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Review and Comparative Analysis of Modern Knee Prostheses with Development of a Conceptual Design †

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Abstract

This paper provides a comprehensive review of the structural features and biomechanical functions of modern passive and semi-active knee prostheses, followed by comparative analysis. Based on findings from scientific literature and engineering practice, a new conceptual knee prosthesis was developed using a modular design approach. The proposed structure was modeled in SolidWorks, and its kinematic behavior and structural integrity were quantitatively evaluated through finite element analysis (FEA). The knee module was specifically designed to integrate with previously developed ankle and foot prosthetic components via an adapter interface. This modular approach allows the prosthesis to be configured according to the individual clinical needs of the patient. Simulation results confirmed that the proposed design meets the requirements for motion accuracy and structural reliability. In future work, the physical prototype will be manufactured using 3D printing with PLA plastic as an initial test material, followed by fabrication with high-strength engineering plastics or metal alloys. This study represents a critical early step toward the development of a fully functional, adaptive lower-limb prosthetic system.

Keywords: knee prosthesis; modular design; biomechanical analysis; passive systems

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1. Introduction

The knee joint is one of the most complex and highly loaded joints in the human musculoskeletal system. It plays a critical role in enabling essential movements such as walking, sitting, standing, bending, and ascending stairs, while also maintaining overall body balance. In recent decades, the frequency of knee joint injuries has increased due to growing mechanical loads. Injuries, osteoarthritis, rheumatoid arthritis, and other degenerative diseases, as well as postoperative complications, can lead to partial or complete loss of knee joint function [1–3].

Knee prostheses are among the primary solutions aimed at restoring mobility and improving patients' quality of life. However, most of the knee prostheses currently

in use still face several limitations. These include insufficient motion precision, low energy efficiency, limited levels of intelligent control, and restricted adaptability to individual users.

This paper presents a comprehensive review of modern knee prosthetic systems, focusing on the comparison of their functional and technical characteristics. In addition, a new conceptual design of a knee prosthesis is developed, aiming to meet specific engineering requirements and biomechanical demands.

The study is based on an interdisciplinary approach that integrates biomedical engineering, rehabilitation technologies, and robotics. The proposed conceptual model serves as the foundation for a modular and adaptive prosthetic system that can be integrated with existing ankle and foot modules. Such a system enables customizable configurations based on the level of amputation and provides the flexibility needed to enhance the rehabilitation process and facilitate patient reintegration into daily life.

2. Review of Modern Knee Prostheses

2.1. Industrial Systems Overview and Academic Research

Currently, major companies specializing in the production of knee prosthetic devices hold leading positions in the global market. Their products are characterized by clinical efficiency, high reliability, and technological sophistication. At the same time, new-generation prosthetic models developed by academic and engineering researchers are gaining attention due to their integration of the latest advances in science and technology. This section first highlights industrial solutions from leading manufacturers and then presents a comparative analysis with academic research projects.

Among the key companies producing knee prostheses are Össur (Reykjavík, Iceland), Ottobock (Duderstadt, Germany), Freedom Innovations (Irvine, CA, USA), as well as brands such as Endolite (Basingstoke, UK), Blatchford (Basingstoke, UK), and Zimmer Biomet (Warsaw, USA) (Figure 1). These products are typically based on advanced biomechanics and microelectronic technologies.



(**a**) (**b**) (**c**)

Figure 1. Modern intelligent industrial knee prostheses: (**a**)—C-Leg (Ottobock); (**b**)—Rheo Knee (Össur); (**c**)—Genium X3 (Ottobock).

– Genium X3 (Ottobock)—This knee prosthesis integrates a hydraulic system, multisensor feedback, and Bluetooth-based smartphone control. It stands out as a high-precision, fully waterproof prosthesis capable of operating in aquatic environments [4].

- Rheo Knee (Össur)—A sensor-driven knee prosthesis utilizing adaptive control algorithms. It automatically detects the user's gait pattern and adjusts the joint stiffness accordingly [5].
- C-Leg (Ottobock)—Designed for elderly individuals or those with low mobility, this safety-oriented prosthesis is equipped with intelligent control systems [6].

These prostheses operate at a bionic level and are capable of reproducing gait trajectories close to natural human movement. However, their high cost and technological complexity significantly limit accessibility in developing countries.

In addition to commercially available products, numerous promising academic and engineering research efforts are being carried out to improve knee prosthesis technologies. These studies aim to overcome current limitations and develop low-cost, adaptive systems. Below are ten of the most notable academic contributions: A semi-active prosthesis was proposed that combines an electric motor and a spring to accurately imitate the natural gait cycle, thereby enhancing biomechanical adaptation and energy efficiency [7]. Another study developed a hydraulically actuated knee prosthesis capable of adapting to various terrains and obstacles, providing responsive dynamic performance suitable for active users [8]. A prosthesis based on a magnetorheological damper was introduced to allow precise control of knee motion by varying fluid viscosity [9]. A motorized clutch mechanism was implemented in a semi-active system to enable dynamic adjustment of stiffness in response to user intent [10]. A passive knee prosthesis driven by ground reaction force (GRF) was developed, incorporating an early stance flexion (ESF) mechanism to absorb impact and improve gait symmetry [11]. A novel design utilizing a virtual locking axis and a six-bar linkage mechanism was proposed to enhance flexibility while maintaining joint stability [12]. A unidirectional friction clutch system was used for swing phase control, offering variable resistance throughout the gait cycle [13]. Configurations involving 5 bar and 7 bar linkages integrated with ESF mechanisms were investigated to reduce ground impact and ensure smooth foot contact [14]. Additionally, a pneumatic system with an adjustable valve was designed to regulate knee flexion and extension based on walking speed, promoting natural motion [15]. Finally, the MIT Knee-2 introduced a virtual locking mechanism with dual stability axes to facilitate smooth transitions between gait phases without fully locking the joint [16].

These studies reveal a wide spectrum of approaches and concepts in knee prosthesis design. Each solution addresses a specific biomechanical challenge—from improving gait naturalness and enhancing energy efficiency to enabling intelligent user adaptation. Collectively, they provide a solid foundation for the future development of intelligent, modular, and user-intent-driven prosthetic systems.

Table 1 provides a structured comparison of industrial and academic approaches to knee prosthesis development. While industrial models offer high technological readiness, integrated ergonomics, and advanced feedback systems, academic prototypes are typically more affordable, modular, and suited for experimental and educational applications. These distinctions highlight the need to further develop research prototypes for practical and clinical use.

Table 1. Comparative Analysis of Industrial vs. Academic Knee Prosthesis Solutions.

Criteria	Industrial Models	Research Prototypes
Price	Very high ($30,000–$100,000+)	Low ($1000–$5000)
Technology	Mature, commercialized	Experimental, sometimes manually controlled
Ergonomics	User-adapted, esthetic	Mainly for laboratory use
Feedback System	Fully integrated (sensors, AI)	Basic or external module-based
Target User	Patients and clinical environments	Research laboratories and educational institutions

2.2. Comparative Analysis

Modern knee prostheses represent a combination of structural components and control systems designed to replicate complex biomechanical functions. As described in the review by [17], various prosthetic knee mechanisms are categorized based on their functional objective stability, early stance flexion (ESF), and resistance during the swing phase. This classification plays an essential role in guiding both prosthesis selection and design.

Stability is a critical function, particularly during the early stance phase, to prevent unintended knee buckling. To achieve this, monocentric, polycentric, and GRF (ground reaction force)-dependent mechanisms are employed. For instance, weight-activated and hyperextension-controlled systems prevent involuntary flexion.

The early stance flexion (ESF) function is aimed primarily at active users and helps absorb shock at heel strikes. This feature improves both energy efficiency and walking comfort. Some passive prostheses implement ESF mechanisms with a predefined flexion range, allowing shock absorption without compromising joint stability. ESF thus contributes to smoother motion and reduces joint loading during the initial gait phases.

Table 2 compares the structural and adaptive characteristics of early stance flexion (ESF) mechanisms used in various prosthetic knee designs. Activation methods range from weight-based triggering to GRF-responsive mechanisms, mechanical resistance, and buffer-limited motion. Some systems operate exclusively during the stance phase, while others provide dual-phase adaptability, including swing control. Such a comparison helps identify the functional benefits of each system, supporting tailored prosthesis selection based on patient needs.

Table 2. Comparative Features of ESF Mechanisms in Knee Prostheses.

Prosthesis Model	Structure Type	ESF Activation Method	Phase Adaptation	Key Features
Blatchford ESK+	Single-axis + ESF	Weight-activated	Stance phase only	Simple and reliable system
(Arelekatti et al. [18])	Locking axis + ESF	GRF-triggered	Locked during stance phase	Spring-assisted return mechanism
Ottobock 3R60	5 bar linkage	Resistance-based flexion	Adapts to stance and swing	High adaptability
Össur Total-2000	7 bar linkage	Buffered limit flexion	Smooth transition during phases	Enhanced shock absorption

Prostheses featuring ESF mechanisms improve the joint's ability to absorb impact and contribute to overall energy efficiency. These features are particularly beneficial for active users, as they reduce joint loading and enhance gait quality.

During the swing phase, the knee must achieve maximum flexion followed by full extension. This phase often relies on frictional, pneumatic, or hydraulic dampers, which reduce impact during terminal extension and enable smoother, more natural gait transitions.

The article also compares the functional features of commercial products (Ottobock, Össur, Blatchford) and research-based passive knee prototypes such as MIT Knee, LCK-nee, and NA-Hybrid. These solutions are categorized by function—stability, ESF, and swing phase resistance highlighting the structural mechanisms used in both industrial and experimental systems.

To ensure stability, weight-brake and locking mechanisms are commonly applied, as seen in OT-3R49, OS-OP4, and BL-Mercury models. The NA-Hybrid prototype provides a research-based alternative in this category. ESF functions are implemented through specialized linkage systems, such as in the OT-3R80 and Össur Total-2000 prostheses, and in academic models like MIT-Knee-1. Swing phase resistance is typically achieved using hydraulic dampers, integrated into commercial designs like OS-OH7 and TL-X6, and research prototypes such as MIT-Knee-2.

This classification system provides a clear understanding of the structural strategies associated with each key function, aiding in both engineering evaluation and clinical application (Table 3).

Table 3. Functional Classification of Structures in Knee Prostheses (Stability, ESF, Swing Resistance).

Function	Mechanism Type	Commercial Examples	Research Prototypes
Stability	Weight-brake, Lock	OT-3R49, OS-OP4, BL-Mercury	NA-Hybrid
ESF	ESF linkage	OT-3R80, Össur Total-2000	MIT-Knee-1
Swing Resistance	Hydraulic damper	OS-OH7, TL-X6	MIT-Knee-2

2.3. Strengths and Limitations of Existing Solutions

Despite advancements in functional mechanisms, current knee prostheses still face challenges in fully adapting to users' mobility needs. The capabilities and limitations of both passive and microprocessor-controlled knee joints become especially evident in specific situations.

Strengths:

- Passive prostheses are characterized by structural simplicity, energy efficiency, and low cost. They generally offer high reliability and require minimal maintenance.
- Microprocessor-controlled prostheses are capable of adapting to dynamic conditions. For instance, hydraulic systems can automatically adjust damping levels based on walking speed, improving the user's gait stability.
- Some modern systems are capable of integrating early stance flexion (ESF) and swing resistance functions within a single device, enhancing gait naturalness and reducing impact forces during walking.

Limitations:

- Limited adaptability to the environment: Passive knee systems often struggle on uneven terrain (e.g., stairs, slopes), while some microprocessor solutions rely on monocentric designs that may not fully replicate natural joint movement.
- Restricted recognition of user intent: Passive systems cannot directly interpret the user's motion intention. They only respond to parameters such as joint angle, force, or acceleration detected via sensors, limiting real-time adaptation to spontaneous movement.
- Latency in finite state machine (FSM)-based control strategies: These systems operate based on previous gait data, which may cause delays (hysteresis) in responding to the current state of motion.
- EMG (electromyography)-based control still presents significant challenges due to weak signal strength, high noise levels, and the limited muscular activity of residual limbs. As such, EMG is not yet reliable for fully independent control.
- Short lifespan and poor technical adaptability: Many current knee prostheses tend to fail within 3–5 years of use. When one component malfunctions, the entire system may need replacement, resulting in additional financial burden for the user.

In summary, existing solutions do not fully meet the requirements of functional biomechanics. Therefore, future developments should focus on modular, adaptive systems with advanced sensor feedback and intelligent semi-active or active control, capable of responding to the user's real-time motion intent.

3. Materials and Methods

3.1. Development of a Conceptual Design

Based on the review and functional-comparative analysis of modern knee prostheses, a new conceptual solution has been developed. This structure meets the biomechanical requirements of a prosthetic knee system and is designed to ensure efficiency in terms of modularity, reliability, ergonomics, and manufacturability.

The proposed conceptual model consists of three main components arranged from top to bottom:

- Upper joint (hinge) mechanism
- Central load-bearing body
- Lower mounting interface module

The main body is machined from aluminum alloy using milling techniques. Its internal hollow geometry is designed to accommodate internal elements such as mechanisms, cables, and dampers. The key dimensions of the model are as follows:

- Total height: 340 mm
- Upper joint unit height: 108 mm
- Central body width (front view): 63 mm
- Maximum width (rear view): 94 mm
- Lower section height: 52 mm

The body surface includes weight-reducing cutouts that help minimize mass and enhance thermal dissipation efficiency.

The dual-axis upper rotary mechanism ensures joint flexibility, enabling the prosthesis to mimic the natural amplitude of human knee motion. It is designed to preserve biomechanical conformity while minimizing motion restrictions. The incorporation of eccentric elements and threaded joints enhances precision and adjustability.

Figure 2 presents the main components of the design, including the upper joint, load-bearing central body, and lower attachment unit. Dimensions are annotated. Lateral cutouts contribute to structural lightness and visual appeal.

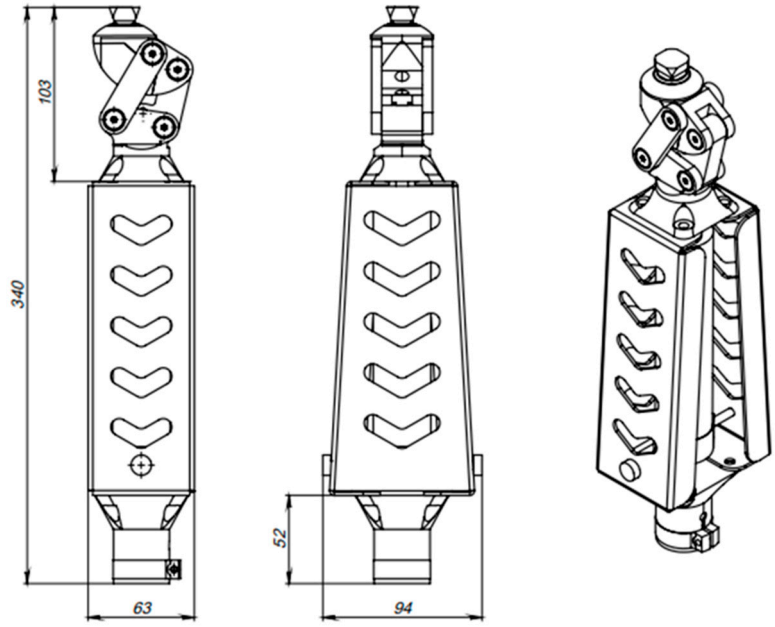


Figure 2. Conceptual knee prosthesis: front, side, and isometric projections.

The lower part includes a standard cylindrical interface designed for compatibility with various foot prosthetic components. This module complies with ISO standards and enables precise and secure attachment via four screw holes.

Figure 3 shows the interface from above, with a width of 63 mm and a length of 94 mm. The central cylindrical mounting hole allows seamless integration with modular prosthetic systems.

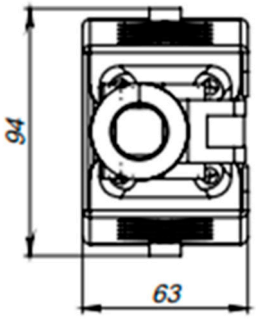


Figure 3. Top view of lower interface module.

The proposed conceptual structure offers several key advantages:

- Modularity—allows integration with different control units or damping systems
- Lightweight and durable—achieved through structural material selection and geometric optimization
- Adaptive architecture—kinematics and geometry tailored to human motion
- Manufacturing flexibility—suitable for CNC machining and 3D printing

This conceptual prototype has the potential to serve as the basis for future intelligent or actively controlled knee prostheses. The design is ready for laboratory simulation and mechanical testing.

3.2. Semi-Exploded View of the Assembled Conceptual Prosthesis

Figure 4 presents a semi-exploded view of the 3D model of the assembled knee prosthesis. This illustration clearly shows the spatial arrangement of each main component and enables a detailed breakdown of the system's functional modules (Table 4).

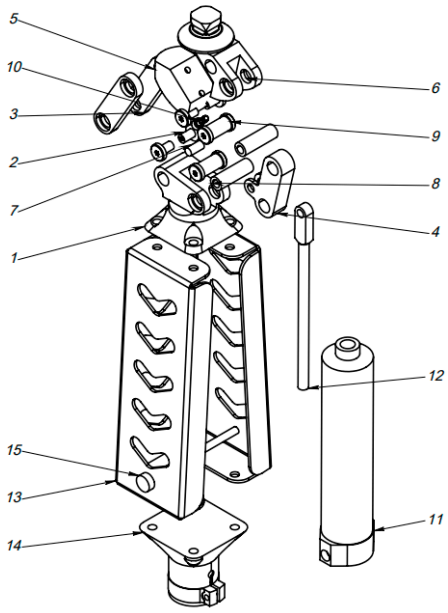


Figure 4. Key components of assembled knee prosthesis.

Table 4. List of components and their corresponding numbers in the semi-exploded view of the knee prosthesis.

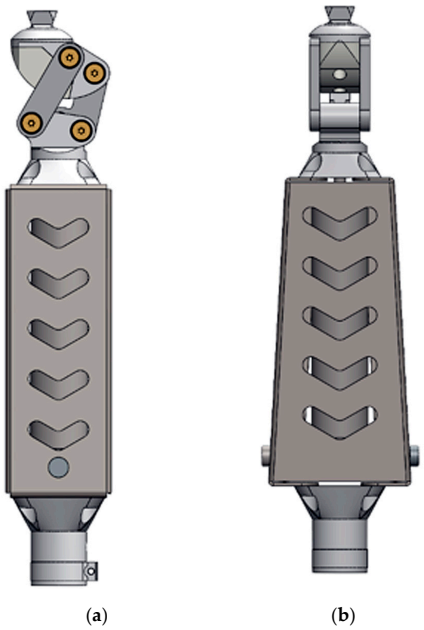
No.	Component Name
1	Main load-bearing body
2	Upper bracket block
3	Lateral support element
4	Push link arm
5	Upper attachment point
6	Rotational joint axis
7	Multi-link mechanism block
8	Support linkage
9	Auxiliary mounting bracket
10	Lateral bracket support
11	Lower interface connector
12	External damping element
13	Screw holes
14	Lower connecting plate
15	Load-bearing axis fixture

This semi-exploded view illustrates the modular architecture of the structure, the role of each component, and their interconnections. Such a design facilitates easier assembly during experimental validation, enables the testing of interchangeable components, and simplifies maintenance and repair procedures.

3.3. Three-Dimensional Model of the Assembled Knee Prosthesis (General View and Lower Interface)

The fully assembled 3D version of the proposed conceptual knee prosthesis clearly demonstrates the external design, geometric compatibility, and interface components of the prototype. The illustrations provide two primary perspectives: front and side projections, along with a top-down view of the lower interface section.

The views in Figure 5 depict the external appearance of the prosthesis in its fully assembled state. The side projection shows the upper joint block and its rotary components, while the front projection highlights the weight-relief cutouts on the central body and the lower mounting mechanism.



(**a**) (**b**)

Figure 5. Front (**a**) and side (**b**) views of assembled conceptual knee prosthesis.

– The side projection clearly shows the eccentric elements and joint axes.
– The front projection displays symmetrical cutouts in the central body, designed to reduce weight and enhance the esthetic appearance.

This Figure 6 shows the construction of the prosthesis's bottom surface. A central circular mounting hole allows for attachment to other prosthetic modules (e.g., foot platform). The structure integrates securely with standard mounting bolts via four screw holes.

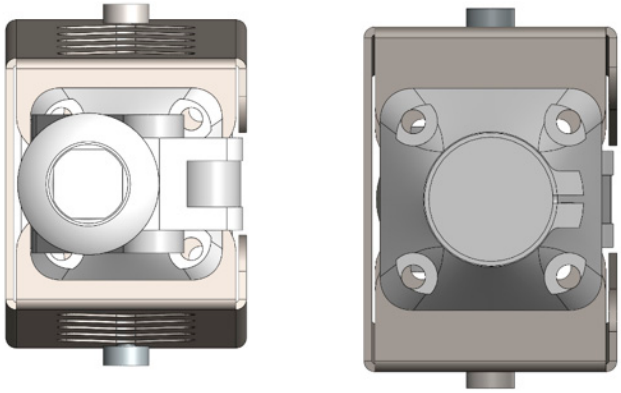


Figure 6. Top-down 3D view of lower interface block.

– The left-side view shows a rendered model with material properties visualized.
– The right-side view represents a technical projection emphasizing geometric specifications.

Design Features:

– The external geometry of the prosthesis is designed for compatibility with CNC machining or 3D printing;
– The interface dimensions comply with ISO standards for modular prosthetic integration;
– The modular connection between the joint block and lower flange allows for easy repair and component replacement;
– The dual-perspective layout reveals the precise geometry and level of mechanical integration within the structure.

3.4. Simulation and Motion Analysis Results

The conceptual knee prosthesis was simulated using SolidWorks 2024 Motion to evaluate its kinematic and dynamic characteristics. The total motion cycle time was 5 s, during which angular displacement, angular velocity, linear acceleration, and linear displacement were recorded.

Figure 7 below illustrates the time-dependent angular velocity of the system. The maximum value reaches approximately 67 degrees per second, and the curve shows both acceleration and deceleration phases. Two peaks represent two complete movement cycles.

Figure 8 represents the angular oscillation of the knee joint. The maximum angular displacement fluctuates between $-19°$ and $0°$. The motion exhibits a sinusoidal pattern, which closely mimics a natural walking cycle.

Figure 9 shows the change in linear acceleration within the system. At the beginning of the motion, the peak acceleration reaches approximately 211 mm/s^2, which then stabilizes through oscillations. This indicates the presence of spring or damping effects in the structure.

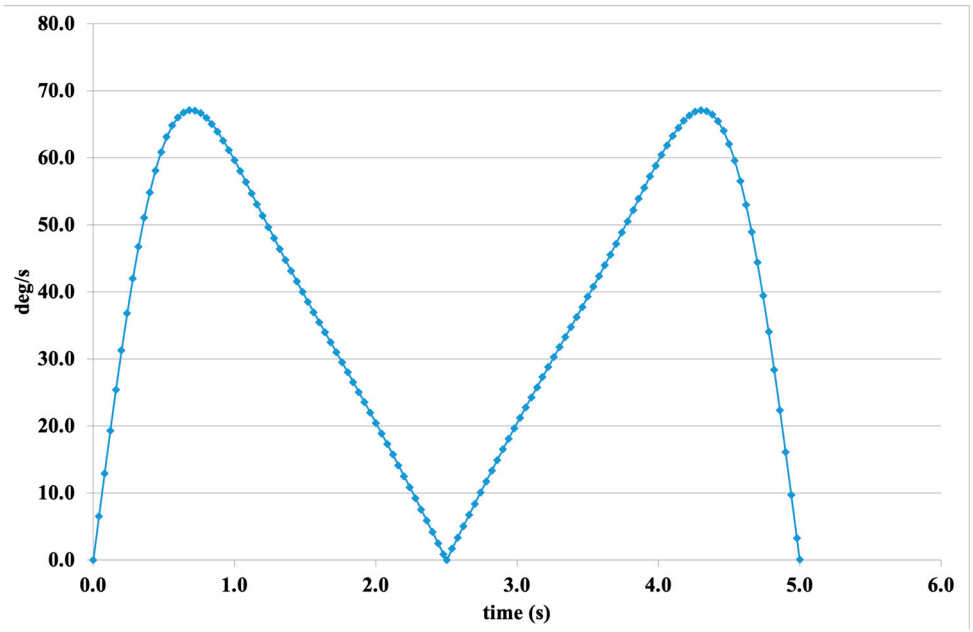


Figure 7. Angular velocity curve.

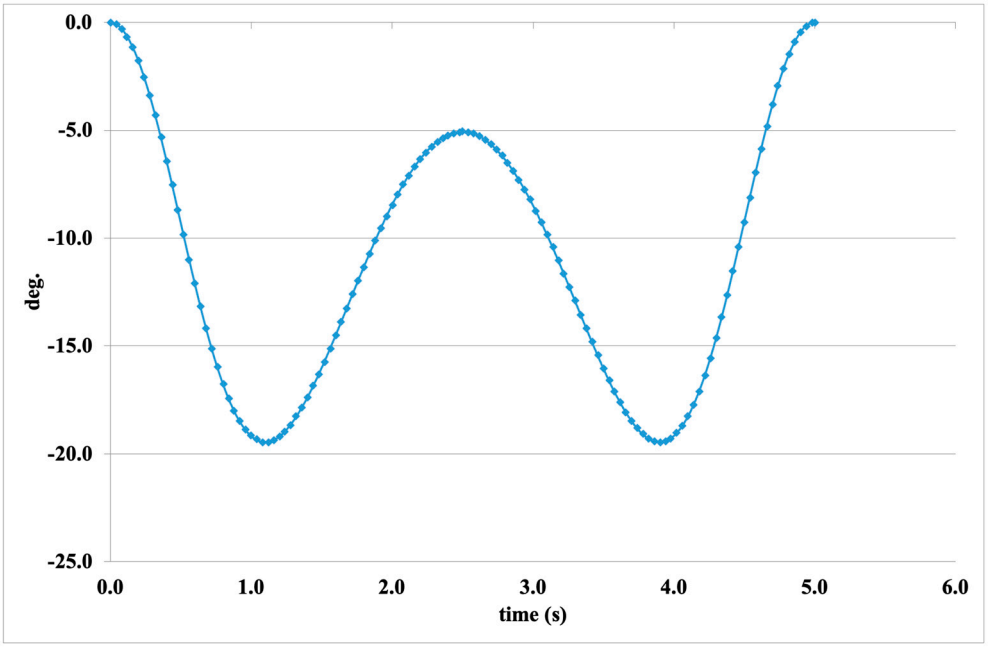


Figure 8. Angular displacement curve.

The linear displacement (Figure 10) demonstrates movement from 76.7 mm to 198.9 mm, indicating the overall range of motion and its variation across repeated cycles.

The simulation results presented above confirm several key characteristics of the prosthesis:

- Natural movement behavior (as seen in the angular displacement curve)
- Stability and repeatability (cycle symmetry)
- Dynamic response (velocity and acceleration values)
- Effective range of motion (linear displacement)

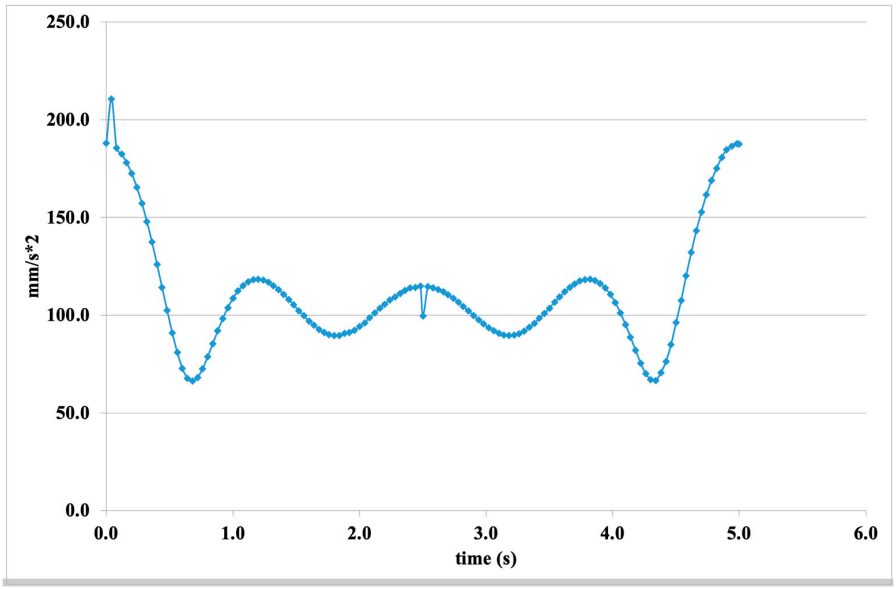


Figure 9. Linear acceleration curve.

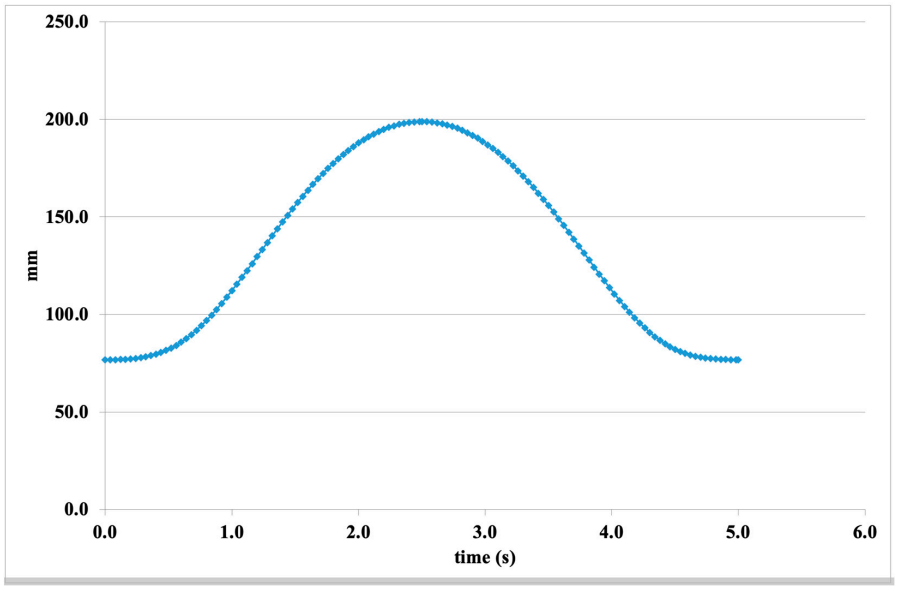


Figure 10. Linear displacement curve.

These findings validate the kinematic efficiency and mechanical compatibility of the structure and provide a reliable quantitative foundation prior to experimental testing.

All key simulation parameters and measured values from the motion analysis are summarized in Table 5. These results reflect the prosthesis's ability to perform smooth, cyclic movements resembling the natural knee joint trajectory.

Table 5. Summary of motion simulation results.

Parameter	Value
Total motion cycle time	5 s
Angular displacement range	–19° to 0°
Peak angular velocity	≈67°/s
Angular velocity pattern	Sinusoidal, with two cycles
Peak linear acceleration	≈211 mm/s^2
Linear displacement range	76.7 mm to 198.9 mm
Motion pattern	Smooth, cyclic movement similar to natural gait

3.5. Static Structural Analysis Results

The conceptual model of the knee prosthesis was analyzed under static loading conditions using the SolidWorks Simulation environment. This analysis was conducted to evaluate the mechanical response of the structure in terms of stress, displacement, and strain. The results demonstrated that the prosthesis geometry and material properties provide sufficient resistance to the applied loads.

The model was meshed with high-quality triangular elements (Figure 11). The mesh quality was set to "Normal (Quality1)" level, which ensured accurate and stable results. The number of elements was selected according to the structural complexity of the system.



Figure 11. Mesh generation of the model.

The stress distribution analysis shows a peak stress value of 535 MPa, located in a localized region near the upper hinge block. Areas of high stress are highlighted in red, while regions of minimal loading appear in blue (Figures 12–14). The critical zones have been annotated in the diagram to enhance interpretability and emphasize regions that may require structural reinforcement or material reassessment. Despite localized stress exceeding the material yield strength, the primary load-bearing structure remains within acceptable safety limits.

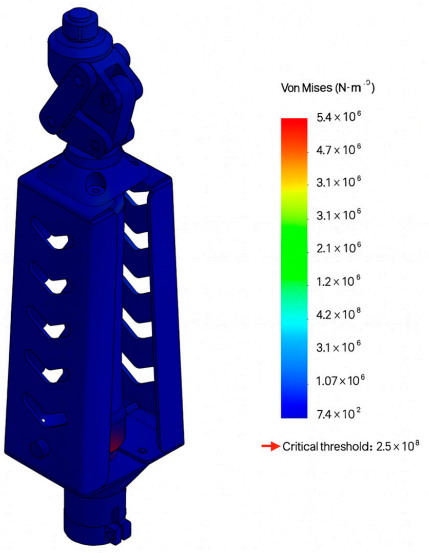


Figure 12. Von Mises stress distribution.

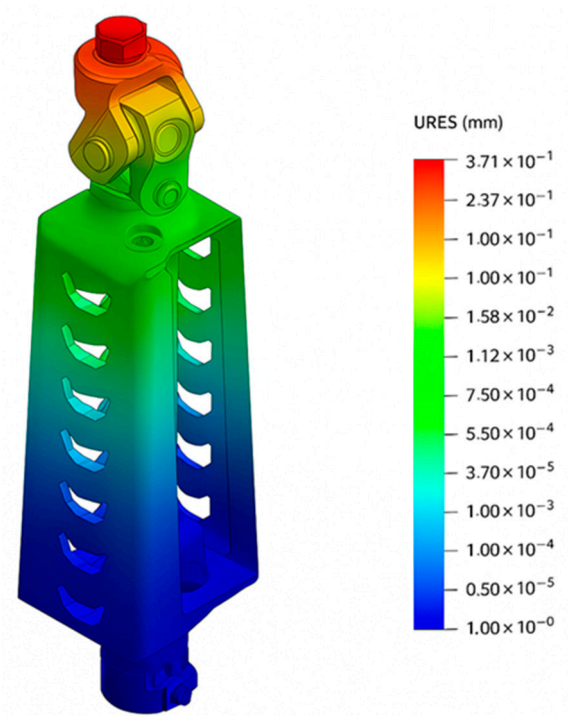


Figure 13. Total displacement.

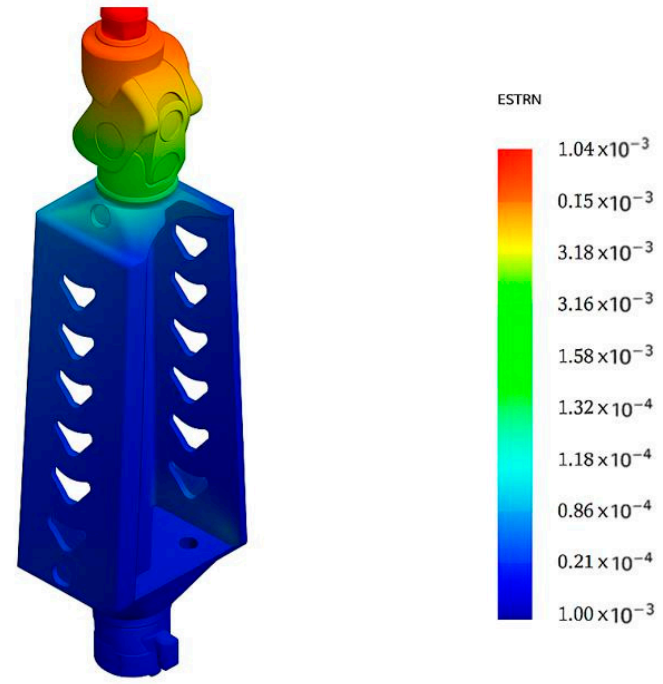


Figure 14. Strain distribution.

The total displacement plot reveals that the maximum displacement is 0.375 mm, while the minimum is approximately 0 mm. Most of the displacement is concentrated around the upper joint block. These values remain within acceptable limits, indicating high structural stiffness.

At this stage of the design process, several simplifying assumptions were made to facilitate numerical analysis. All contact surfaces between components were modeled as fully bonded, eliminating relative motion and friction between parts. This approach provides a preliminary estimate of the structural strength and stiffness of the prosthesis

but does not account for realistic movable connections such as hinges or bolted joints. Future simulations will incorporate more accurate contact definitions, including frictional interactions and degrees of freedom at mechanical joints, in order to improve the precision of stress and displacement evaluations particularly in critical connection areas.

The maximum equivalent strain is 1.06×10^{-3}, while the minimum is 1.80×10^{-12}. Strain is predominantly localized in the upper joint area where stress concentration is observed.

Summary of Findings:

- Mesh quality was adequate for reliable result interpretation.
- Stress concentration was observed in localized areas but remained within safety margins for the majority of the structure.
- Displacement values were minimal ($\leq$0.375 mm), confirming the high stiffness of the design.
- Strain was primarily present in the upper joint, with negligible deformation in the main load-bearing body.

These findings confirm that the proposed design can withstand realistic loads and is structurally sound for initial prototyping. However, reinforcement in high-stress regions or reevaluation of material selection may be necessary for final production.

3.6. Boundary Conditions and Simulation Setup

To ensure reproducibility, realism, and engineering accuracy in the static structural analysis of the knee prosthesis, the following boundary conditions and simulation parameters were defined:

- Analysis type—Linear static, without time-dependent or dynamic stress variations.
- Material—Aluminum alloy 6061-T6 (Kaiser Aluminum, Foothill Ranch, California, USA), known for its high strength-to-weight ratio and suitability for both CNC machining and 3D printing.
- Contact type—All mating components were assigned bonded (fixed) contacts, which restrict relative motion or sliding. This simplification is appropriate for the initial stage of structural evaluation.
- Fixtures—The bottom mounting surface of the prosthesis was fully constrained in all degrees of freedom, simulating a rigid fixation to a support surface.
- Load—A vertical force of 800 N was applied at the upper hinge joint, representing the body weight of an 80 kg user under static conditions.
- Coordinate system—A Cartesian coordinate system was used, with the Z-axis oriented vertically downward (in the direction of gravitational force).

This simulation setup was selected to estimate the structural response of the prosthesis under worst-case loading conditions and provides a foundation for further dynamic and fatigue analyses (Table 6).

Table 6. Mechanical Properties of Aluminum Alloy 6061-T6.

Property	Value	Units
Elastic modulus (Young's modulus), E	68.9	GPa
Poisson's ratio, ν	0.33	–
Yield strength	276	MPa
Ultimate tensile strength	310	MPa
Density	2.70	g/cm^3
Allowable strain (max)	0.002	–
Brinell hardness	95	HB
Elongation at break	12	%

The surface where the load was applied during the simulation is shown in Figure 15. A vertical force of 800 N was applied to the highlighted hexagonal face to simulate body weight under static conditions.

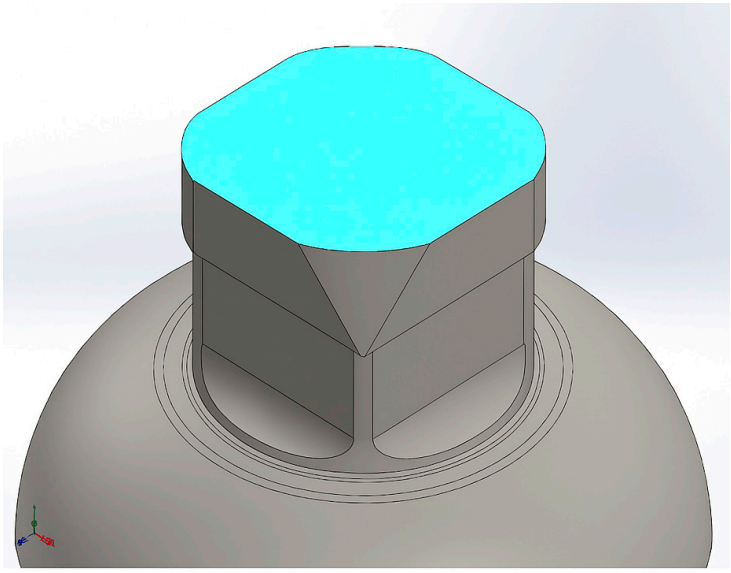


Figure 15. Load application surface in simulation model.

4. Future Work and Research Directions

Within the framework of this study, a conceptual model of a knee prosthesis was developed, and its kinematic and mechanical characteristics were evaluated. However, this work represents only one component of a comprehensive prosthetic system. Further research will continue in several directions aimed at developing a fully functional lower-limb prosthetic complex.

As part of this project, two additional important prosthetic systems were also developed [19]:

- Passive spring-damper foot without electric actuation: This system is based on spring elements and passive shock absorption mechanisms. It connects to the ankle module via an adapter and provides energy-free adaptation to ground conditions.
- Autonomous active ankle joint: This 2 DoF module operates in both the sagittal and transverse planes and is equipped with an intelligent control system. It is integrated with either the knee or foot structures through a ball-and-socket platform (BSP).

All components have been designed according to a modular principle. This approach allows each prosthetic joint to be used independently and configured according to the patient's clinical needs (e.g., level of amputation). For example, if only an ankle or only a knee prosthesis is needed, the corresponding module can be applied separately.

In the near future, the physical prototype of the knee prosthesis will be fabricated and tested through a multiphase process:

- Phase one: The initial prototype will be fabricated using PLA plastic through 3D printing to evaluate dimensional accuracy and basic mechanical compatibility.
- Phase two: Based on the outcomes of initial functional testing, a revised version will be produced using high-strength thermoplastics (such as PETG, ABS, or nylon) or lightweight aluminum alloys (e.g., AlSi10Mg or 6061-T6) to verify load-bearing performance.
- Final phase: The final version of the prosthesis will be manufactured using AISI 304 stainless steel, applying either Selective Laser Melting (SLM) metal 3D printing

or high-precision CNC machining, to ensure durability, corrosion resistance, and biomechanical reliability.

When using Selective Laser Sintering (SLS) or Selective Laser Melting (SLM) technologies, it is important to account for the anisotropic nature of the material's mechanical properties due to the layer-by-layer manufacturing process. Such components often exhibit different strength and stiffness characteristics depending on the direction of the applied load particularly between the build (Z) axis and the in-plane (XY) directions. For this reason, future simulations will incorporate orthotropic material models based on experimental data obtained from test samples fabricated using the same printing parameters as the final prototype. This approach will allow for a more accurate prediction of structural performance under real-world conditions and help reduce the risk of premature failure.

Clinical Adaptability

- The modular construction allows easy assembly and disassembly for testing;
- Each module is removable and replaceable as needed;
- Knee, ankle, and foot modules can be freely combined via an adapter;
- Full adaptation to the patient's clinical condition facilitates rehabilitation and daily use.

The current study focuses on static structural evaluation, future work will involve a more comprehensive assessment of the prosthesis under real-life operating conditions. A dynamic analysis is planned to simulate time-dependent and variable loads associated with activities such as walking, stair climbing, and transitional movements. In addition, a fatigue analysis based on stress–number of cycles (S–N) curves will be conducted to determine the endurance limit of the structure. These investigations will help account for the cyclic nature of loading and provide a more accurate prediction of the prosthesis's long-term durability during repetitive use.

5. Conclusions

This study presented a review and comparative analysis of the technical and functional characteristics of modern knee prostheses. Both industrial and research-based prototypes utilizing various mechanical principles were analyzed to identify their strengths and limitations. Additionally, a new conceptual design of a knee prosthesis was proposed, modeled in the SolidWorks environment, and evaluated in terms of its kinematic behavior and structural integrity.

The developed model is modular, biomechanically adaptive, and efficient from a manufacturing standpoint. Simulation results confirmed its motion accuracy and structural stiffness. In the future, this knee module is intended to be integrated into a complete lower-limb prosthetic system alongside the previously developed ankle and foot modules. Fabrication of the prototype will begin with PLA plastic and continue with engineering-grade polymers or aluminum alloys. The next phase of the project will involve experimental testing and user-specific functional evaluation.

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