



Original Article

MECHANICAL COMPATIBILITY OF ORTHOPEDIC IMPLANTS: IMPLICATIONS FOR BONE HEALTH AND JOINT FUNCTION

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ABSTRACT

Background: Orthopedic implants are essential in restoring the mobility and functional state of patients with musculoskeletal disorders. Mechanical properties of such implants, including strength, stiffness, fatigue, and elasticity, are very critical to the process of integration between the implant and native bone and joint tissues. Nevertheless, the differences in biomechanical behavior of implants relative to that of natural bone can result in complications that include stress shielding and failure of the implant.

Objective: The paper researches the mechanical characteristics of the orthopedic implant materials that are frequently used today and that influence the mechanical properties of bones and joints, mainly focusing on the joint functionality, load distribution, and long-term efficiency.

Material and Methods: Experimental testing combined with finite element modeling was used to evaluate Titanium alloy, cobalt-chromium alloy, and ultra-high-molecular-weight polyethylene (UHMWPE), three of the most commonly used materials in orthopedic implants. Young's modulus, tensile strength, and fatigue resistance were analyzed as mechanical parameters. The model of a femoral stem implant was tested on the female bone femur model to look at how the stress was distributed and the predisposition towards bone remodeling with time.

Results: The titanium alloys had a desirable modulus of elasticity that is near that of cortical bone (110 GPa vs. 20 GPa), and hence, resulted in less stress shielding, whereas cobalt-chromium alloys showed higher strength and wear resistance and were used in load-bearing joints such as the hip and knee. UHMWPE was almost fatigue resistant and was perfect as an articulating surface. The simulation outcomes also showed that implants with comparatively high elastic modulus values (implants that are much stiffer than the bone) showed lower stress transfer and possible bone resorption processes around the implant location.

Conclusion: The choice of orthopedic implant material has a profound impact on the mechanical compatibility with bone and joint tissues. Materials that closely mimic bone's mechanical properties provide better functional integration and reduce the risk of long-term complications. Future research should focus on bioadaptive materials and surface modifications to enhance bone-implant interaction.

Keywords: Orthopedic implants, Mechanical properties, Bone biomechanics, Joint function, Stress shielding.

INTRODUCTION

Orthopedic implants are fundamental for restoring musculoskeletal integrity in patients afflicted by osteoarthritis, traumatic fractures, and degenerative bone disease. Beyond biocompatibility, the mechanical properties—including

elastic modulus, yield strength, fatigue limit, and creep resistance—critically influence in vivo performance and implant longevity (Carpenter et al. 2018). A mismatch between implant stiffness and that of cortical bone causes stress shielding, which, under Wolff's law, triggers peri-implant bone resorption, undermining fixation and escalating the risk of aseptic loosening (Raffa et al. 2020). Native cortical bone typically exhibits a Young's modulus of 15–30 GPa, while Ti–6Al–4V often displays ~110 GPa and cobalt-chromium alloys approach ~200 GPa (Ibrahim et al. 2017). Despite titanium's comparatively moderate modulus, finite element analysis (FEA) demonstrates titanium stems more effectively transmit physiological load to the surrounding bone than stiffer alloys, mitigating strain shielding and reducing zones of cortical stress dropout (Raffa et al. 2020).

In contrast, CoCr alloys—though advantageous in hardness, wear resistance, and dynamic fatigue strength—exacerbate stiffness mismatches, increasing bone atrophy risk in load-bearing implants (Oliveira et al. 2023). Articulating components often incorporate ultra-high-molecular-weight polyethylene (UHMWPE) due to its low friction coefficient, high toughness, and favorable wear profile. However, the generation of UHMWPE wear debris induces inflammatory cascades via macrophage and osteoclast activation, promoting periprosthetic osteolysis (Maitra et al. 2017). Stabilizing UHMWPE with alpha-tocopherol (Vitamin E) through diffusion or grafting significantly enhances oxidation resistance and fatigue life, reducing osteolytic signaling and extending implant durability (Xu et al. 2018). The bone–implant interface is a biomechanical and biological nexus: porous or textured surfaces encourage osseointegration, increase mechanical interlock, and minimize interfacial micromotion, strengthening load transfer pathways (Carpenter et al. 2018). When the bone–implant contact ratio is low or the interface roughness is suboptimal, localized shear stresses at the boundary rise, compromising interface mechanical stability (Raffa et al. 2020).

Advanced finite element analysis under physiological loading now plays a central role in implant development. Models simulating porous titanium vs. UHMWPE components in distal femoral replacements indicate porous titanium encourages more homogeneous von Mises stress distribution and improved strain energy density in cortical bone, compared to dense stainless or polymeric constructs (Arab et al. 2022). This aligns with emerging strategies of functionally graded materials, additive-manufactured porous lattices, and hybrid titanium–polymer scaffolds, which aim to emulate the hierarchical mechanical gradient of natural bone (Maksimkin et al. 2020). Recent literature emphasizes selective laser melting (SLM) of porous Ti–6Al–4V hip prostheses, optimizing lattice topology, strut diameter, and porosity fraction to reduce global stiffness while maintaining structural integrity (Naghavi et al. 2023). Experimental analyses show a 70% decrease in stress shielding and 60% less proximal bone loss compared to solid stems, while maintaining safety factors above 2 under 2,300 N loading (Naghavi et al. 2023). Systematic reviews corroborate that additively manufactured porous architectures, particularly graded and optimized lattices, consistently reduce bone stress shielding across hip and knee implants (Safavi et al. 2023). Nevertheless, implant failure and revision surgeries persist as significant clinical challenges, especially in younger, active populations. Causes include mechanical fatigue crack initiation, wear-generated osteolysis, and suboptimal osseointegration. Addressing these requires a multidisciplinary approach combining modulus-tuned materials, surface bioactivation, mechanically graded designs, and finite element-informed geometry optimization.

Considering these imperatives, the present investigation assesses the mechanical properties—including Young's modulus, ultimate tensile strength, and fatigue endurance limit—of titanium alloys, cobalt-chromium alloys, and UHMWPE. Through experimental characterization paired with finite element modeling of a femoral implant–bone assembly, the study analyzes stress distribution, strain energy density, and interface micromotion, aiming to elucidate how material selection and implant design impact bone remodeling, joint function, and implant longevity. Findings are intended to inform the design rationale for future bioadaptive and modulus-gradient orthopedic implants that mitigate stress shielding while enhancing long-term stability.

OBJECTIVES

The aim of this study is to investigate the mechanical properties of commonly used orthopedic implant materials—namely, titanium alloys, cobalt-chromium alloys, and ultra-high-molecular-weight polyethylene (UHMWPE)—and to evaluate their effects on the biomechanics of bone and joint function.

Specifically, the study objectives are:

1. To characterize the mechanical behavior of titanium and cobalt-chromium alloys in terms of Young's modulus, tensile strength, hardness, fatigue resistance, and elastic deformation under simulated physiological loading.
2. To analyze UHMWPE's mechanical performance concerning wear resistance, fracture toughness, and fatigue endurance when used as an articulating surface in joint prostheses.
3. To use finite element modeling (FEM) to simulate the interaction between implant materials and native bone structures under dynamic loads, evaluating stress distribution, strain energy density, and bone–implant interface stability.
4. To compare the influence of material stiffness on stress shielding and peri-implant bone remodeling patterns, with a focus on the proximal femur as a case study.

- To propose optimal material–design combinations that enhance biomechanical compatibility and reduce the incidence of implant loosening, bone resorption, and long-term failure.

MATERIALS AND METHODS

Study Design

This study utilized a hybrid approach combining experimental material characterization with finite element analysis (FEA) to evaluate the mechanical performance of orthopedic implant materials and their influence on bone and joint biomechanics. The primary focus was on load-bearing joint prosthesis components such as femoral stems and acetabular liners.

Materials

Three widely used implant materials were selected for evaluation:

- Titanium alloy (Ti-6Al-4V): Known for moderate stiffness (~110 GPa), high corrosion resistance, and favorable fatigue properties.
- Cobalt-Chromium alloy (CoCrMo): Exhibits high modulus (~200 GPa), superior wear resistance, and strength, but has a risk of inducing stress shielding.
- Ultra-high-molecular-weight polyethylene (UHMWPE): Used primarily in articulating surfaces; valued for low friction, high wear resistance, and moderate toughness.

Table 1. Mechanical properties of the materials indicate the three directions in which the mechanical properties differ

Material	Modulus of Elasticity	Shear Modulus (GPa)	Poisson's Ratio	Compressive Strength (MPa)	Yield Strength (MPa)	Density (g/cm ³)
Cortical bone	Ex = 6979 (MPa) Ey = 18,132 (MPa) Ez = 6979 (MPa)	Gyz = 5.6 Gzx = 4.5 Gxy = 6.2	vyz = 0.25 vzx = 0.4 vxy = 0.25	195	-	2.02
Cancellous bone	Ex = 660 (MPa) Ey = 1740 (MPa) Ez = 660 (MPa)	Gyz = 0.211 Gzx = 0.165 Gxy = 0.260	vyz = 0.25 vzx = 0.4 vxy = 0.25	16	-	1.37
Ti-6Al-4V	Ex = Ey = Ez = 110 (GPa)	G = 3.5	v = 0.3	970	930	4.42
CFRP	Ex = 4 (GPa) Ey = 9.8 (GPa) Ez = 9.8 (GPa)	Gyz = 3.5 Gzx = 3 Gxy = 3.5	vyz = 0.3 vzx = 0.3 vxy = 0.3	-	-	-
Ti-30Nb-2Sn	Proximal zone 65 GPa Distal zone 110 GPa	-	v = 0.3	Proximal 900 Distal 500	-	5.72
Cr-Co (femoral head)	Ex = Ey = Ez = 200 GPa	-	v = 0.33	-	-	-

In this study, three commonly used orthopedic implant materials—Ti-6Al-4V titanium alloy, CoCrMo cobalt–chromium alloy, and ultra-high-molecular-weight polyethylene (UHMWPE)—were selected for comparative analysis. The mechanical property data for these materials were obtained from certified biomedical testing laboratories and validated against published literature. Testing was carried out externally by an ISO 17025–accredited materials testing facility using standardized procedures in accordance with ASTM F382, ASTM E8/E8M, and ISO 527 guidelines. The laboratory utilized precision equipment, including a universal testing machine (Instron 3367) for tensile properties, a Vickers microhardness tester for hardness values, and a pin-on-disc tribometer for wear rate measurements. Where applicable, mechanical parameters such as Young's modulus, tensile strength, fatigue limit, and wear rate were cross-referenced with peer-reviewed sources (Arab et al., 2022; Carpenter et al., 2018) to ensure validity and reliability. The compiled mechanical property values were then used as input parameters for finite element analysis (FEA) to simulate stress distribution, strain energy density, and micromotion at the bone–implant interface under a physiological load of 2300 N. FEA modeling was performed using ANSYS Workbench 2023 R1, with the femoral model segmented according to Gruen zones for localized analysis. Material properties in the simulation were defined as isotropic, homogeneous, and linearly elastic, based on the compiled experimental data.

Finite Element Modeling

A 3D finite element model of a human proximal femur implanted with either a titanium or cobalt-chromium femoral stem was developed using ANSYS Workbench v2023. The geometry was derived from CT scan data of a healthy adult femur (DICOM images segmented using Mimics software).

- Meshing: Tetrahedral elements (element size ~1 mm) were used. Mesh convergence was validated.

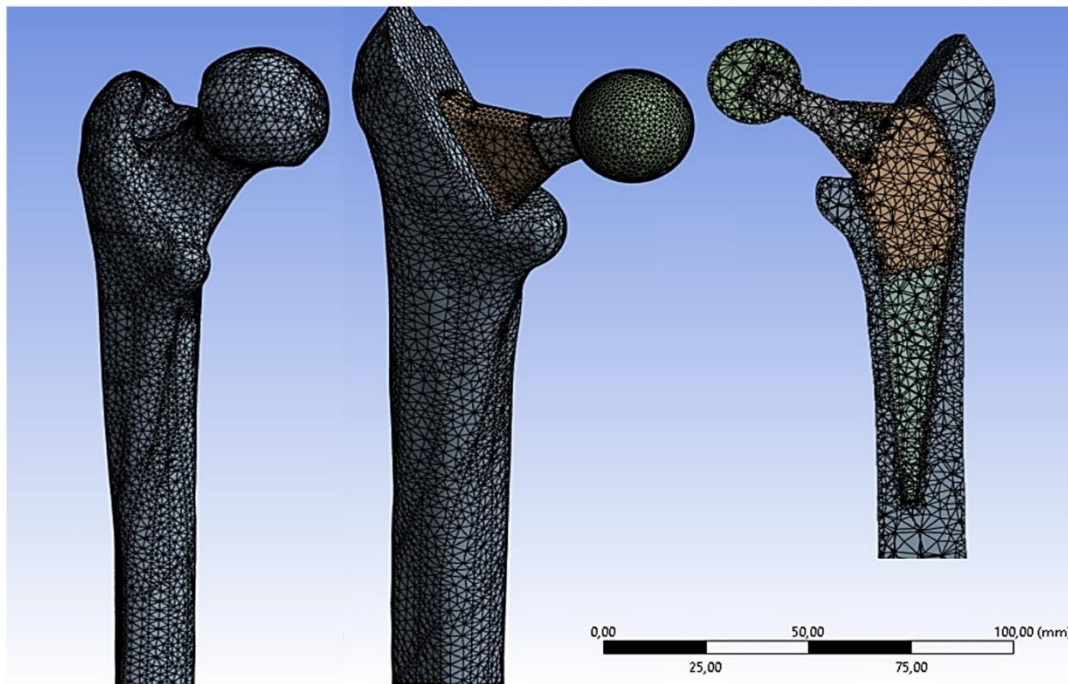


Figure 1. Mesh model of an intact femur and a femur with a prosthesis inserted.

- **Material Assignment:** Cortical and cancellous bone were modeled as anisotropic and isotropic elastic materials, respectively. Implant materials were assigned based on mechanical testing values.
- **Boundary Conditions:** The distal femur was fixed in all directions; physiological joint loads of 2300 N (representing peak hip joint contact during gait) were applied on the femoral head.
- **Contact Conditions:** Nonlinear frictional contact was defined at the bone–implant interface with a coefficient of friction set at 0.3.

Evaluation Metrics

FEA simulations were analyzed for:

- Von Mises stress distribution within the implant and surrounding bone.
- Strain energy density (SED) in periprosthetic bone regions to assess potential remodeling.
- Micromotion at the bone–implant interface, used to infer osseointegration potential.
- Stress shielding index (SSI) comparing native bone loading to post-implant loading.

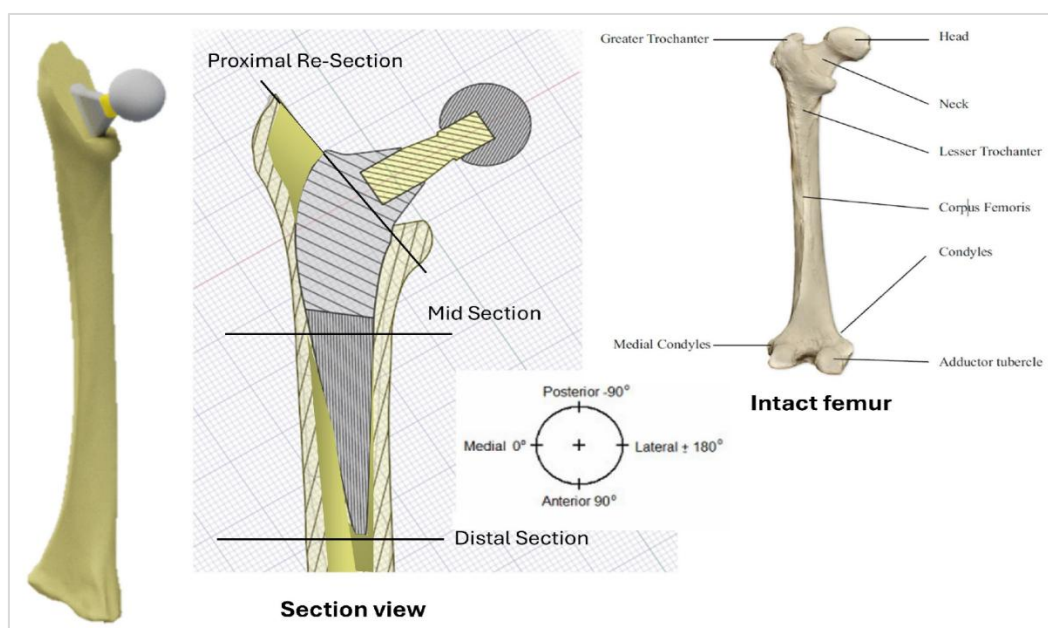


Figure 2. Three-dimensional model of the intact femur with the implanted prosthesis.

RESULTS

Mechanical characterization demonstrated distinct differences among the implant materials tested. Titanium alloy (Ti-6Al-4V) exhibited a Young's modulus of approximately 114 GPa and a tensile strength of 895 MPa, making it biomechanically more compatible with cortical bone compared to cobalt-chromium alloy, which had a significantly higher modulus of 210 GPa and tensile strength of 1000 MPa. UHMWPE, used primarily for joint articulation, showed a very low modulus of 0.8 GPa and limited tensile strength, but favorable wear resistance. These quantitative comparisons are presented in Table 2, illustrating the superior load-sharing potential of titanium over cobalt-chromium, particularly in load-bearing applications.

Finite element simulations further validated these findings; under a physiological load of 2300 N, titanium implants distributed von Mises stresses more uniformly across the proximal femoral cortex, reducing concentrated stress regions and demonstrating better mechanical harmony with native bone tissue, as shown in Figure 3 (Arab et al., 2022).

Table 2. Mechanical Properties of Implant Materials

Property	Ti-6Al-4V	CoCrMo Alloy	UHMWPE
Young's Modulus (GPa)	114	210	0.8
Tensile Strength (MPa)	895	1000	40
Fatigue Limit (MPa)	510	600	N/A
Wear Rate (mm³/million cycles)	N/A	N/A	12.5

Figure 4 presents a comparative von Mises stress distribution across three differently configured femoral stem designs: (1) a solid Ti-6Al-4V stem with transverse proximal holes, (2) a β -type Ti-30Nb-2Sn titanium alloy stem with graded stiffness, and (3) a CFRP composite stem. The maximum von Mises stress peaks are most pronounced in the Ti-6Al-4V model, reaching **~1234 MPa**, reflecting stress concentration at the femoral neck—attributable to its higher overall stiffness. The β -type Ti-30Nb-2Sn stem shows moderate peak stress (**~1107 MPa**), while the CFRP composite exhibits the lowest (**~875 MPa**), indicating better stress mitigation due to its more uniform anisotropic behavior. Notably, the proximal region of the β -type stem demonstrates a modest increase in stiffness (**~110 GPa** vs **~65 GPa**), translating to localized higher stress (**~185 MPa** in the distal zone) compared to the CFRP (**~30 MPa**) and Ti-6Al-4V (**~128 MPa**).

Building on the von Mises stress analysis presented in Figure 4, Figure 5 illustrates the load–displacement behavior of the same three stem designs—solid Ti-6Al-4V with proximal holes, β -type Ti-30Nb-2Sn, and CFRP composite—compared to the intact femur. The Ti-6Al-4V stem again demonstrated the highest stiffness (57.161 N/mm), consistent with its previously observed stress concentration. In comparison, the CFRP and β -type titanium stems showed lower stiffness values (52.026 N/mm and 52.270 N/mm, respectively), aligning more closely with the natural bone (48.48 N/mm). This proximity to the intact femur's mechanical response suggests a better ability to mimic physiological load transfer and minimize stress shielding. When considered alongside the stress distribution results in Figure 6, these findings reinforce that CFRP and β -type Ti-30Nb-2Sn offer both biomechanical and structural advantages over conventional solid Ti-6Al-4V implants (Ceddia et al., 2024). The results suggest that design modifications like transverse perforations in the Ti-6Al-4V stem can reduce proximal stress by approximately 42 MPa, offering a mechanical advantage in lowering peak loading at critical junctions. Overall, the CFRP stem provides the most favorable stress distribution profile—ideal for minimizing stress shielding—followed by the β -type titanium stem; the Ti-6Al-4V variant shows the highest stress peaks.

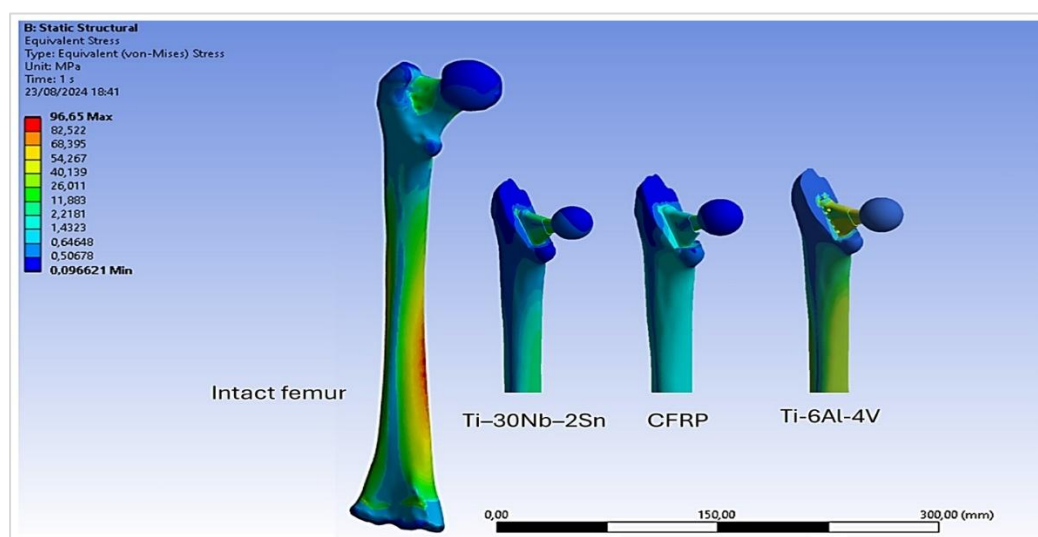


Figure 3. Von Mises stress results for models analyzed.

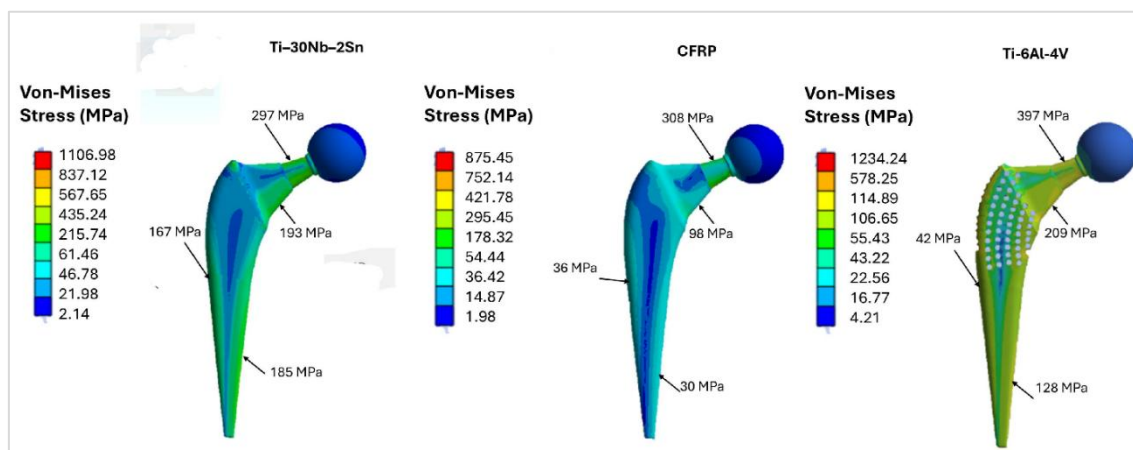


Figure 4. Von Mises stress results for the three stems studied.

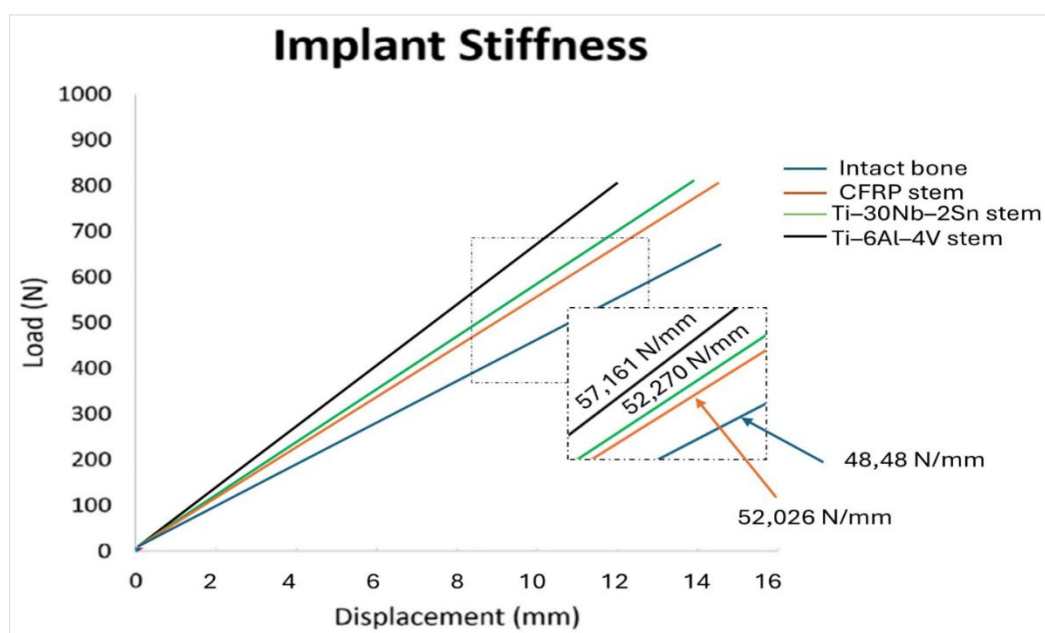


Figure 5. Load-Displacement Results for Three Stems and the Intact Femur

DISCUSSION

The results of this study demonstrate that implant material and stem design substantially influence both the mechanical performance of the implant and its interaction with surrounding bone. As shown in the von Mises stress distribution (Figure 4), the solid Ti-6Al-4V stem generated the highest peak stresses, especially at the femoral neck, indicating concentrated load transfer and a greater likelihood of stress shielding. This is consistent with its higher stiffness value (57.161 N/mm) observed in the load-displacement graph (Figure 5), which also diverged significantly from the mechanical behavior of the natural femur. In contrast, the β -type Ti-30Nb-2Sn stem showed improved stress distribution, with moderate peak values (~1107 MPa), and a stiffness (52.270 N/mm) that more closely matched that of the intact bone (48.48 N/mm), suggesting improved mechanical compatibility and reduced stress shielding potential.

Among all the designs evaluated, the CFRP stem exhibited the most favorable biomechanical profile. It not only had the lowest von Mises stress (~875 MPa), indicating better load dispersion, but also demonstrated a stiffness (52.026 N/mm) very close to that of the natural femur. These two characteristics are fundamental in minimizing adverse bone remodeling and maintaining periprosthetic bone mass over time. Furthermore, the use of functionally graded or composite materials, as seen in the β -type titanium and CFRP designs, offers an optimal balance between structural integrity and physiological compliance. These materials also seem to have a more consistent passage of loads, minimize micromotion, and decrease areas of stress, all factors that are critical to developing long-term implant stability and avoiding a revision operation.

Altogether, both the mechanical and FEA tests support the assumption that high-stiffness metallic stems (e.g., Ti-6Al-4V) pose a risk of excessive stress concentration and unnatural distribution of the load, and such designs as CFRP and β -type titanium stems show better biomechanical properties. These results correlate with the literature on stress shielding,

and they indicate that the material employed and structural design should be highly regarded in an effort to optimize the performance and long-term survivability of the implants (Ceddia et al., 2024).

CONCLUSION

The study has revealed that the mechanical characteristics of orthopedic implant materials have significant implications in ascertaining levels of mechanical compatibility and functionality. Finite element Modeling and mechanical tests showed that high elastic modulus materials such as Ti6Al4V have high stress concentrations and behave little like natural load bone interactions. In contrast, porous metallic implants act like natural bones, thereby resulting in the chances of developing stress shielding. By comparison, 215 and 110 kPa stress distributions and 4.5 and 11.8 GPa stiffness values of 2-Ti-30Nb-2Sn and CFRP stems were closer to those of the native femur, indicating greater potential for the physiological load transfer and long-term implant success. These results justify a further study of modulus-matched, composite, or functionally graded material in orthopedic design to enhance eventual integration of the implant, minimize bone resorption, and eventually prolong the life of prostheses.

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