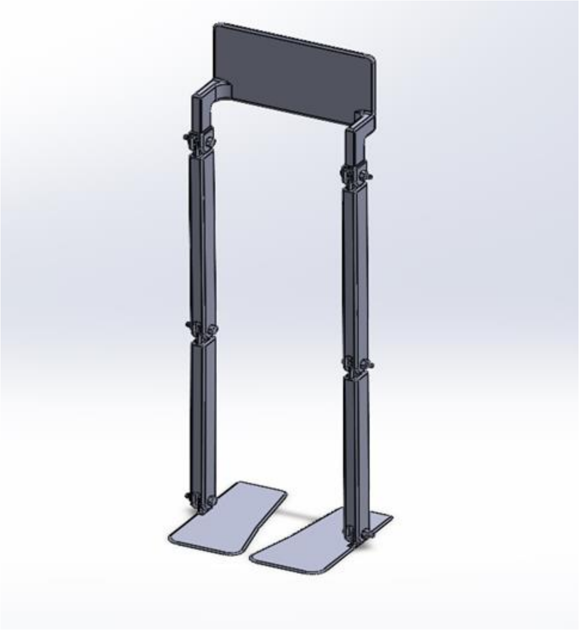


Fig. 4.2 Exoskeleton in Extension Phase.

Fig. 4.3 Exoskeleton in Momentum Transfer Phase.

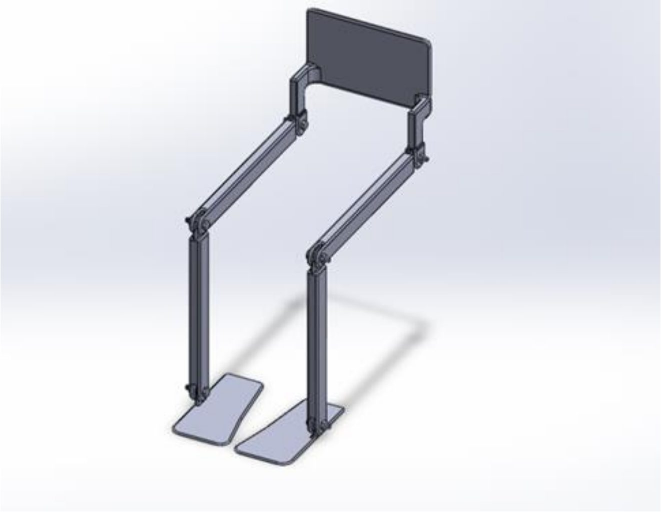


Fig. 4.4 Exoskeleton in Flexion Phase.

Figures 4.2, 4.3, 4.4 shows the postural phases during sit-to-stand transition respectively.

4.2.2 Postural phases in Walking cycle

The postural phases during walking are as follows:

1. Heel-strike
2. Foot-flat
3. Midstance
4. Heel-off
5. Toe-off

Heel-Strike: The first touch of one foot with the ground.

Foot-Flat: The point at which the entire foot makes contact with the ground and bears the weight of the body.

Midstance: The point at which the body's centre of mass is directly above the ankle joint, and the hip joint is higher than the ankle joint.

Heel-Off: When the foot lifts off the ground in preparation for forward momentum.

Toe-Off: The last point of contact during the stance phase.

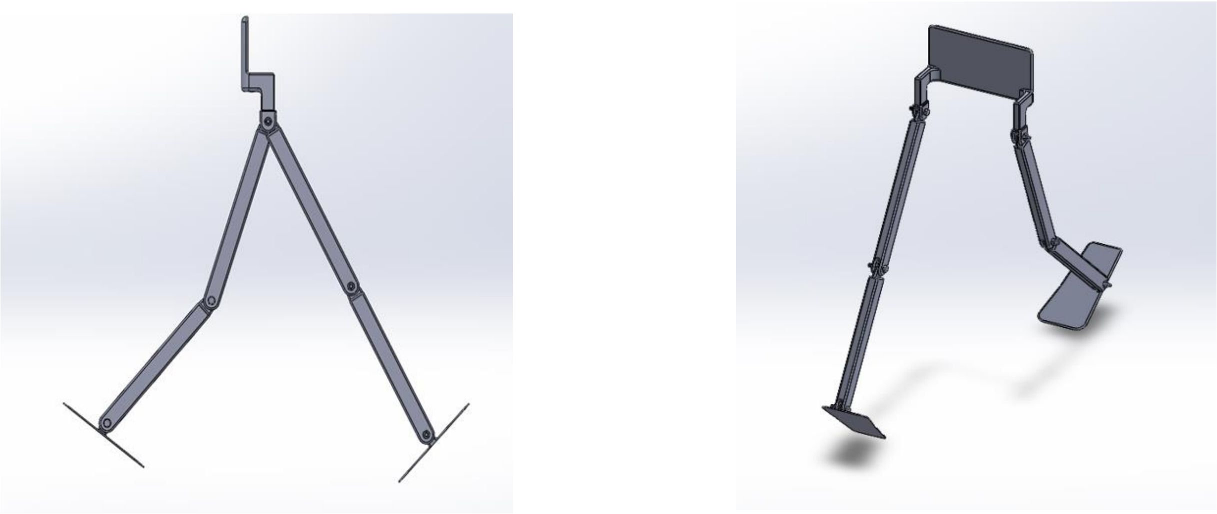


Fig. 4.5 Exoskeleton in Heel-Strike Phase.

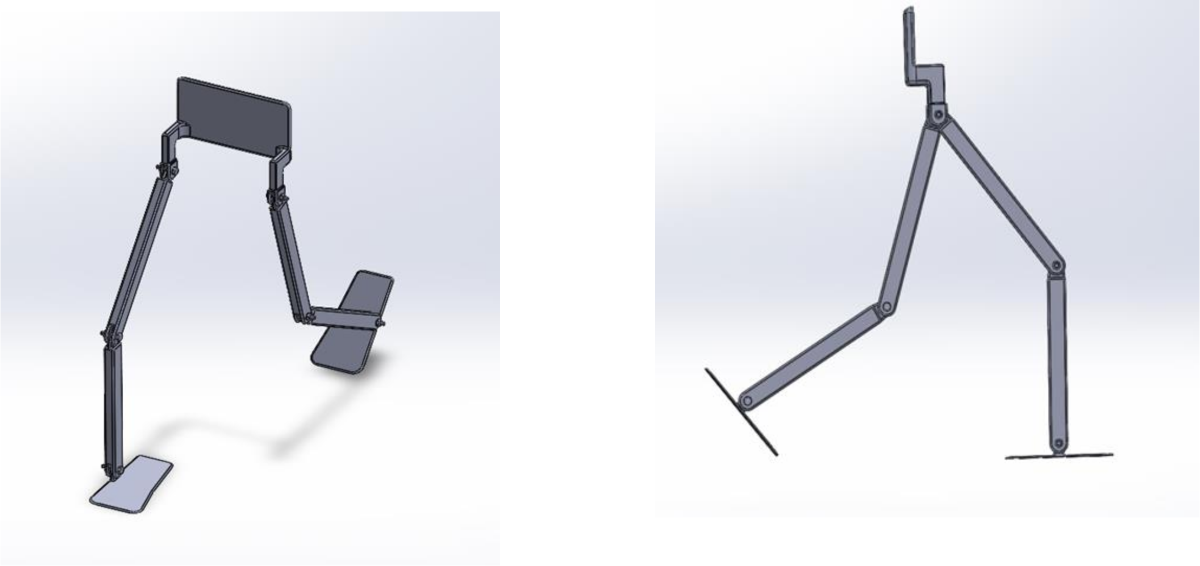


Fig. 4.6 Exoskeleton in Foot-Flat Phase.

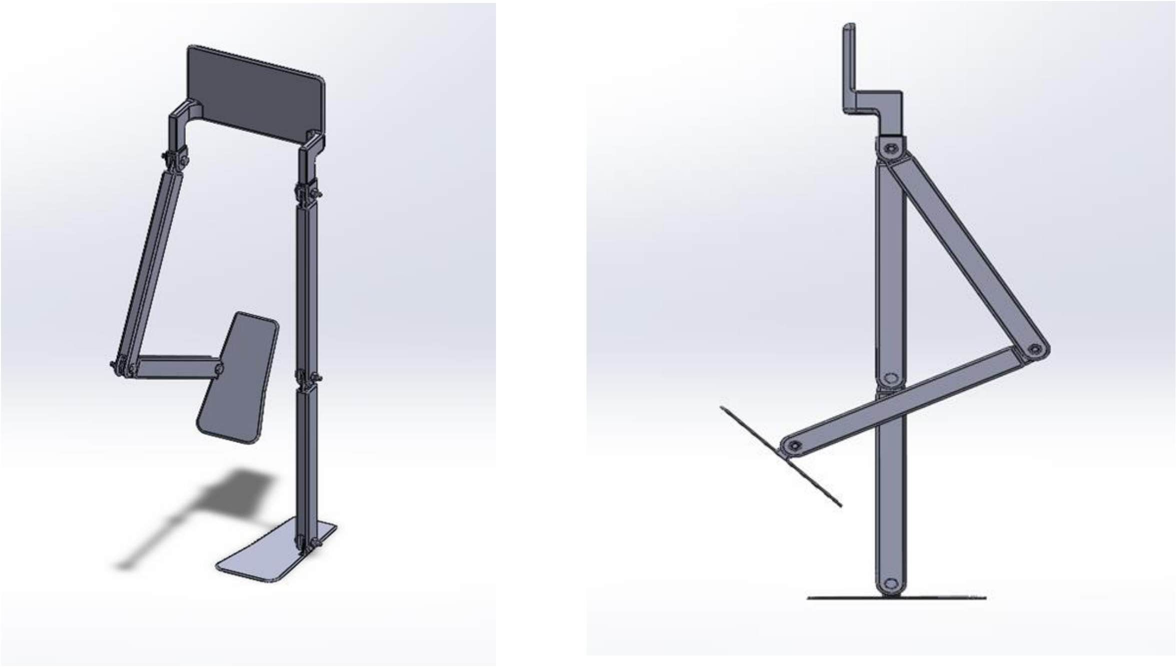


Fig. 4.7 Exoskeleton in Midstance Phase.

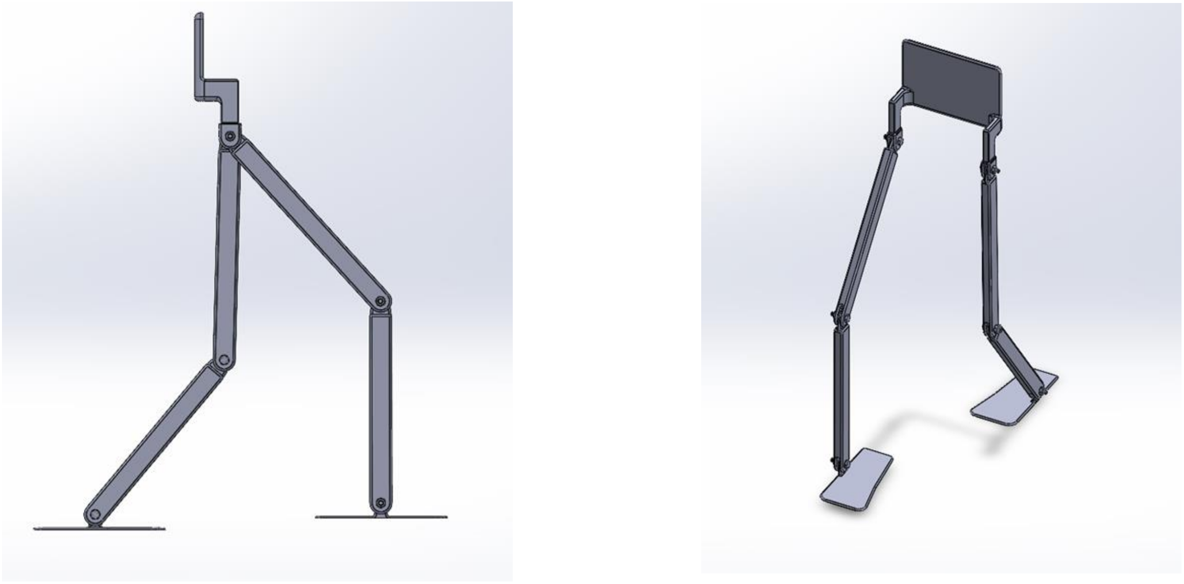


Fig. 4.8 Exoskeleton in Heel-off Phase.

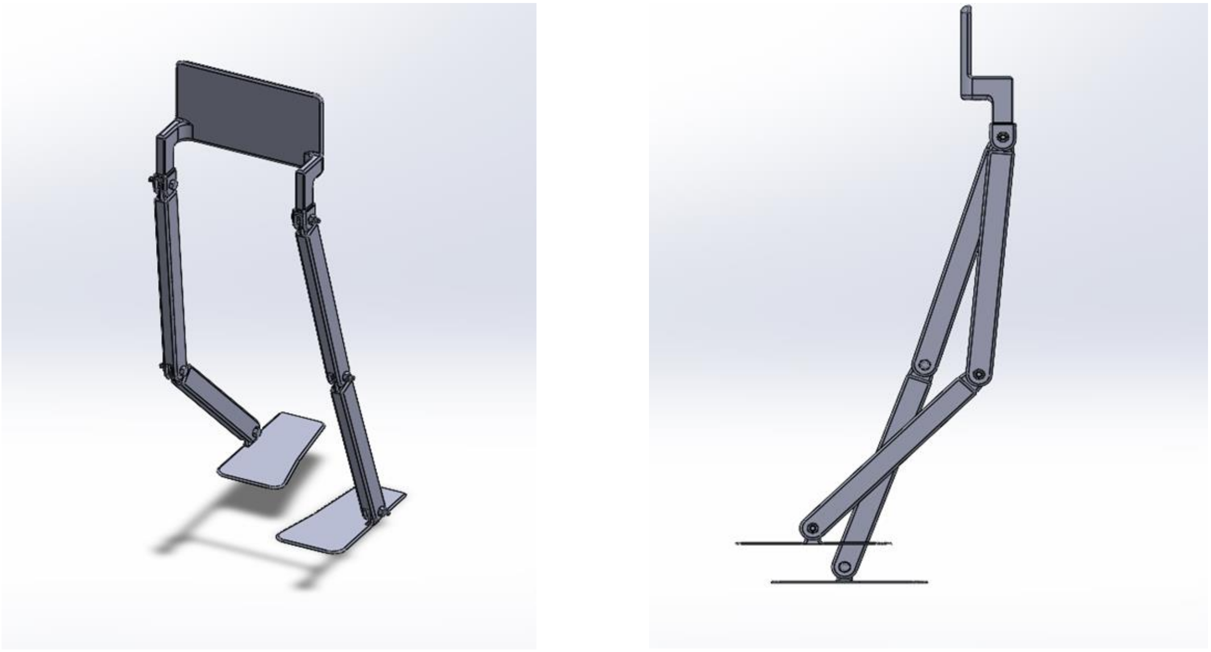


Fig. 4.9 Exoskeleton in Toe-Off Phase.

Figures 4.5, 4.6, 4.7, 4.8, 4.9 shows different postural phases i.e., Heel-strike, Foot-flat, Midstance, Heel-off, Toe-off respectively.

4.3 Materials used

The construction of an exoskeleton requires a lightweight material capable of bearing large forces, with commonly used materials including alloys. The chosen material must be able to withstand the weight of the user and be biocompatible, durable, cost-effective, and readily available. To minimize discomfort, the exoskeleton is designed for external use. The specific materials chosen for the construction of the exoskeleton are Aluminium alloy 7068 T6, with Titanium Grade 5 used for bolt and nut locking.

Aluminium alloy 7068 is a high-strength aluminium alloy that contains several elements in addition to aluminium. The chemical composition of aluminium alloy 7068 is:

Aluminium (Al): 92.9 - 94.5%
Zinc (Zn): 6.0 - 7.0%
Magnesium (Mg): 1.8 - 2.8%
Copper (Cu): 0.15 - 0.40%
Chromium (Cr): 0.04 - 0.35%
Zirconium (Zr): 0.04 - 0.16%
Titanium (Ti): 0.01 - 0.06%
Manganese (Mn): 0.01 - 0.03%
Iron (Fe): 0.01 - 0.03%

Table 4.1 Material Properties of Al 7068

Density	4.43 g/cc
Melting Point	1604-1660 °C
Solidus	1604 °C
Liquidus	1660 °C
Beta Transus	980 °C
Ultimate Tensile Strength	1170 MPa
Yield Tensile Strength	1100 MPa
Elongation At Break	10%
Modulus Of Elasticity	114 GPa
Brinell	334
Rockwell	C 363
Vickers	36

Table 4.2 Material Properties of Titanium Grade 5

Name	Aluminium Alloy 7068 T6
Phase at STP	Solid
Density	2850 kg/m^3
Ultimate Tensile Strength	640 MPa
Yield Strength	590 MPa
Young’s Modulus of Elasticity	73 GPa
Brinell Hardness	190 BHN
Melting Point	597 °C
Thermal Conductivity	190 W/mK
Heat Capacity	1050 J/gK

4.4 Loads acting on lower limb exoskeleton

Lower limb exoskeletons are typically designed to provide support, stability, and assistance to the wearer, particularly during activities that involve walking, running, or jumping. The types of loads that act on lower limb exoskeletons can vary depending on the specific design and application of the exoskeleton, but some common examples include:

Weight-bearing load: This refers to the load exerted on the exoskeleton by the wearer's body weight. Lower limb exoskeletons are designed to bear some or all of the weight of the wearer, which can help to reduce the load on the wearer's lower limbs.

External load: This refers to any additional load that is placed on the exoskeleton, such as carrying a heavy object. Some lower limb exoskeletons are designed to assist with carrying heavy loads by transferring some of the weight to the exoskeleton.

Shear load: This refers to the load that is generated when forces act on the exoskeleton in different directions, such as when the wearer changes direction or turns. Lower limb exoskeletons need to be designed to withstand shear loads to prevent damage or failure.

Overall, lower limb exoskeletons need to be designed to withstand a variety of loads while providing support and assistance to the wearer.

4.5 Calculations

Consider the human subject to be 100 kgs. The mass of each body part according to the percentage is tabulated below.

Table 4.3 Mass of each body part according to the percentage

Body part	Percentage of mass
1. Upper arm	2.7%
2. Fore arm	1.6%
3. Hand	0.66%
4. Head	7.3%
5. Trunk	50.80%
6. Thigh	9.88%
7. Lower leg	4.65%
8. Foot	1.45%

To calculate the strength of thigh link and shank link first we need to find the total load acting on them.

Total load on the thigh link:

= mass of head + 2 × mass of the upper arm + 2 × mass of fore arm + 2 × mass of head + mass of the trunk

= (7.3%) 100 + 2 × (2.7%) 100 + 2 × (1.6%) 100 + 2 × (0.66%) 100 + (50.80%) 100

= 7.3 + 5.4 + 3.2 + 1.32 + 50.80

= 68.02 kg + 2 × mass of thigh = 87.78 kg

= 861.12N (Force on each thigh link F1 = 430.56 N)

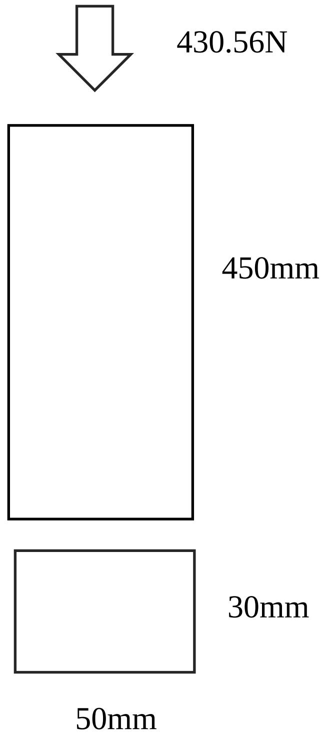
Total load on the knee link:

= load on the both thigh link + 2 (mass of the knee)

= 87.78 + 9.3

= 97.08 kg

= 952.35 N (Force on each knee link F2 = 467.17N)



Thigh:

Aluminium alloy 7068

σ_T= 640MPa σ_y = 590MPa

FOS = 1.5 E = 73GPa = 73 × 10^9 N/m^2

Compression:

$\sigma_{allowable}$ = σ_T/1.5 =320 KN/m^2

σ_{act} = 430/0.05×0.03 =286 KN/m^2

σ_{actual} = $\sigma_{allowable}$

Buckling load:

P $_{critical}$ = π^2 EI/L^2 (or) π^2 E/ (KL/r)^2 × A

I$_y$ = 1/12(ba^3) = 1/12 (30×50^3) = 3.125× 10^{-7} m^4

I$_x$ = 1/12(ab^3) = 1/12 (50×20^3) = 1.125× 10^{-7} m^4

$$r_x = \sqrt{\frac{Ix}{A}} = \sqrt{7.5} \times 10^{-5} = 8.66 \times 10^{-3} m$$

$$r_y = \sqrt{\frac{Iy}{A}} = \sqrt{2.08} \times 10^{-4} = 0.0144\ m$$

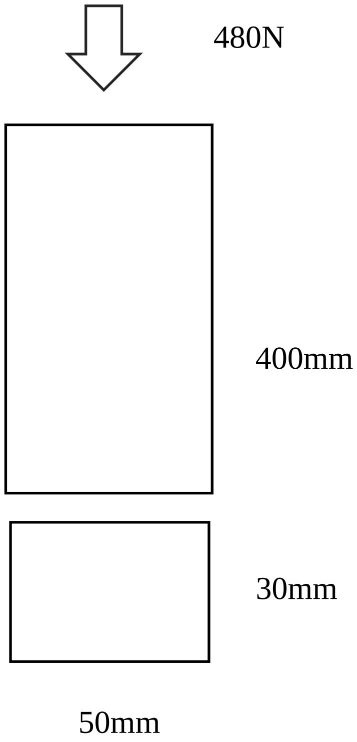
Effective length factor for rotation free, translation fixed column is k=1 (r= Radius of Gyration)

K$_x$ =K$_y$= 1

KL/r = max {k$_x$ l$_x$/r$_x$, k$_y$ l$_y$/r$_y$}

= max {51.96, 31.25}

KL/r = 51.96



P $_{\text{critical}} = \frac{\pi^2 EA}{\left(\frac{KL}{r}\right)^2} = (\pi^2 \times 73 \times 10^9 \times 1.5 \times 10^{-3})/(2704))$

$= 399675.17$N

$\sigma_{\text{critical}} = \sigma_{\text{critical}}/\text{A} = 266.45$MPa

$$\boxed{\sigma_{\text{critical}} < \sigma_{\text{y}}}$$

The link will buckle before yielding.

Knee:

σ_{t}= 640 Mpa, σ_{y} = 590 Mpa

FOS = 1.5, E = 73 GPa = $73\times 10^9 \frac{N}{m^2}$

Compression:

$\sigma_{\text{allowable}} = \sigma_{\text{T}}/1.5 = 427\text{k N/m}^2$

$\sigma_{\text{act}} = 320\text{k N/m}^2$

$\sigma_{\text{act}} < \sigma_{\text{allowable}}$

P $_{\text{critical}} = \frac{\pi^2 EI}{L^2}$ (or) $\frac{\pi^2 E}{\frac{KL}{r}} \times A = 399675.17$ N

$\sigma_{\text{critical}} = P_{\text{critical}}/\text{A} = 266.45$ MPa

$\sigma_{\text{critical}} < \sigma_{\text{y}}$

Strength of the knee and thigh links are determined, stress developed in the links are less than the yield strength.

4.6 Constraints loading

For a 100kg person force of 981N ≅ 100N is exerted. Assume, equal amount of force is acting on both the legs. Load is applied for all the postural phases of the exoskeleton.

4.6.1 Final Stand

The Fig. 4.10 shows that the exoskeleton is considered to be in the final stand position. When standing the predominant force 500N is applied on the thigh and knee links of each leg, both the foot links are fixed constraints.

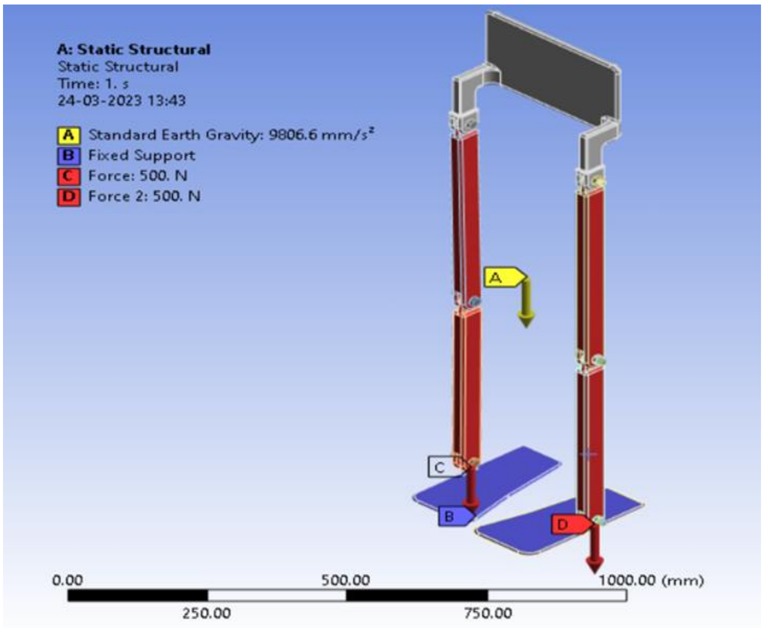


Fig. 4.10 Constraints Load in Standing Posture.

4.6.2 Sit-to-Stand transition

In this transition, the exoskeleton is in sit-to-stand transition and the waist link is a fixed constraint as shown in the Fig. 4.11. Force of 500N is applied on thigh, knee and foot links of each leg.

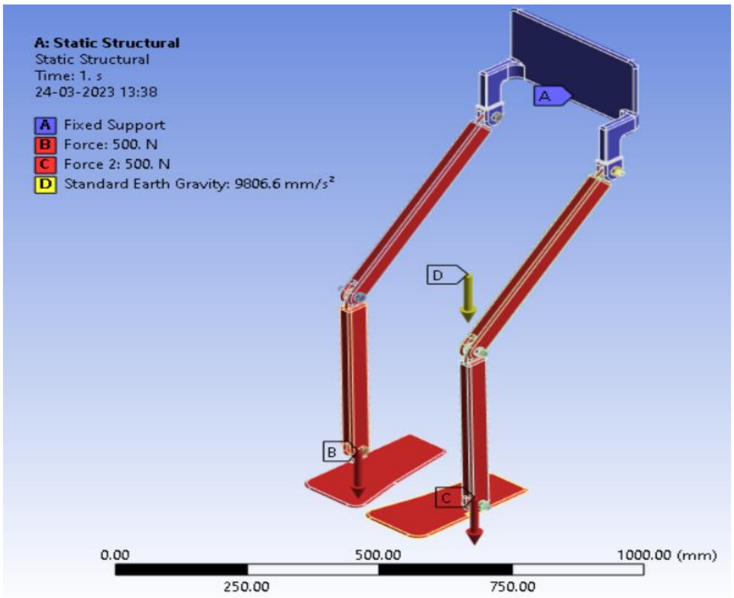


Fig. 4.11 Constraints Load in Sit-to-Stand Transition Posture.

4.6.3 Sitting

The Fig. 4.12 shows that upper and lower legs are inclined at 90°and the foot of the exoskeleton is resting on the ground. The waist link of the exoskeleton is a fixed constraint, force of 500N is applied on the thigh, knee and foot links of each leg.

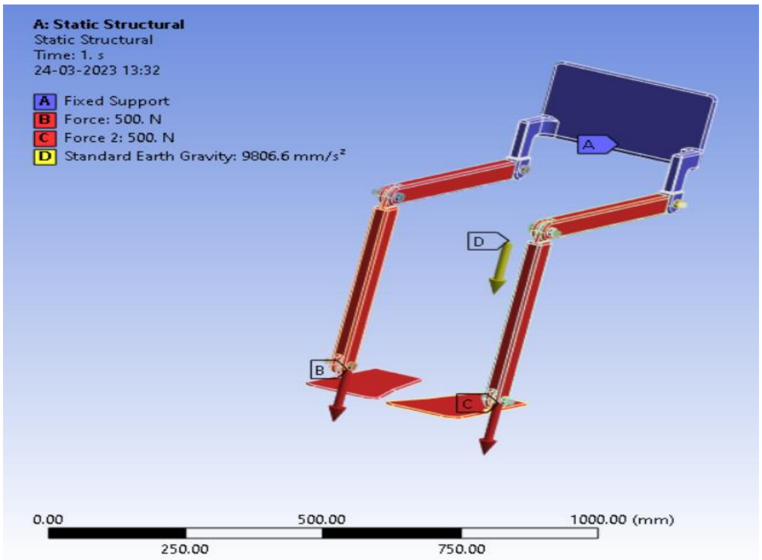


Fig. 4.12 Constraints Load in Sitting Posture.

4.6.4 Heel-Strike

In this posture, both the foot links are fixed constraints. Force of 500N is applied on thigh and knee links of each leg as shown in the Fig. 4.13.

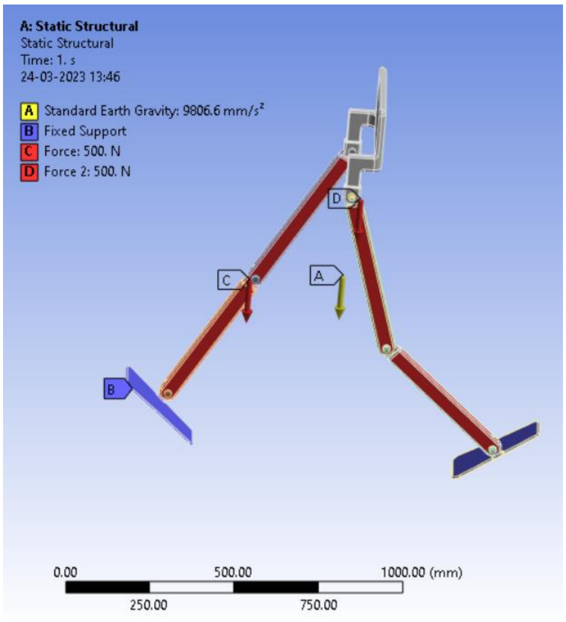


Fig. 4.13 Constraints Load in Heel-Strike

4.6.5 Foot-Flat

In this posture, both the foot links are fixed constraints. Force of 500N is applied on thigh and links of each leg as shown in the Fig. 4.14.

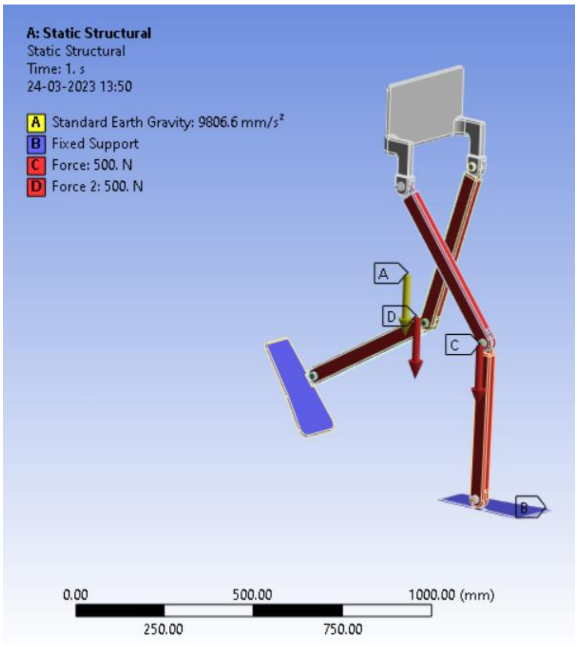


Fig. 4.14 Constraints Load in Foot-Flat Posture.

4.6.6 Heel-Off

In this posture, both the foot links are fixed constraints. Force of 500N is applied on thigh and links of each leg as shown in the Fig. 4.15.

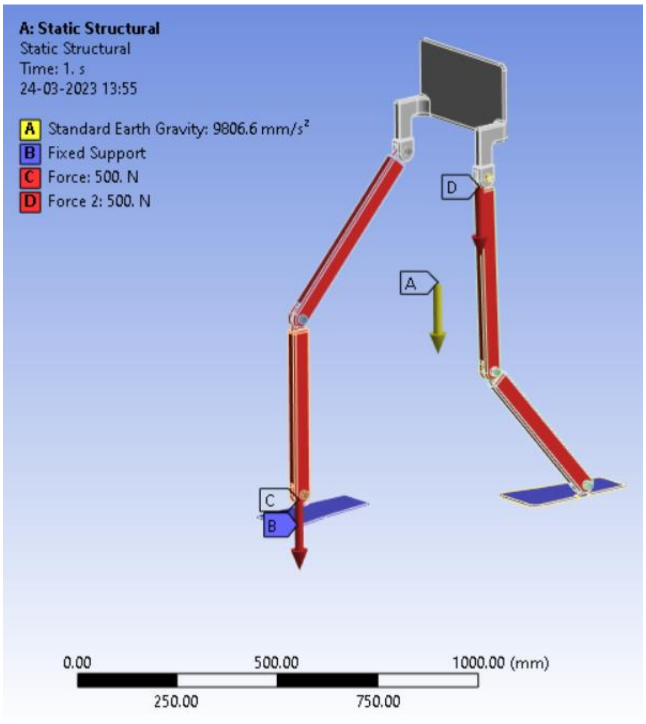


Fig. 4.15 Constraints Load in Heel-Off Posture.

4.6.7 Midstance

In this posture, both the foot links are fixed constraints. Force of 500N is applied on thigh and links of each leg as shown in the Fig. 4.16.

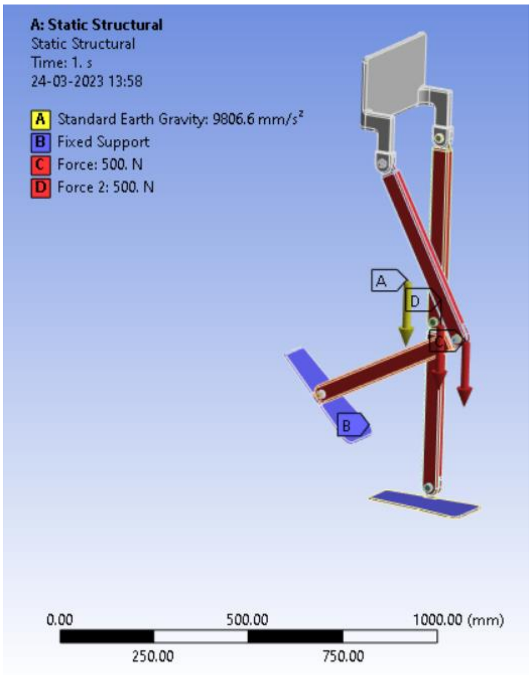


Fig. 4.16 Constraints Load in Midstance Posture.

4.6.8 Toe-Off

In this posture, both the foot links are fixed constraints. Force of 500N is applied on thigh and links of each leg as shown in the Fig. 4.17.

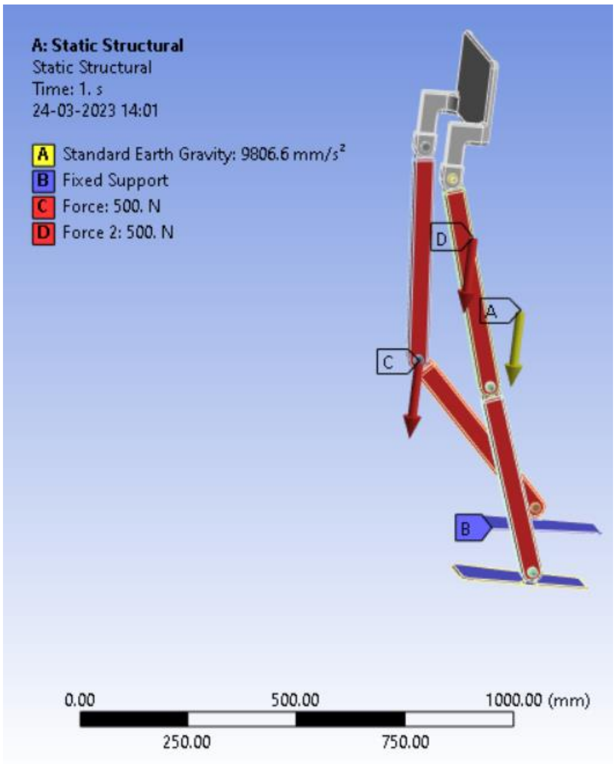


Fig. 4.17 Constraints Load in Toe-Off Posture.

4.7 Analysis

Analysis of the fin is done in ANSYS MECHANICAL WORKBENCH software considering the designing conditions and material properties of aluminium, copper, brass, bronze, stainless steel, polymers etc.,

4.7.1 History of ANSYS

ANSYS, Inc. is a software developer based in Pennsylvania that provides engineering analysis software across various disciplines including finite element analysis, structural analysis, computational fluid dynamics, and heat transfer. The company was founded in 1970 as Swanson Analysis Systems, Inc. with the goal of developing and marketing finite element analysis software for structural physics that could simulate static, dynamic, and thermal problems. Over time, the company grew alongside advancements in computer technology and engineering needs, and in 1994, it was sold to TA Associates who designated ANSYS, the company's leading software, as their flagship product and renamed the company ANSYS, Inc.

4.7.2 Introduction to ANSYS mechanical

ANSYS Mechanical is a software tool for finite element analysis that enables the modelling of behaviour in linear, non-linear, and dynamic studies for a wide range of mechanical design problems. It includes capabilities for thermal analysis, coupled physics, and supports material models and equation solvers. ANSYS Mechanical is used for the design and optimization of complex systems that may be too difficult to analyse by hand due to their geometry, scale, or governing equations. It is used as a teaching tool in many mechanical engineering departments, and also in civil and electrical engineering, physics, and chemistry departments. Virtual prototyping techniques using ANSYS allow for the exploration of product performance in a cost-effective way, reducing the risk and cost of ineffective designs. The multifaceted nature of ANSYS also enables users to see the effects of design on the overall behaviour of the product, including electromagnetic, thermal, and mechanical aspects.

4.7.3 Static Analysis

Static analysis is a type of analysis that predicts the response of a structure or component to a static load or set of loads, without taking into account the effect of time or dynamic effects. ANSYS is a powerful software package used for finite element analysis (FEA), which includes various static analysis tools.

In ANSYS, you can perform static analysis using the following steps:

1. Create a 3D solid model of the structure or component you want to analyse in ANSYS.
2. Import the model into ANSYS and define the material properties of the model.
3. Mesh the model with finite elements. The mesh size and type can be chosen based on the level of accuracy required and the complexity of the geometry.
4. Apply the boundary conditions and loads to the model. This step involves defining where the loads are applied, how they are applied, and how the structure is restrained.
5. Run the static analysis and obtain the results. ANSYS provides a variety of results, such as displacements, stresses, strains, and reaction forces.
6. Interpret and evaluate the results. This step involves analysing the results and determining whether the structure or component is safe and meets the design requirements.

4.7.4 Modal Analysis

Modal analysis is a type of analysis commonly performed in Ansys, a popular finite element analysis software. Modal analysis is used to determine the natural frequencies and mode shapes of a structure or system.

The natural frequencies of a structure are the frequencies at which the structure will naturally vibrate if it is excited or disturbed. The mode shapes describe the manner in which the structure vibrates at each of its natural frequencies.

To perform modal analysis in Ansys, you will first need to create a finite element model of your structure or system. This typically involves creating a 3D model using Ansys' geometry tools, and then meshing the model to create a finite element model.

Once you have created your finite element model, you can perform modal analysis by selecting the Modal analysis option in Ansys. In the Modal analysis settings, you will need to specify the type of analysis you want to perform (e.g., modal, harmonic, transient), and specify the frequency range of interest.

After running the analysis, Ansys will provide you with a list of natural frequencies and their corresponding mode shapes. You can use this information to better understand the behaviour of your structure or system, and to optimize its design for specific applications.

4.8 Static Analysis Results

Sitting

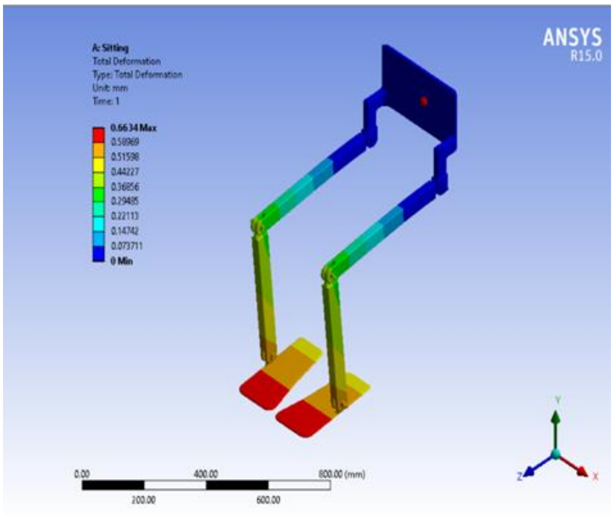


Fig. 4.18 Sitting Position under Deformation

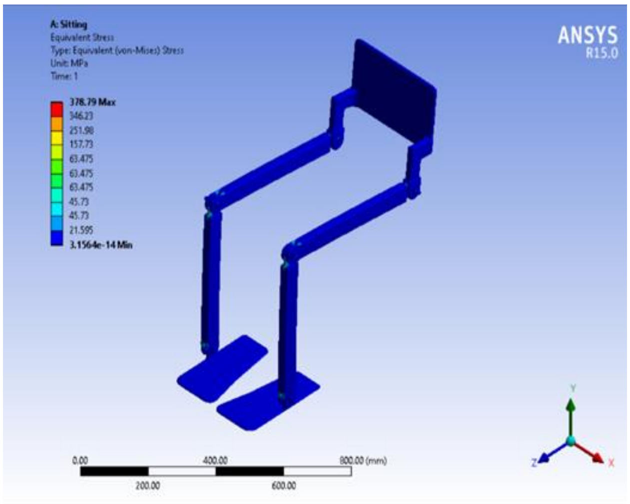


Fig. 4.19 Sitting Position under Stress

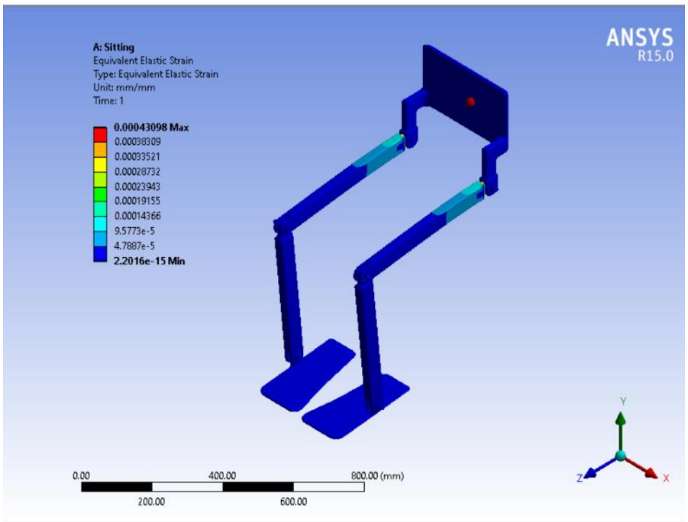


Fig. 4.20 Sitting Position under Strain

Fig. 4.18, 4.19, 4.20 show that the maximum deformation of the lower limb exoskeleton structure was 0.6634 mm and the maximum stress value of the lower limb exoskeleton was 378.79 MPa and the maximum strain value of the lower limb exoskeleton was 0.00043098 mm/mm which appeared in Sitting position.

Sit-to-Stand

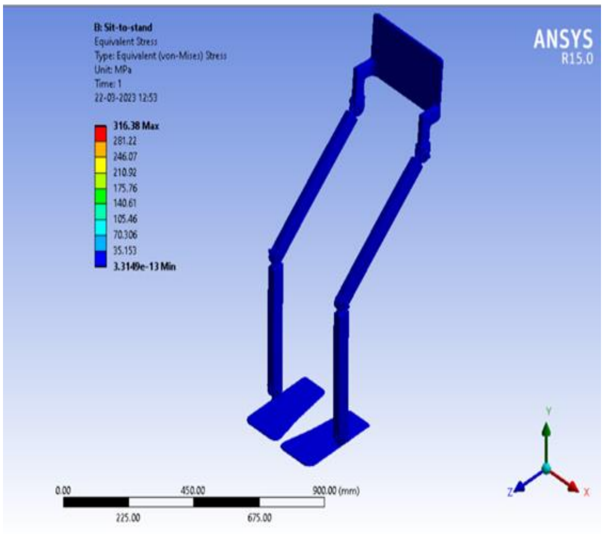


Fig. 4.21 Sit-to-Stand Position under Stress

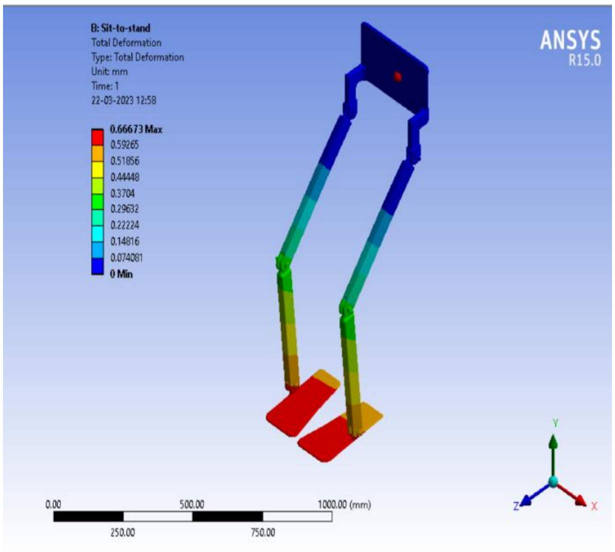


Fig. 4.22 Sit-to-Stand Position under Deformation

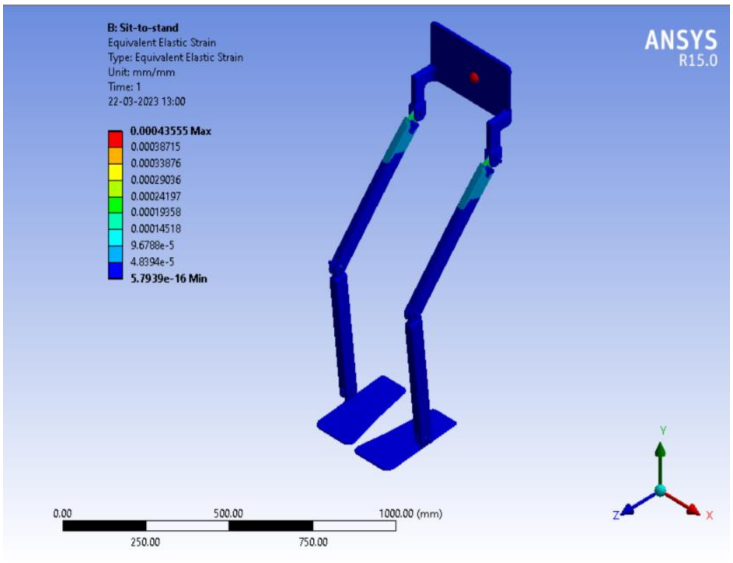


Fig. 4.23 Sit-to-Stand Position under Strain

Fig. 4.21, 4.22, 4.23 show that the maximum deformation of the lower limb exoskeleton structure was 0.66673 mm and the maximum stress value of the lower limb exoskeleton was 316.38 MPa and the maximum strain vale of the lower limb exoskeleton was 0.00043555 mm/mm which appeared in Sit to Stand position.

Final Stand

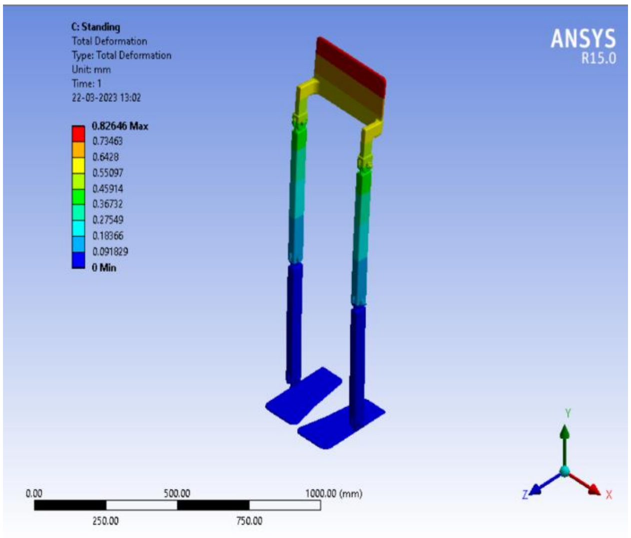


Fig. 4.24 Final Stand Posture under Deformation

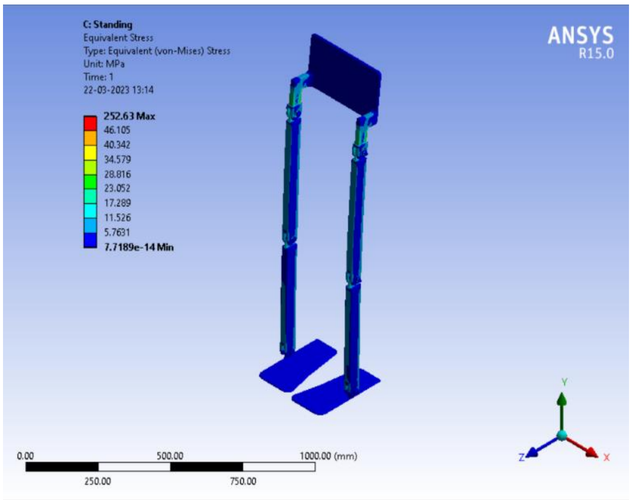


Fig. 4.25 Final Stand Posture under Stress

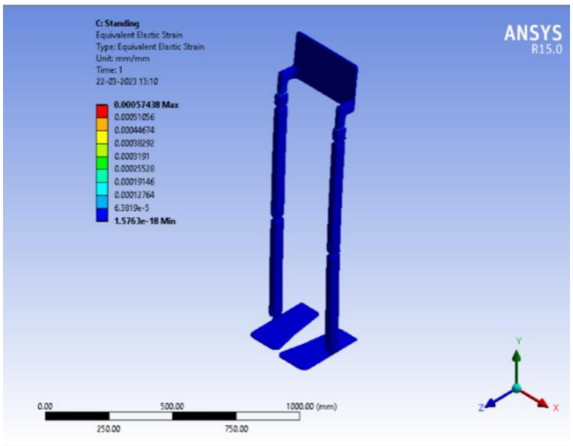


Fig. 4.26 Final Stand Posture under Stress

Fig. 4.24, 4.25, 4.26 show that the maximum deformation of the lower limb exoskeleton structure was 0.82646 mm and the maximum stress value of the lower limb exoskeleton was 252.63 MPa and the maximum strain vale of the lower limb exoskeleton was 0.00057438 mm/mm which appeared in Final Stand position.

Heel-Strike

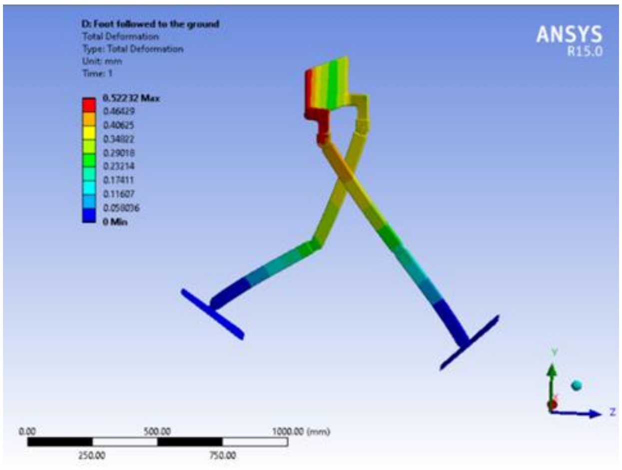


Fig. 4.27 Heel-Strike Posture under Deformation

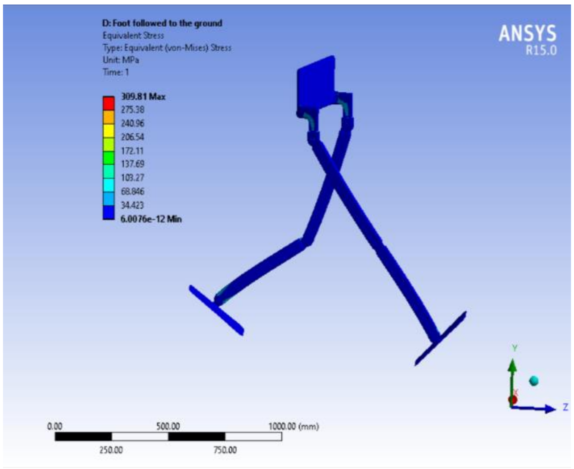


Fig. 4.28 Heel-Strike Posture under Stress

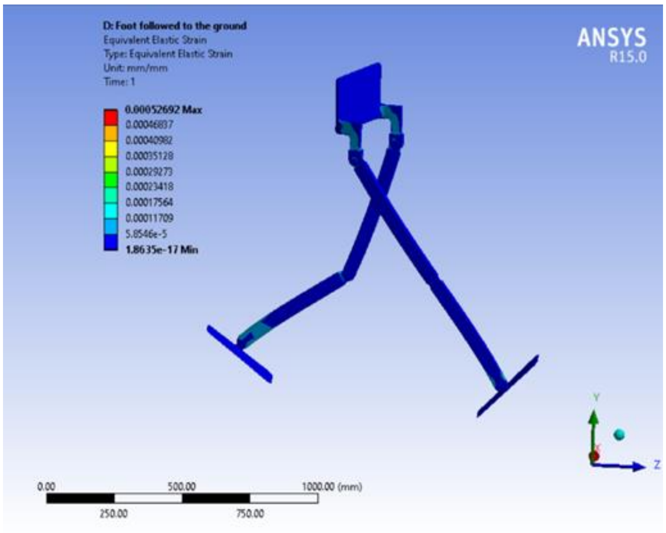


Fig. 4.29 Heel-Strike Posture under Strain

Fig. 4.27, 4.28, 4.29 show that the maximum deformation of the lower limb exoskeleton structure was 0.*52232* mm and the maximum stress value of the lower limb exoskeleton was *309.81* MPa and the maximum strain vale of the lower limb exoskeleton was 0.0005*2692* mm/mm which appeared in Heel-Strike position.

Foot-Flat

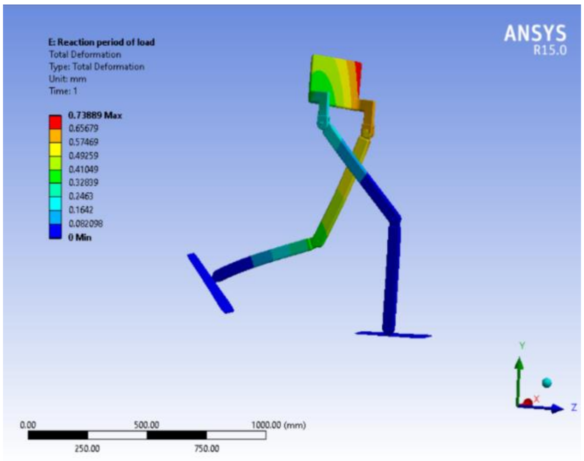


Fig. 4.30 Foot-Flat Posture under Deformation

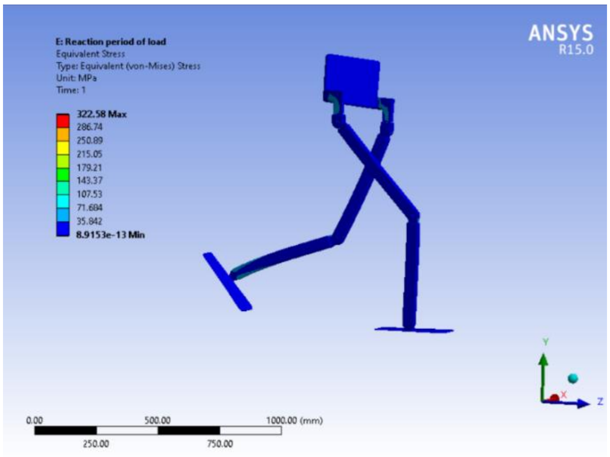


Fig. 4.31 Foot-Flat Posture under Stress

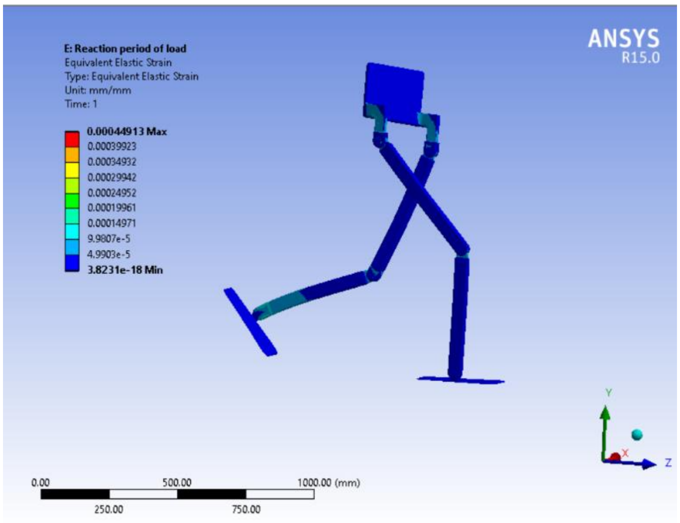


Fig. 4.32 Foot-Flat Posture under Strain

Fig. 4.30, 4.31, 4.32 show that the maximum deformation of the lower limb exoskeleton structure was 0.*73889* mm and the maximum stress value of the lower limb exoskeleton was *322.58* MPa and the maximum strain vale of the lower limb exoskeleton was 0.00*44913* mm/mm which appeared in Foot-Flat position.

Heel-Off

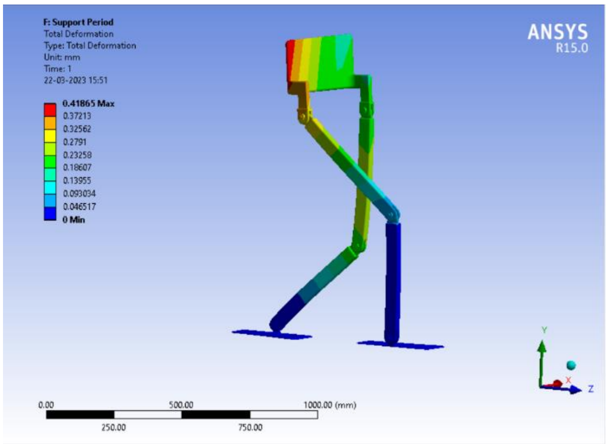


Fig. 4.33 Heel-Off Posture under Deformation

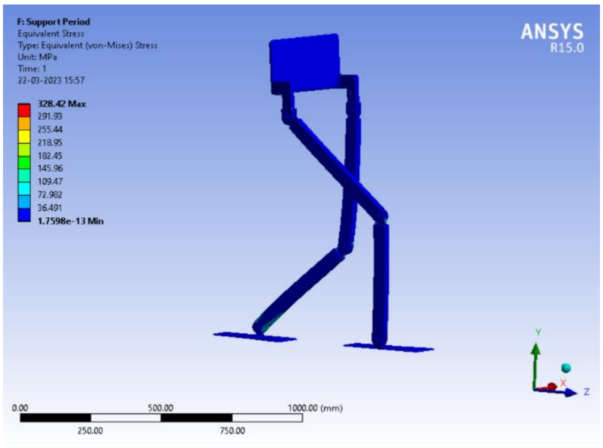


Fig. 4.34 Heel-Off Posture under Stress

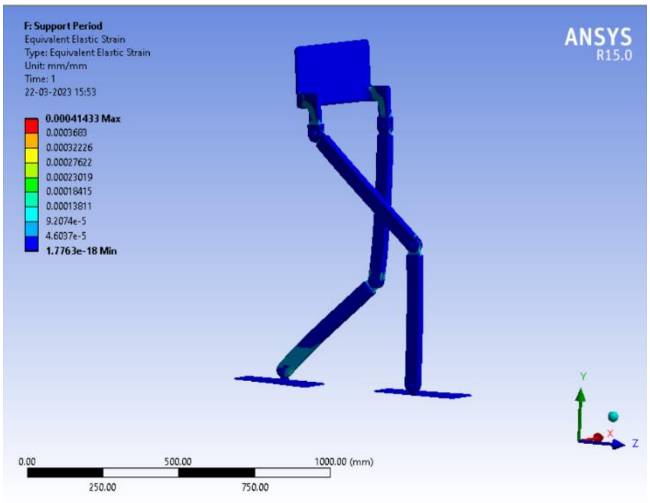


Fig. 4.35 Heel-Off Posture under Strain

Fig. 4.33, 4.34, 4.35 show that the maximum deformation of the lower limb exoskeleton structure was 0.41865 mm and the maximum stress value of the lower limb exoskeleton was *328.22* MPa and the maximum strain vale of the lower limb exoskeleton was 0.00*41433* mm/mm which appeared in Heel-Off position.

Midstance

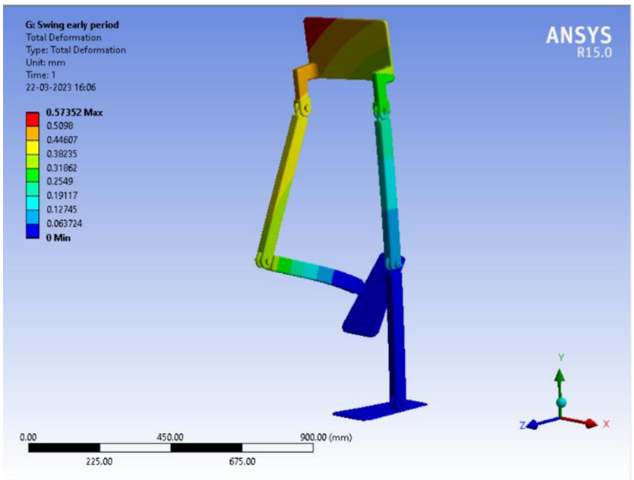


Fig. 4.36 Midstance Posture under Deformation

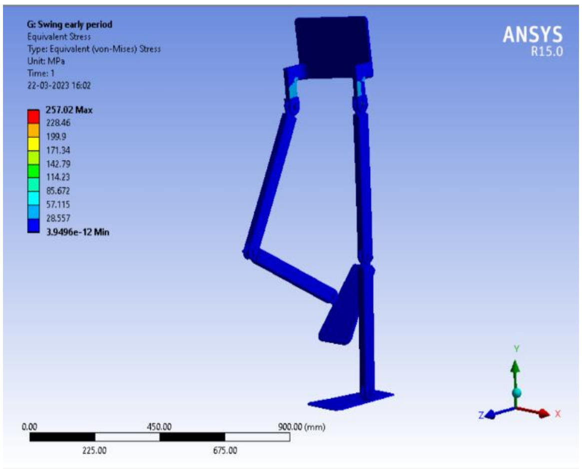


Fig. 4.37 Midstance Posture under Stress

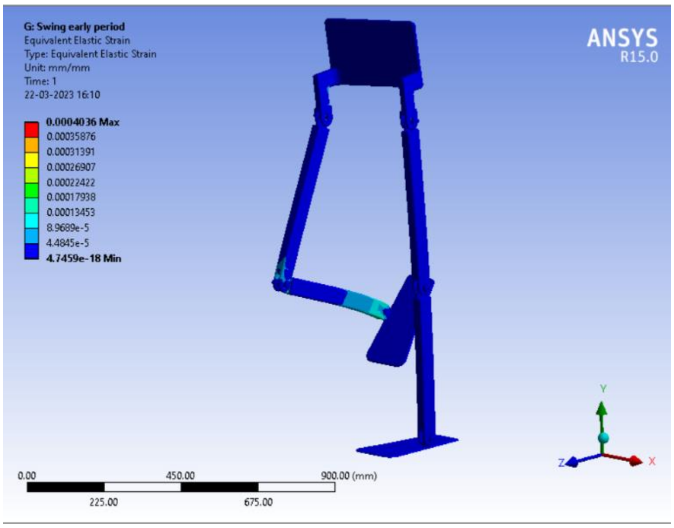


Fig. 4.38 Midstance Posture under Strain

Fig. 4.36, 4.37, 4.38 show that the maximum deformation of the lower limb exoskeleton structure was 0.57352 mm and the maximum stress value of the lower limb exoskeleton was *257.02* MPa and the maximum strain vale of the lower limb exoskeleton was 0.000*4036* mm/mm which appeared in Midstance position.

Toe-Off

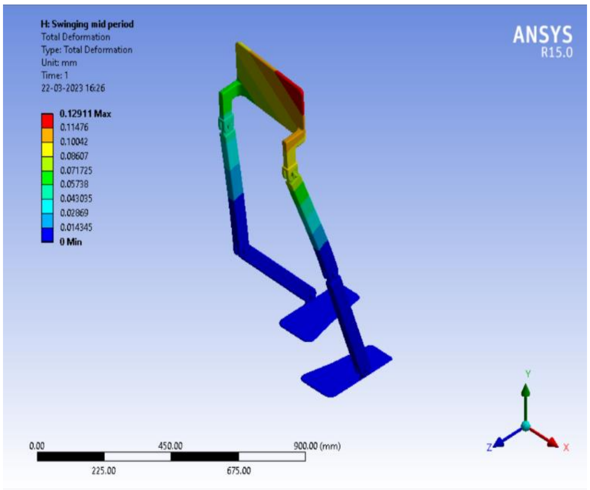


Fig. 4.39 Toe-Off Posture under Deformation

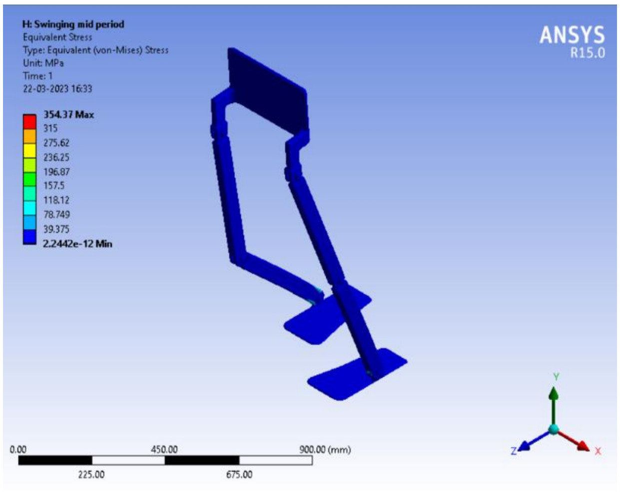


Fig. 4.40 Toe-Off Posture under Stress

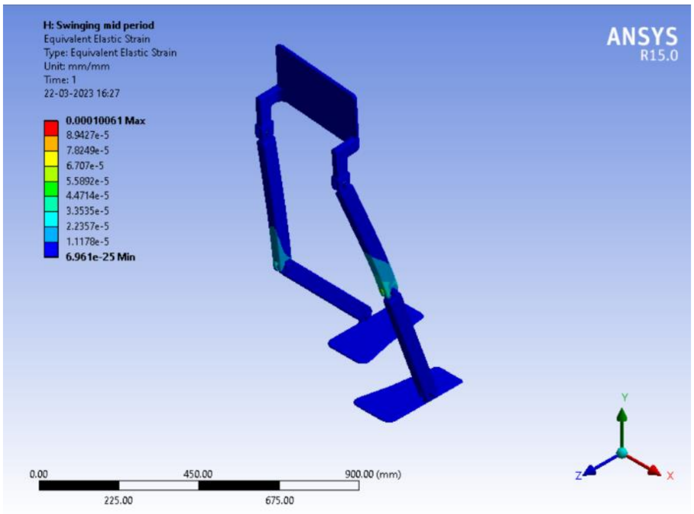


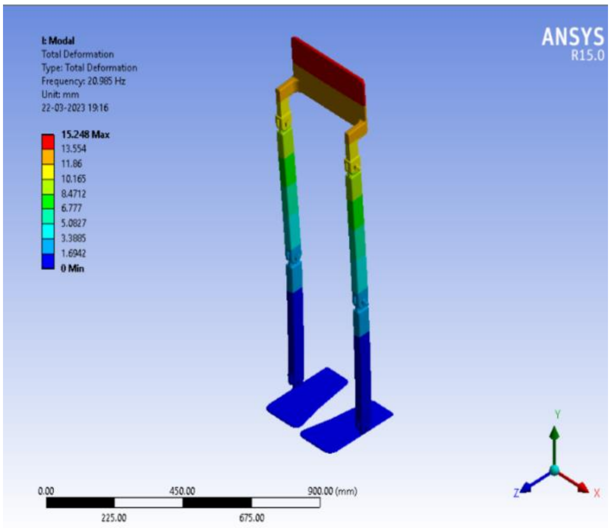
Fig. 4.41 Toe-Off Posture under Strain

Fig. 4.39, 4.40, 4.41 show that the maximum deformation of the lower limb exoskeleton structure was 0.12911 mm and the maximum stress value of the lower limb exoskeleton was *354.37* MPa and the maximum strain vale of the lower limb exoskeleton was 0.000*10061* mm/mm which appeared in Toe-Off position.

4.9 Modal Analysis Results

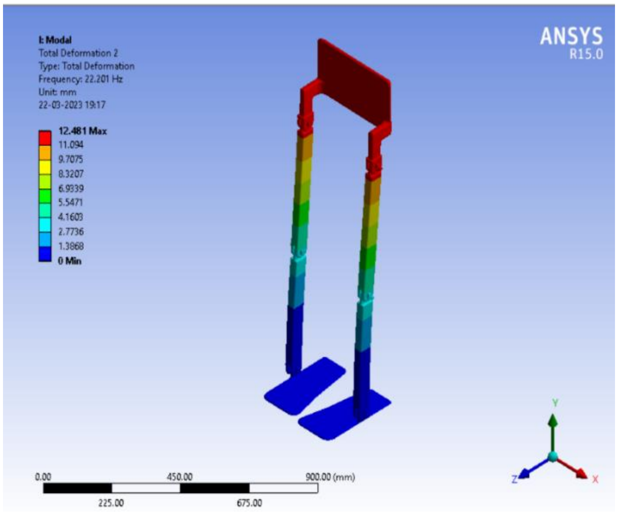
Modal analysis of the lower limb exoskeleton is carried out in all the postural phases of walking and sit-to-stand cycle. The total deformation of five modes is determined and discussed in the results.

First Mode:



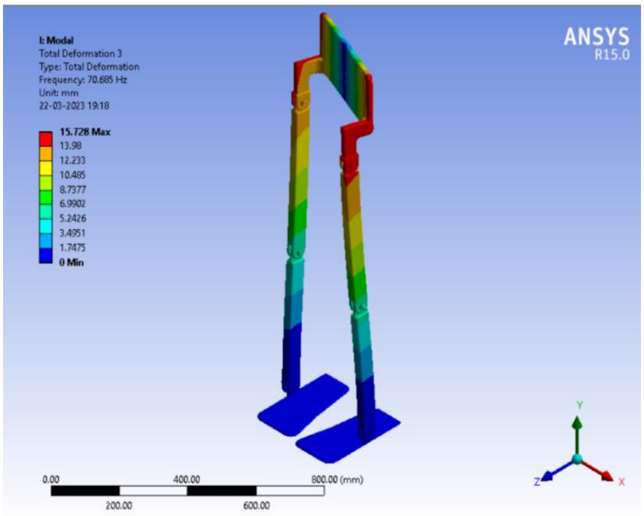
(a)

Second Mode:



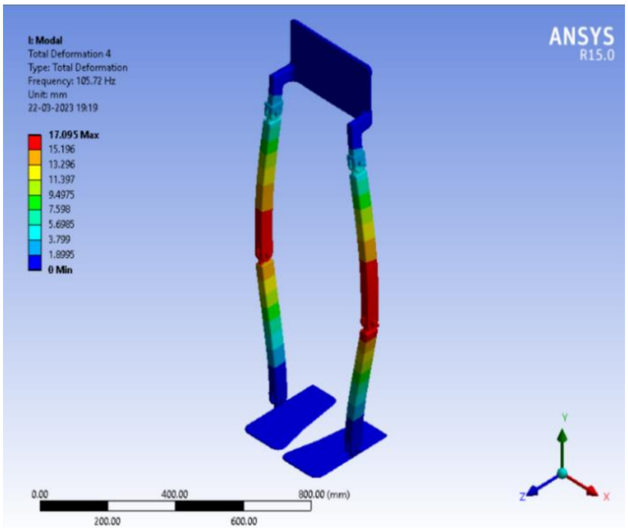
(b)

Third Mode:



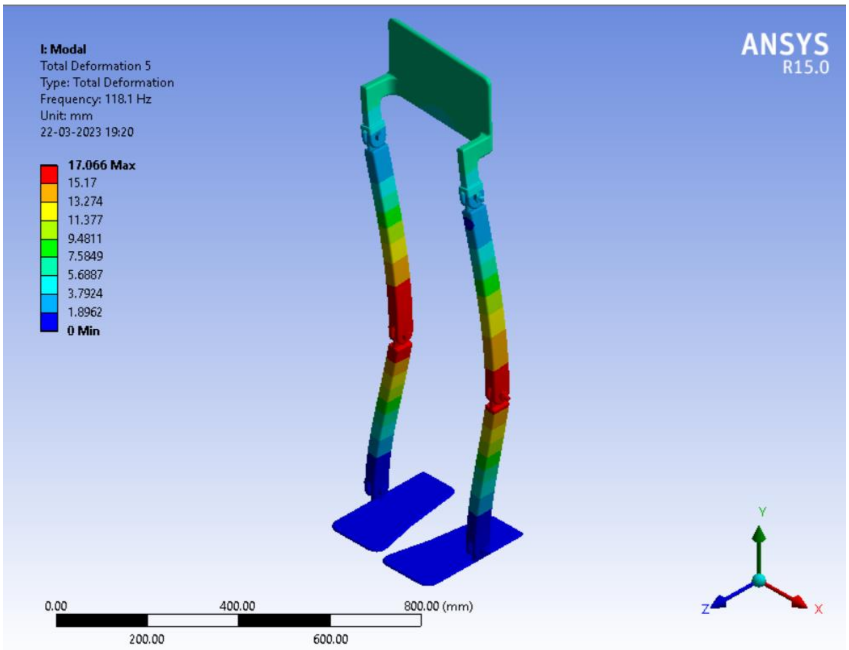
(c)

Fourth Mode:



(d)

Fifth Mode:



(e)

Fig. (a), (b), (c), (d), (e) show the total maximum deformation of the lower limb exoskeleton structure 15.246mm, 12.461mm, 15.128mm, 17.095mm, 17.066mm respectively appeared in the Final Stand position.

CHAPTER-5

RESULTS AND DISCUSSION

Static stress and modal analysis are carried out for the lower limb exoskeleton structure to determine the maximum total deformation, maximum equivalent stress and maximum equivalent strain. The results are tabulated and discussed below.

Table 5.1 Static Analysis

Position of the exoskeleton	Deformation (mm)	Von-Mises Stress (MPa)	Von-Mises Strain (mm/mm)
Sitting	0.6634	378.79	0.000430
Sit-to-Stand	0.6667	316.38	0.000435
Standing	0.82646	252.63	0.000574
Foot followed to the ground	0.5223	309.81	0.000526
Reaction period of load	0.7388	322.58	0.000449
Support period	0.4186	328.42	0.000414
Swing early period	0.5735	257.02	0.000403
Swinging mid period	0.1291	354.37	0.000100

Table 5.1 shows the maximum stress and deformation obtained in the lower limb exoskeleton. The maximum stress is 378.79 Mpa, which appeared in supporting the thigh and shank links; the maximum deformation is 0.82646 mm in supporting the right hip; stress distribution of the lower limb exoskeleton structure was more homogeneous, mainly concentrated in between 40 - 80 Mpa.

Table 5.2 Modal Analysis

Position of the exoskeleton	**First Mode** (Hz)	**Second Mode** (Hz)	**Third Mode** (Hz)	**Fourth Mode** (Hz)	**Fifth Mode** (Hz)
Sitting	26.097	27.459	77.497	94.359	97.234
Sit-to-Stand	22.235	22.833	74.425	101.26	108.58
Standing	20.985	22.201	70.685	105.72	118.1
Foot followed to the ground	19.476	33.509	61.986	103.29	111.19
Reaction period of load	19.826	33.652	61.519	98.967	107.63
Support period	20.219	30.476	66.865	99.859	109.04
Swing early period	22.762	25.000	72.028	91.997	97.632
Swinging mid period	21.905	22.838	67.695	104.53	107.21

Table 5.2 shows the maximum deformation of the lower limb exoskeleton in modal analysis. The modal analysis is performed for five different modes for eight different postures of the exoskeleton.

Based on the overall analysis, it has been proven that the structure of the exoskeleton is capable of withstanding the weight of a human and the strength of the design is within the limit for a normal application of an exoskeleton. This suggests that the exoskeleton design is safe and suitable for use by individuals for whom it is intended.

CHAPTER-6

CONCLUSION

In the present investigation,

1. The study aimed to analyse the human gait cycle to determine the range of motion of the hip, knee, and ankle joints. This information is necessary to construct lower limb orthosis, which is a device used to support or correct abnormal limb movement. The results showed that the average range of motion for hip extension is 10°, and hip flexion is 115°. The walking knee flexion is limited to approximately 70˚, and the average ankle flexion range is from -38° to +35°. This information can be used to design and customize orthotic devices that meet the needs of individuals with specific mobility requirements.
2. A lower limb orthosis structure is designed for the dimensions required using SolidWorks 2022.
3. Forces acting on the lower limb orthosis links are determined for the loads acting on thigh and knee due to the human body weight. The maximum forces acting on each thigh and knee links are 430N and 470N respectively.
4. Stresses caused due to the human body weight and buckling load are determined using theoretical calculations. The maximum stress caused due to buckling load and body weight is 267Mpa and 286Mpa respectively. The determined values are less than the yield strength(590Mpa) of the material Aluminium Alloy 7068 T6.
5. In Ansys workbench R15.1, a static structural analysis was performed to determine the maximum deformation, stress, and strain for various postural phases. The study found that the maximum deformation of 0.82646mm occurred in the standing posture, while the maximum stress of 378.79Mpa occurred in the sitting posture.

   The maximum equivalent stress obtain in static structural analysis is less than the yield strength of the material selected i.e., Aluminium Alloy 7068 T6.
6. Modal analysis performed on an exoskeleton design during different postural phases. The goal of the analysis was to identify the natural frequency of vibration of the design and the resulting deformation of the exoskeleton due to mode vibrations. The maximum frequency for resonance was found to be 26.097Hz during the sitting posture.

FUTURE SCOPE

The investigation can be further extended to concentrate on the following:

- The design of exoskeleton can be incorporated with actuators, sensors, batteries and computer processors to help users accomplish daily tasks and provide medical support.
- The design of the project can be included the use of mechanical gear and motor systems to provide increasing amounts of support as the user lifts their leg, and will focus on back support and motion sensing.
- Further there is scope to provide suspension system and internal damping to reduce vibrations.
- Once the exoskeleton is fully equipped with the following it can be fabricated and commercialised and it can be taken into the market and make sure it is available in different segments and in different ranges of pricing.

REFERENCES

[1] Shubham S. Kawalea,M. Sreekumara, “Design of a Wearable Lower Body Exoskeleton Mechanism for Shipbuilding Industry”, Procedia Computer Science 133, 2018; 1021–1028.

[2] Hoda Mahmoud Saleh Samir, “Design and biomechanical analysis of upper limb exoskeleton for industrial applications”, 2020; 184687MAHM.

[3] Moyao Gao, Zhanli Wang, Shuang Li, “Design and optimization of exoskeleton structure of lower limb knee joint based on cross four-bar linkage”, 2021; AIP Advances 11, 065124.

[4] Deepak kumar, Devanand, Prakash Narayanan, “Design and Fabrication of Electrically Powered Exoskeleton for Work Augmentation”, 2017; IJIRSET0605010.

[5] Akash Gupta, Amit Kumar Mondal, Mukul Kumar Gupta,Kinematic, “Dynamic Analysis and Control of 3 DOF Upper-limb Robotic Exoskeleton”, 2019; Vol. 52, No. 3, June, pp. 297-304.

[6] Luis I. Minchala, Fabián Astudillo-Salinas, Kenneth Palacio-Baus and Andrés Vazquez-Rodas, “Mechatronic Design of a Lower Limb Exoskeleton”, 2017; dx.doi.org/10.5772/674.

[7] Qiang Yan, Jianjun Zhang, and Kaicheng Qi, “Structure Design and Kinematics Analysis of a Novel Unpowered Load-Carrying Lower Extremity Exoskeleton with Parallel Topology”, 2018, Volume 2018, Article ID 4128520.

[8] Lalchand Kumawat, Abdul Salam. M, Ponnapalli Naga Sai Vivek, Sajja Sri Bharath, Mustafa Ali Mustafa Emam, “Modular Design of Full Body Exoskeleton suit for Industry, Construction and Military Purpose”, 2021; ISSN: 2249-8958, Volume-10.

[9] N. Siva Nagamani, V. Mohan Srikanth, D. Tarun, “Design and Analysis of Lower Limb Exoskeleton”, 2017; ISSN: 2349-6010.

[10] Fangzheng Wang, Lei Yan, Jiang Xiao, Lei Fan, “Design and simulation analysis of an improved wearable power knee exoskeleton”, 2019; ISSN: 2538-8460.

[11] Swapnil Manyar, Hemant Mali, Siddhesh Vishe, Vinay Kulkarni, “Design and Analysis of Pneumatic System Based Exoskeleton Arms”, 2021; SJIF: 7.169.

[12] Philippe Malcolm, Wim Derave, Samuel Galle, Dirk De Clercq, “A Simple Exoskeleton That Assists Plantarflexion Can Reduce the Metabolic Cost of Human Walking”, 2013; journal. pone.0056137.

[13] Andrew Chu, H. Kazerooni, and Adam Zoss, “On the Biomimetic Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)”, 2005; IEEE CA 94720.

[14] Manoj M. Jadhav, Komal C. Kale, Harshada H. Wategaonkar, “Design and Analysis of Lower Body Exoskeleton”, 2021; Volume9, ISSN: 2320-2882.

[15] Shaik Mubarak Basha, B. Sreenivasa Kumar Reddy, V. Venugopal Reddy, “Design, Fabrication & Analysis of Exoskeleton on Aluminium Alloy 6082(T6)”, 2018; e-ISSN: 2395-0056 Volume.

[16] Ionut Daniel Geonea and Daniela Tarnita, “Design and evaluation of a new exoskeleton for gait rehabilitation”, 2017; Mech. Sci., 8, 307–321.

[17] Brian Flynn, “Synthesizing an Adjustable Lower-Limb Exoskeleton Device for Clinical Rehabilitation”, 2016.

[18] Kai Yang, “Structural design and modal analysis of exoskeleton robot for rehabilitation of lower limb”, 2018; Journal of Physics: Conf. Series 1087,062004.