DESIGN AND ANIMATION-BASED SIMULATION OF A MECHANICAL PROSTHETIC LIMB

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Abstract: *The paper presents the design and virtual simulation of a mechanical lower-limb prosthesis developed using three-dimensional modeling tools. The study focuses on the geometric construction of the prosthetic components and on the realization of animation sequences in order to simulate the flexion and extension of the knee joint. A digital prototype was created and assembled in a CAD environment, followed by the definition of motion constraints that reproduce the real mechanical behavior of the prosthetic joint. The animation allowed the observation of angular displacement, alignment between components, and possible interference during movement. The results highlight the usefulness of virtual simulation in validating prosthetic motion before physical fabrication.*

Key words: prosthesis design, biomechanical simulation, CAD modeling, animation, kinematic analysis

1. INTRODUCTION

The design of lower-limb prostheses has evolved significantly over the past decades, moving from purely structural solutions to systems that attempt to replicate natural biomechanical motion [1]. The knee joint, in particular, represents one of the most complex articulations in the human body, combining rotation, controlled load transfer, and dynamic stabilization during gait [2].

In engineering terms, a prosthetic knee must satisfy two essential conditions: structural resistance under cyclic loading and controlled kinematic behavior. During walking, the knee undergoes repeated flexion–extension cycles, with angular amplitudes that may exceed 60° in normal gait and even higher values in specific activities [3]. Therefore, even a simplified mechanical prosthesis must ensure precise axis positioning and predictable rotational behavior.

Digital modeling and animation tools provide an intermediate validation stage between conceptual design and physical prototyping. By simulating movement in a controlled environment, the designer can observe the mechanical coherence of the system and identify potential alignment errors. This approach reduces material consumption and shortens development time, particularly in educational or experimental prosthetic projects.

2. PROSTHETIC DESIGN AND 3D MODELING

The prosthesis was modeled as a modular mechanical assembly consisting of two main structural segments: a femoral component and a tibial component. These two elements are connected through a rotational joint that simulates the knee articulation.

The geometric configuration of the prosthesis was established based on proportional anatomical references. Although the model does not replicate biological tissues, its dimensions were selected to approximate the relative proportions between femur and tibia segments.

Particular attention was given to the definition of the rotational joint. In biomechanical systems, the knee does not behave as a simple hinge; however, for mechanical simplification and simulation purposes, a revolute joint was adopted. This choice allows clear evaluation of angular displacement and eliminates unnecessary complexity during animation.

Wall thickness and component geometry were adjusted iteratively to ensure mechanical stability. Sharp edges were avoided, and smooth transitions between structural regions were introduced in order to reduce stress concentration areas. Even though the present study focuses on kinematic simulation rather than structural loading, maintaining geometric continuity contributes to more realistic behavior.

The complete digital assembly is shown in Figure 1, where the alignment between the upper and lower segments can be observed.

Figure 1. Three-dimensional model of the mechanical prosthesis

The geometric design was developed gradually. First, the main dimensions were defined based on proportional relationships specific to lower-limb anatomy. Afterwards, the structural thickness of the components was adjusted to ensure sufficient rigidity while maintaining a realistic overall shape.

3. SIMPLIFIED KINEMATIC AND MECHANICAL MODEL

To further evaluate the simulated motion, the prosthetic knee was treated as a planar single-link rotating system. The tibial segment was considered as a rigid body rotating around a fixed axis.

The angular position of the tibial segment can be expressed as:

$$\theta(t) = \theta_0 + \omega t \tag{1}$$

where:
$\theta(t)$ – angular displacement at time t
θ_0 – initial angular position
ω – angular velocity (rad/s)
t – time (s)
For a constant-speed animation, ω remains constant, resulting in uniform angular motion.
The angular velocity is:

$$\omega = \frac{d\theta}{dt} \tag{2}$$

and the angular acceleration:

$$\alpha = \frac{d^2\theta}{dt^2} \tag{3}$$

Even though the study focuses on kinematic simulation, a simplified mechanical estimation can provide insight into joint loading.

If the tibial segment is approximated as a rigid bar of length L and mass m, the gravitational moment around the knee axis during flexion can be estimated as:

$$M = mg\frac{L}{2}\sin\theta \tag{4}$$

where:
m – mass of tibial segment
g – gravitational acceleration (9.81 m/s^2)
L/2 – distance of center of mass from joint axis
θ – flexion angle

This expression shows that the moment increases with flexion angle and reaches its maximum at 90°. Even though the digital model does not simulate dynamic loading, this relation indicates the importance of proper axis alignment and structural stiffness in real prosthetic applications [2], [5].

4. ANIMATION AND MOTION SIMULATION

After completing the assembly, motion constraints were introduced in the CAD environment. The knee joint was defined as a revolute connection, allowing rotation around a single axis. The angular range was set between 0° (full extension) and approximately 90°

(flexion). The animation stage required the precise definition of motion constraints. The rotational axis was positioned concentrically within the joint housing. Any deviation from the central axis would have resulted in visible displacement during flexion. The movement was defined in discrete angular increments. This method allowed the creation of a smooth animation curve and provided better control over the simulated trajectory. The extension position (0°) is shown in Figure 2, while intermediate and maximum flexion stages are presented in Figures 3 and 4.

The selected angular range of approximately 90° corresponds to typical knee flexion required for sitting or stepping movements [3].

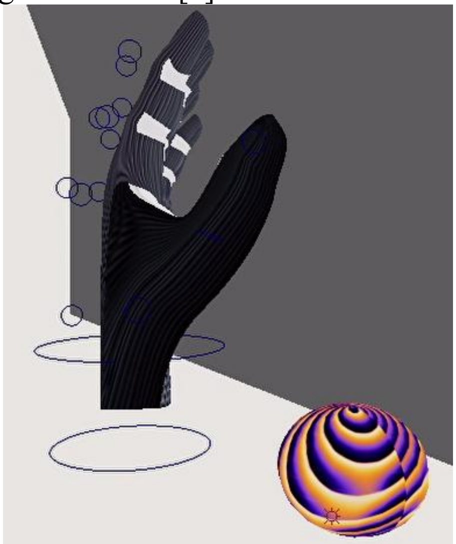

Figure 2. Prosthesis in extension position

The animation was created by defining incremental angular displacement over time. This method allowed the joint to rotate gradually, making the movement appear continuous and realistic.

An intermediate stage of the flexion movement is shown in Figure 3.

Figure 3. Intermediate flexion stage

The maximum flexion position is presented in Figure 4.

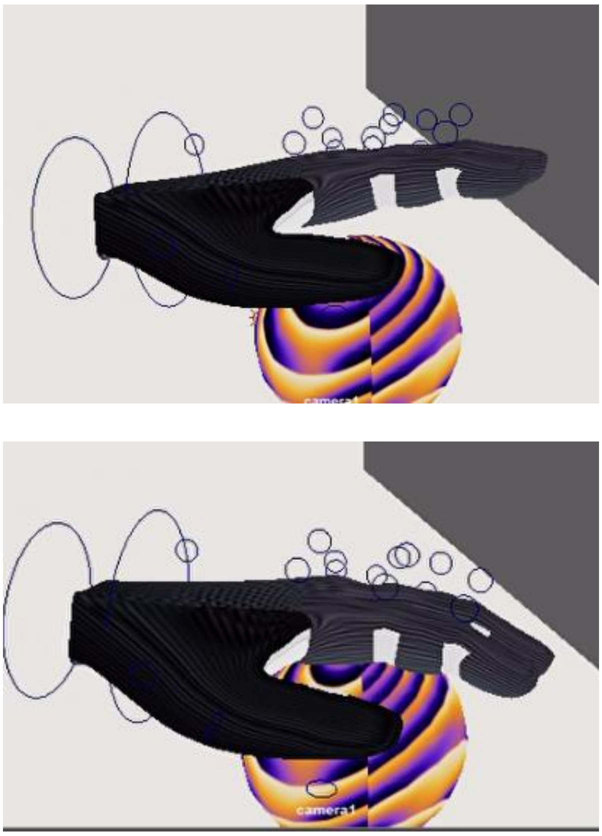

Figure 4. Maximum flexion

Throughout the animation, the motion was monitored carefully to observe how the two structural segments interact.

One of the main advantages of animation-based simulation is the possibility of detecting interference between components. During the simulated motion, the model was analyzed to verify:

- whether any parts overlapped or collided,
- whether the rotation remained centered on the defined axis,
- whether the geometry allowed smooth movement.

The simulation showed that the prosthesis maintains correct alignment during the entire flexion range. No unexpected displacement or geometric interference was observed.

The animation process confirmed that the proposed prosthetic configuration allows controlled flexion–extension movement. The rotational joint behaved consistently within the defined angular limits.

An important observation was that correct positioning of the rotation axis significantly influences the realism of the movement. Small adjustments made during the modeling stage improved the smoothness of the animation and prevented mechanical overlap between structural elements.

The virtual evaluation also highlighted the importance of maintaining adequate clearance between the femoral and tibial segments. Even in a simplified mechanical model, improper spacing can restrict movement or create unrealistic contact points.

Compared to static modeling, animation provides a dynamic perspective. It allows the designer to observe not only the geometry but also how the components behave during motion. This step represents a valuable intermediate phase before manufacturing a physical prototype.

5. CONCLUSION

The study presented the design and animation-based simulation of a mechanical lower-limb prosthesis. Through three-dimensional modeling and controlled motion constraints, the flexion–extension behavior of the knee joint was successfully reproduced in a virtual environment.

The animation confirmed correct joint alignment and smooth angular displacement within the selected range. The absence of interference between components indicates that the geometric configuration is mechanically coherent.

Virtual simulation proved to be an effective tool for validating prosthetic motion prior to fabrication. By identifying and correcting geometric inconsistencies during the digital stage, the development process becomes more efficient and cost-effective.

Future work will include load analysis and dynamic force simulation in order to evaluate the structural response of the prosthesis under realistic walking conditions.

The simplified moment estimation highlights the mechanical implications of increasing flexion angles. As θ increases, the gravitational moment around the joint axis becomes larger. This observation emphasizes the importance of adequate material selection and joint reinforcement in real prosthetic systems.

Even though the present model does not include force simulation, introducing this analytical approximation strengthens the engineering understanding of the prosthesis behavior.

Furthermore, defining angular velocity explicitly allowed better control of animation smoothness. Excessive angular speed would generate unrealistic motion, while very low speed would not reflect functional gait conditions.

6. REFERENCES

[1]. **Angeles, J.** *Fundamentals of Robotic Mechanical Systems*. Sitech Publishing House, Craiova, 2001

[2]. **Winter, D.A.** *Biomechanics and Motor Control of Human Movement*. John Wiley & Sons, 2009

[3]. **Perry, J., Burnfield, J. Gait** - *Analysis: Normal and Pathological Function*. SLACK Incorporated, 2010.

[4]. **Norton, R.** *Design of Machinery: An Introduction to the Synthesis and Analysis of Mechanisms.* McGraw-Hill, 2012.

[5]. **Radcliffe, C.W**. *The Biomechanics of Knee Prostheses*. University of California Press, 1994.Angeles, J. Fundamentals of Robotic Mechanical System.