Abstract

The human ankle plays a critical role in locomotion, enabling multi-planar movements essential for balance, propulsion, and stability. This project presents the design and development of a mechanical robotic ankle capable of replicating human-like ankle motion across two primary axes—sagittal and transverse—along with a metatarsal hinge for toe flexion. The system employs servo motors coupled through spur gear transmission for torque amplification, and linkage actuation for metatarsal movement. Ball bearings are integrated at all rotational joints to ensure smooth operation and minimize friction. The design, modeled in Fusion 360, achieves approximately 45° of motion in the sagittal plane and 15° in the transverse plane, closely mimicking natural gait mechanics. The objective of this work is to study the biomechanics of ankle motion and establish a mechanical proof-of-concept for future prosthetic ankle systems and bipedal robots. The project emphasizes mechanical motion analysis rather than sensor-based feedback or control.

Introduction

The human ankle joint is a complex biomechanical structure responsible for enabling mobility, balance, and stability during locomotion. It allows motion primarily in the sagittal plane (dorsiflexion and plantarflexion) and secondary movements in the transverse plane (inversion and eversion). Replicating this intricate range of motion mechanically is crucial for understanding gait dynamics and for developing advanced prosthetic devices and robotic systems. The human gait cycle involves sequential actions—heel strike, mid-stance, and toe-off—each requiring precise coordination between the ankle and metatarsal joints to generate propulsion and maintain stability.

In recent years, robotic ankle mechanisms have gained significance in both rehabilitation and humanoid robotics. However, most existing designs focus on electronic control rather than studying the underlying mechanical motion behavior. Understanding the dynamics of joint rotation, torque amplification, and axis alignment is essential before integrating sensors and control systems. Therefore, this project focuses on the mechanical design and motion simulation of a robotic ankle joint that reproduces realistic gait-like motion.

The proposed system consists of two rotational axes that simulate sagittal and transverse plane movements, driven by servo motors through spur gear transmission to achieve torque amplification. Additionally, a metatarsal hinge joint actuated through a linkage mechanism replicates toe flexion during push-off. All rotational joints incorporate ball bearings to ensure frictionless and stable movement.

The entire design is developed using Fusion 360 CAD software, providing precise modeling and motion study capabilities. With an achievable motion range of approximately 45° in the sagittal plane and 15° in the transverse plane, the design successfully simulates natural ankle behavior. This project serves as a biomechanical motion study and a proof-of-concept prototype for future robotic and prosthetic ankle mechanisms, forming a foundation for subsequent control, actuation, and gait analysis research.

Design Methodology

The design methodology adopted for the mechanical robotic ankle system follows a structured approach inspired by human ankle biomechanics. The aim was to create a mechanical replica capable of reproducing natural ankle motion in multiple planes using servo-driven gear actuation. The overall workflow comprised anatomical study, concept generation, CAD modeling, mechanical design detailing, and assembly integration in Fusion 360. Each step was focused on maintaining biomechanical accuracy while ensuring mechanical feasibility for future 3D printing and actuation tests.

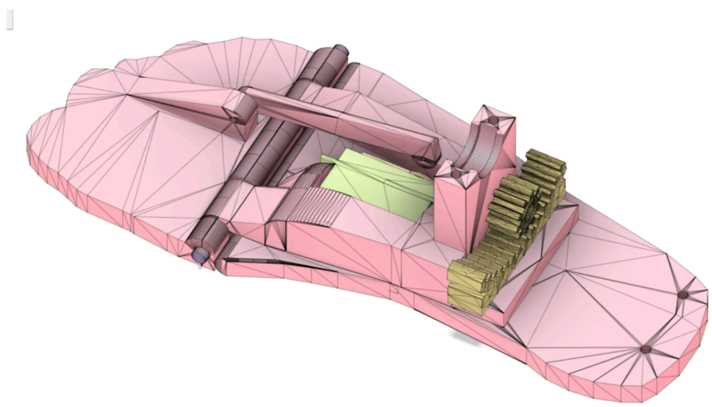

Fig 1. Base Plate

1. Anatomical and Functional Analysis

The first step involved studying the human ankle joint's range of motion and functional anatomy. The ankle primarily allows rotation about two major axes:

- **Sagittal plane motion (Dorsiflexion and Plantarflexion):** approximately ±45°, responsible for forward and backward foot rotation during walking

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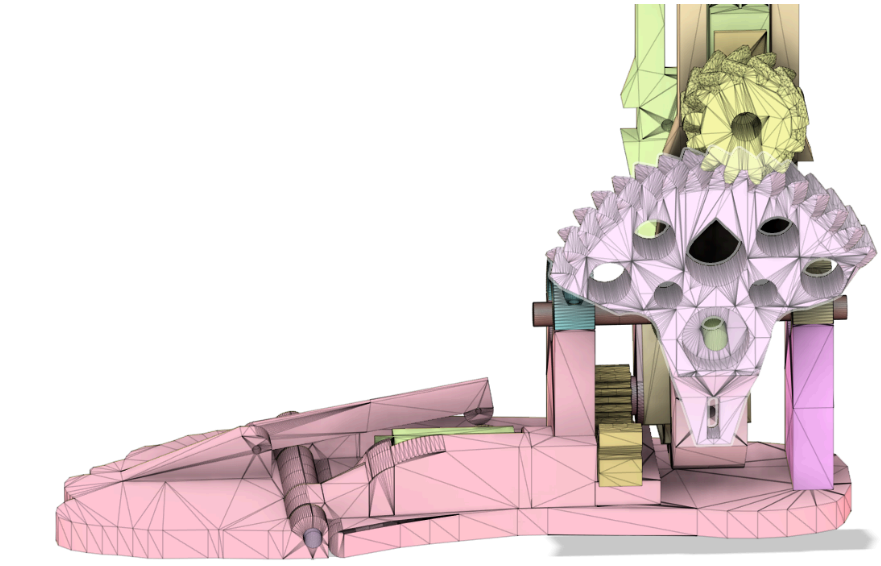

Fig 2. Sagittal plane movement through spur gears

- **Transverse plane motion (Inversion and Eversion):** approximately ±15°, enabling side tilting for balance and adaptability on uneven surfaces.

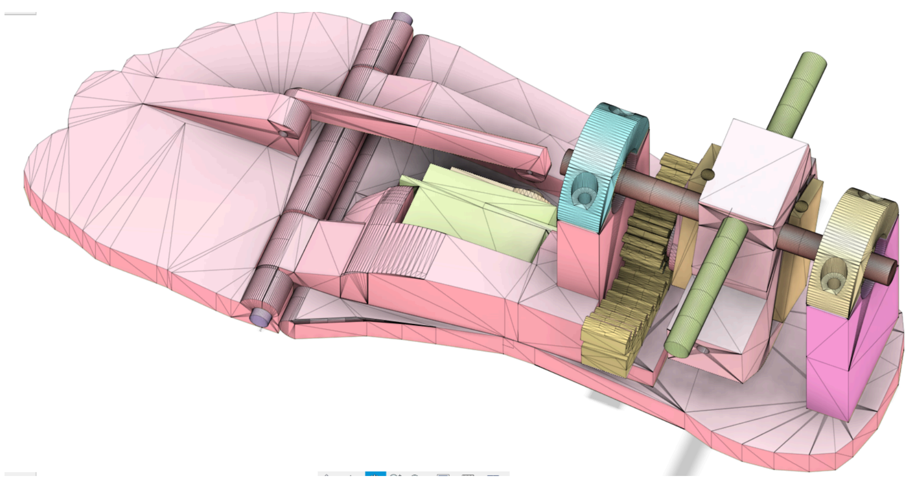

Fig 3. Transverse plane movement, linkage mechanism for meta tarsal joint

- The metatarsal joint located near the ball of the foot contributes to the toe-off phase of gait by allowing flexion and extension of the forefoot.
  These motion ranges formed the fundamental design constraints for the mechanical system.

2. Conceptual Design and Actuation Approach

To replicate these motions, a servo-based actuation system was selected due to its compactness, controllability, and ease of integration with CAD models. The design uses:

- Spur gear transmission for the sagittal and transverse joints to achieve torque amplification and precise motion transfer.

- A linkage mechanism for the metatarsal hinge to simulate toe flexion.

Unlike belt or chain drives, the spur gear mechanism ensures minimal backlash and compact assembly, making it suitable for a robotic joint where precise angular control is essential. The metatarsal linkage was modeled to convert the servo's rotary motion into linear movement, enabling realistic toe push-off motion during gait.

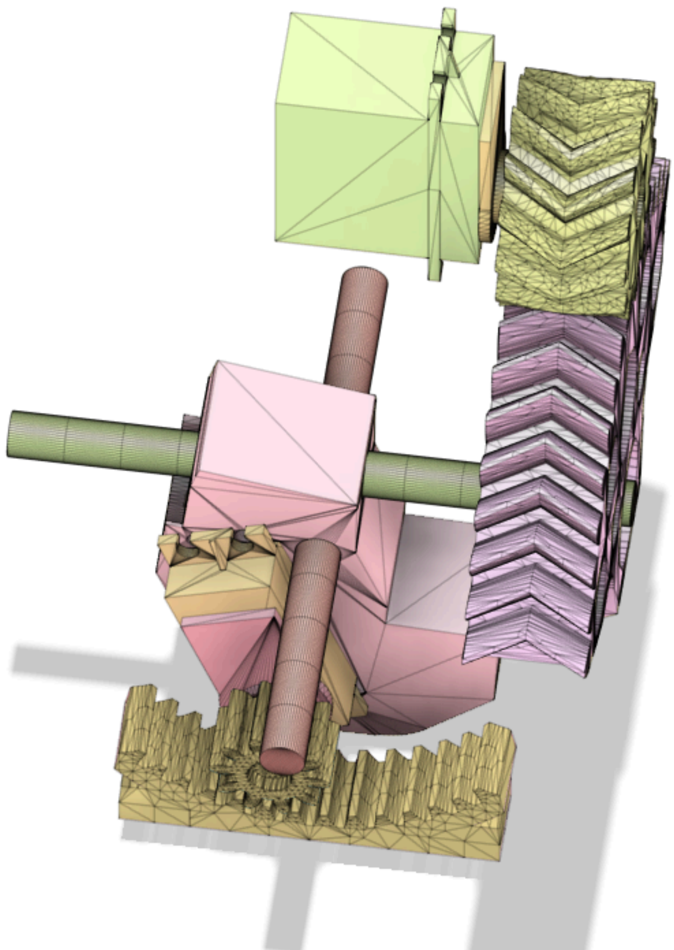

Fig 4. Core drive assembly

3. CAD Modeling in Fusion 360

The complete assembly was modeled using Autodesk Fusion 360, chosen for its robust motion study and assembly constraints features. The design was divided into three major subassemblies:

1. **Sagittal Axis Assembly:**
 The primary ankle rotation occurs here. A servo motor drives a spur gear mounted on the ankle shaft, which rotates the foot platform about the sagittal axis. Ball bearings are placed at both ends of the shaft to ensure smooth rotation and load support.

2. **Transverse Axis Assembly:**
 Mounted perpendicular to the sagittal axis, this assembly allows side-to-side rotation. The servo and gear system are positioned at the base, with the entire ankle module rotating relative to the lower leg housing.

3. **Metatarsal Hinge Mechanism:**
   Located near the forefoot, this hinge is connected to a servo through a **linkage arm**. The motion mimics toe flexion and extension that occurs during the terminal stance and pre-swing phases of gait.

4. Mechanical Components and Design Considerations

Each joint employs ball bearings to minimize friction and provide realistic joint articulation. Spur gears were dimensioned to maintain an appropriate gear ratio for torque multiplication, ensuring that even small servo motions produce sufficient angular displacement. The use of metal shafts and bearing housings (in CAD) allows for future physical realization using 3D printed PLA parts with embedded metal components.

The design also accounts for modularity, allowing independent or combined actuation of joints. The entire assembly was modeled with motion constraints replicating the physiological motion limits observed in humans. The servo motor placeholders were dimensioned for standard hobby servos, making future physical integration straightforward.

5. Assembly Integration and Kinematic Verification

After modeling each component, all subassemblies were integrated into a single mechanical structure. The ankle base, foot platform, and metatarsal hinge were aligned to maintain realistic kinematic relationships. Motion studies were carried out virtually within Fusion 360 to verify the achievable range of motion, gear alignment, and absence of interference between components during actuation. The final model demonstrated approximately 45° motion in the sagittal plane and 15° in the transverse plane, aligning well with physiological limits.

The working principle of the mechanical robotic ankle is based on the replication of human ankle kinematics through servo-driven gear actuation and linkage-based motion transfer. The system consists of three primary motion axes: the sagittal plane for dorsiflexion and plantarflexion, the transverse plane for inversion and eversion, and the metatarsal hinge for toe flexion and extension. Each motion is actuated independently using servo motors, allowing the model to reproduce the sequential phases of human gait.

The sagittal plane motion is achieved through a spur gear transmission system, where the servo motor drives a smaller gear meshed with a larger output gear connected to the ankle shaft. This configuration amplifies torque and enables a rotation of approximately 45°, simulating the natural up-and-down movement of the foot during walking. Ball bearings placed at the rotational points minimize friction and provide smooth angular displacement, allowing for consistent motion transmission.

For transverse plane movement, another servo motor is mounted orthogonally at the ankle base. It drives a similar gear pair that rotates the entire ankle-foot assembly side-to-side within a ±15° range. This motion replicates the subtle twisting or tilting that occurs during balance adjustments and directional changes in gait.

The metatarsal hinge joint near the forefoot is actuated through a linkage mechanism. When the servo rotates, the linkage converts its rotary motion into angular flexion at the hinge, mimicking the toe-off phase of the gait cycle. This motion enables the foot to pivot naturally during propulsion.

All three mechanisms operate synchronously or independently to reproduce key phases of human walking—heel strike, mid-stance, and toe-off. The system thus demonstrates how coordinated mechanical actuation can emulate complex ankle biomechanics, forming a strong foundation for prosthetic and robotic gait simulation research.

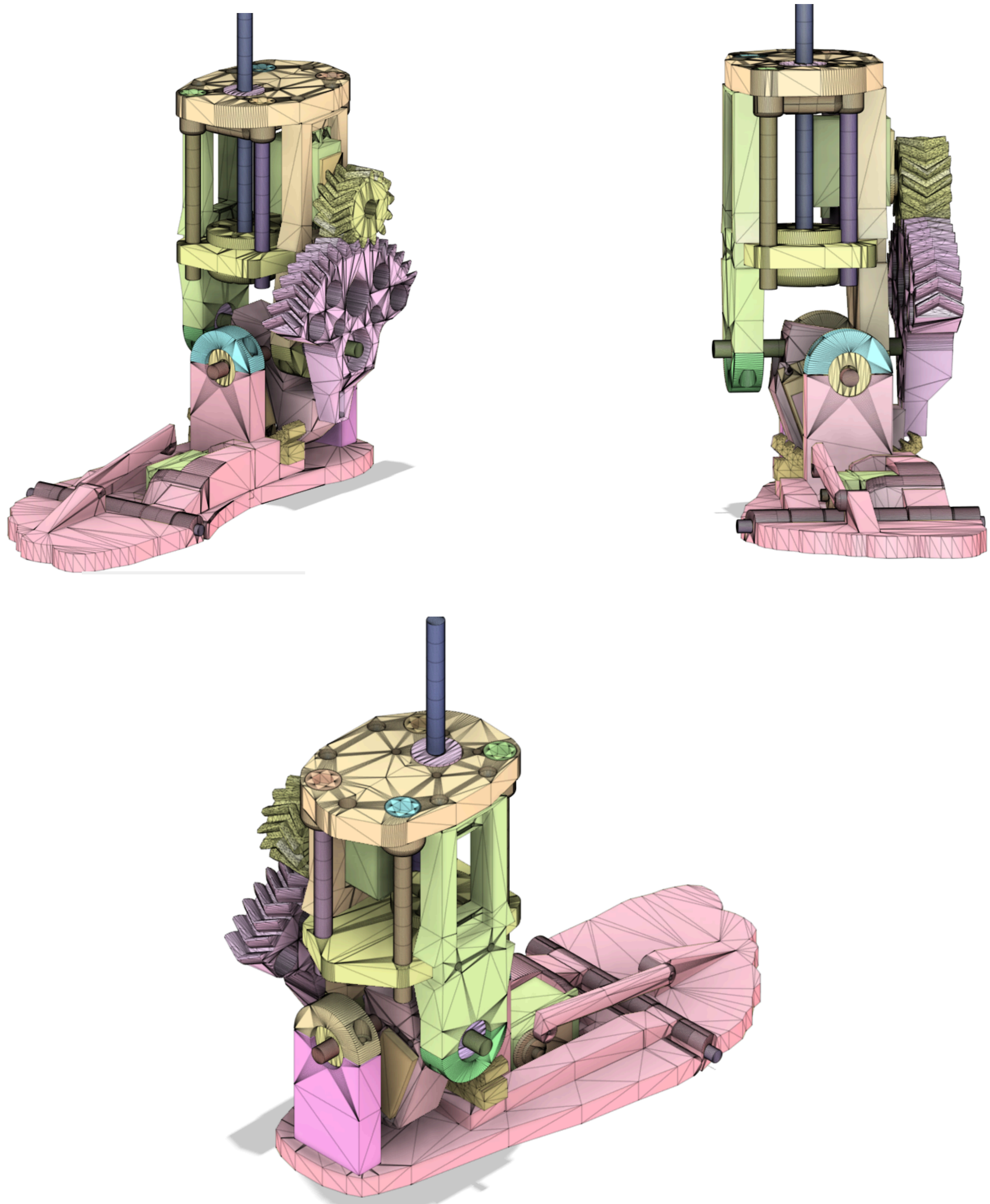

Fig 5,6 &7. Front and lateral views

Results

The designed robotic ankle model was virtually tested using motion studies within Autodesk Fusion 360 to verify the movement ranges, joint alignment, and mechanical response. The simulations demonstrated smooth and stable actuation across all axes without interference between moving components. The sagittal plane achieved approximately 45° of rotation, accurately representing dorsiflexion and plantarflexion, while the transverse plane achieved 15° of side rotation, replicating inversion and eversion. The metatarsal hinge, actuated via linkage, exhibited realistic toe flexion consistent with the terminal stance phase of gait. Ball bearings effectively minimized friction during rotation, confirming proper mechanical articulation. The results validated that the proposed design can successfully reproduce natural ankle motion patterns and serve as a reliable mechanical framework for studying gait dynamics and evaluating future prosthetic or robotic ankle systems before electronic integration.

This prototype bridges the gap between biomechanical motion understanding and functional robotic limb development, forming the groundwork for designing intelligent, adaptive prosthetic ankles and lower-limb robotic systems that mimic natural human gait patterns.

Future Scope

Future development of this project will focus on transforming the current mechanical prototype into a fully functional mechatronic system. Integration of sensors such as IMUs, potentiometers, or torque sensors will allow real-time motion feedback and enable closed-loop control of ankle positioning. Advanced microcontroller-based systems or embedded control boards (e.g., Arduino or STM32) can be used to synchronize the servo actuation for dynamic gait phase transitions. The design can also be enhanced using lightweight composite materials and metal-reinforced joints for better load distribution and durability once the prototype is 3D printed and physically assembled.