

Computational Simulation for Material Selection of Femoral Component in Total Knee Replacement (TKR)

^{1*}Ronak Shah, ²Dr. Mitesh Popat, ³Dr. Amit Sata, and ⁴Dr. Megha Karia

¹Research Scholar, Gujarat Technological University, Ahmedabad

²Principal, Kalol Institute of Technology & Research Center, Kalol

³Professor, Department of Mechanical Engineering, Marvadi University, Rajkot

⁴Assistant Professor, Department of Mechanical Engineering, VVP Engineering College, Rajkot

Abstract

Introduction: The field of total knee replacement (TKR) has witnessed a diverse array of biomaterials being employed for the fabrication of the femoral component. With the advent of 3D printing technology, there is a newfound potential for enhancing the performance of knee replacements by incorporating novel designs and utilizing a variety of biomaterials. The material chosen for the femoral component must possess a set of crucial and desirable properties to ensure its long-term effectiveness and durability in clinical applications. To meet the demands of TKR, the material used in the femoral component should exhibit exceptional biocompatibility, ensuring compatibility with the patient's body and minimizing the risk of adverse reactions or complications. Furthermore, it is essential for the material to possess superior mechanical strength and stability, as the femoral component experiences substantial loads and forces during normal knee joint movement. This mechanical robustness ensures the component's ability to withstand the repetitive stresses and strains encountered during daily activities.

Objectives: To effectively address these requirements, computational simulation techniques have emerged as a valuable tool for material selection in TKR. By utilizing computational models, researchers and engineers can evaluate the performance of different biomaterials under varying loading conditions, predicting their mechanical behaviour, wear characteristics, and long-term performance. This enables informed decision-making in material selection, allowing for the identification of optimal biomaterials that can enhance the performance and longevity of the femoral component in total knee replacement procedures.

Methods: Five different biomaterials were analyzed for better sustainability. CAD model of femoral component was created. Maximum equivalent stress (von mises stress), maximum shear stress, maximum principal stress and total deformation have been evaluated for selected biomaterials and various load conditions range from 500 N to 3000 N.

Results: It is important to note that NiTi's suitability as the most suitable material for the femoral component of TKR is based on the specific context of the computational simulations and analysis performed in this study. Other factors, such as cost-effectiveness, manufacturing feasibility, and surgeon preference, may also influence the final material selection decision in clinical practice.

Conclusions: The material selection process for the femoral component in total knee replacement is a critical factor influencing the success and longevity of the implant. Through the application of 3D printing technology and computational simulation, researchers and clinicians can explore innovative designs and evaluate a wide range of biomaterials to identify the most suitable options.

Keywords: femoral component, total knee replacement, TKR, material selection, computational simulation, biomaterials, 3D printing technology, biocompatibility, NiTi.

1. Introduction

The lower end of the thighbone (the femur), the higher end of the shinbone (the tibia), and the kneecap are the three bones that comprise the knee

(patella). These three bones each have a smooth material covering their ends. This substance serves two purposes: it protects the bones and allows them to move freely inside the joint. The knee is the most

important joint in the human body because of its role as a key "weight-bearing" point. The knee is an extremely important joint since it not only contributes to the overall movement of the body but also serves to sustain the body's weight. Knees that are both healthy and robust are an absolute need for everyone who leads an active lifestyle. The human knee is the biggest joint in the body and is often considered to be the most strained joint. The femoral component must be able to successfully execute several duties while being subjected to varying loading conditions. Developing novel materials for use in femoral components is now recognised as one of the most difficult challenges facing the field of material research.

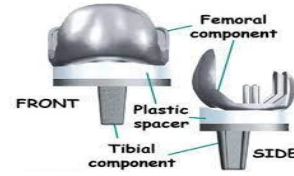


Fig. 1 Components of Knee Joint

2. Materials and Methodology

Biomaterials may be man-made or naturally occurring, and their purpose is to repair or replace sick or damaged biological systems in order to enhance human life's overall durability and quality. The evaluation, treatment, and eventual replacement of any tissue, organ, or bodily function in the body may be accomplished with the help of biomaterials since they are engineered to interact with biologically active systems. To be considered biocompatible, a substance must be able to perform its intended function within a physiological setting. The advancement of technology has led to the creation of new materials that are both innovative and useful. The necessary characteristics of the materials NiTi, Co-Cr alloys, Ceramic ZTA, Al₂O₃, and SS L316 are broken down into their essential components here.

Table 1. Different materials and its properties selected for femoral component.

Material	Density (Kg/ m ³)	Young's Modulus (GPa)	Poisson's Ratio	Tensile Yield (MPa)	Compressive Yield (MPa)	Tensile Ultimate (MPa)	Compressive Ultimate (MPa)
Co-Cr alloy	9120	240	0.21	824	1030	1269	2025
NiTi	6500	69	0.33	550	860	895	1000
Ceramic ZTA	4400	320	0.26	2750	2758	2500	3000
SS L 316	8000	193	0.33	172	58	483	150
Al ₂ O ₃	2770	413	0.3	280	1476	310	1920

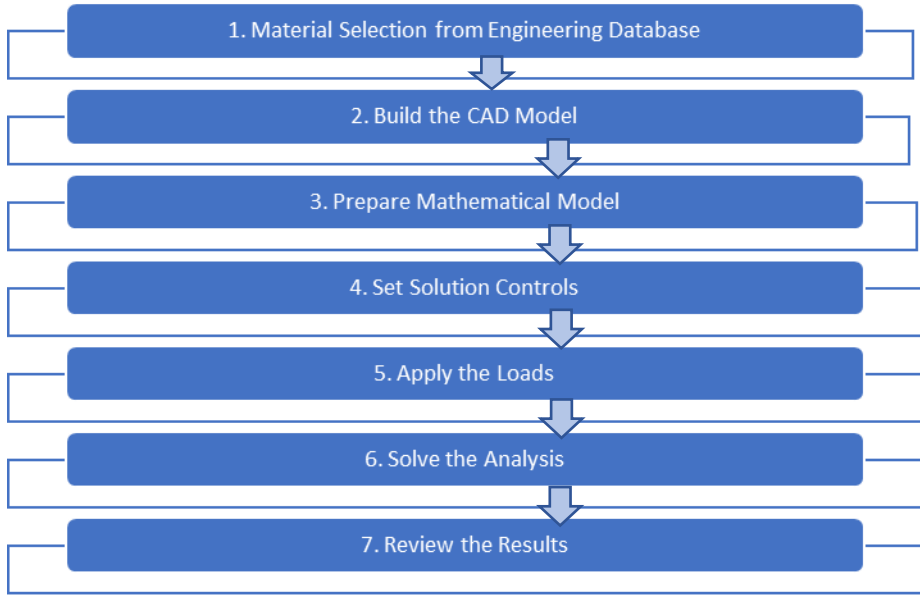


Fig. 2 Steps for performing static structure analysis.

Fig. 2 shows proposed workflow for simulation of femoral component. CAD model of femoral component was created in CREO 2.0. Then, CAD model is imported in ANSYS for static structural analysis. Analysis for different load conditions and biomaterials were performed to predict von mises stress, maximum shear stress, maximum principal stress and total deformation.

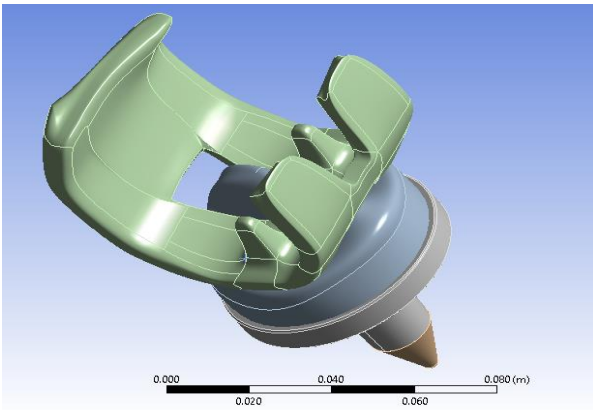


Fig. 3 CAD model of femoral component

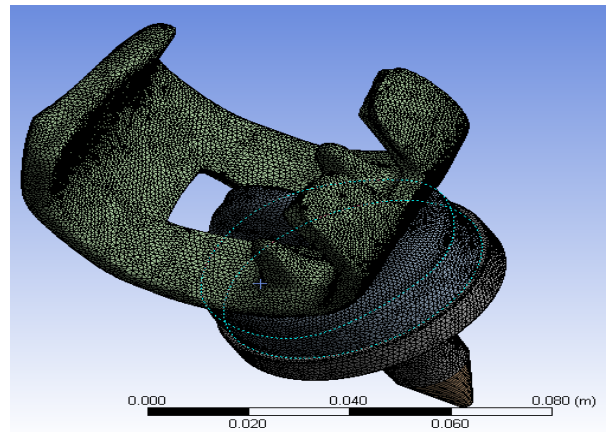


Fig. 4 Mesh model of femoral component

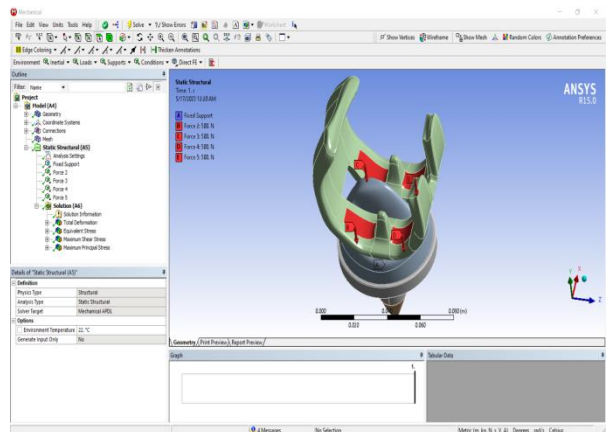


Fig. 5 Load applied on surface of femoral component.

3. Result and Discussions

Von mises stress, maximum shear stress, maximum principal stress and total deformation obtained from the static structural analysis of femoral component for selected materials at different load conditions are shown in figure 6,7,8, and 9.

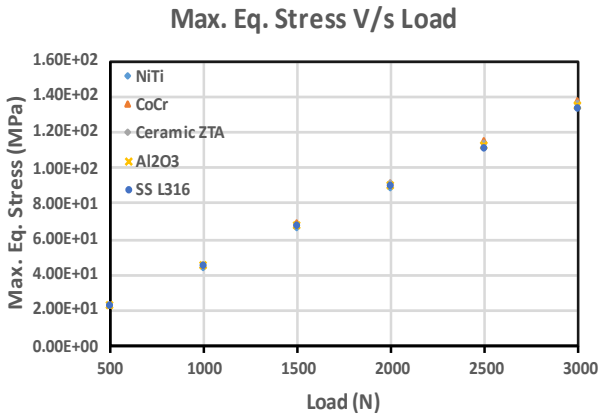


Fig. 6 Max. Eq. Stress with load conditions

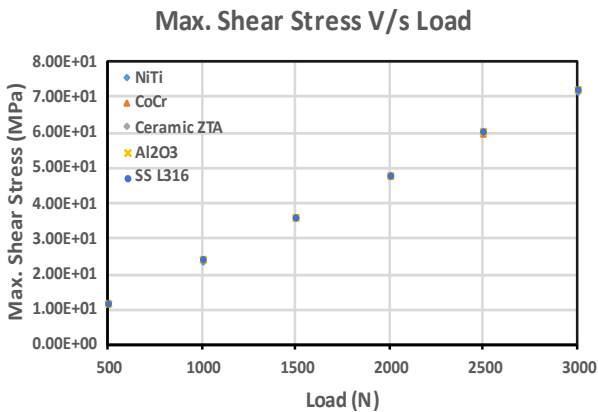


Fig. 7 Max. Shear Stress with load conditions

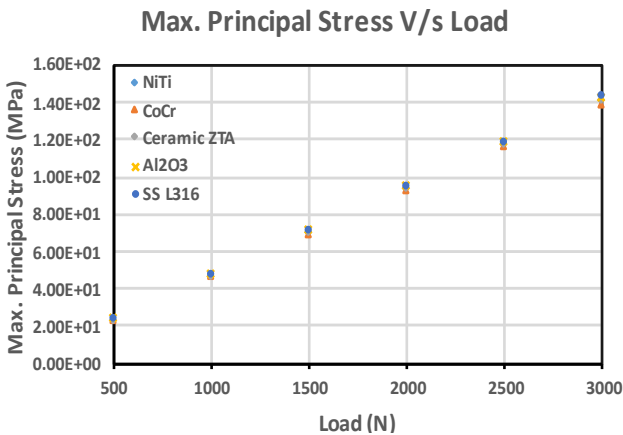


Fig. 8 Max. Principal Stress with load conditions

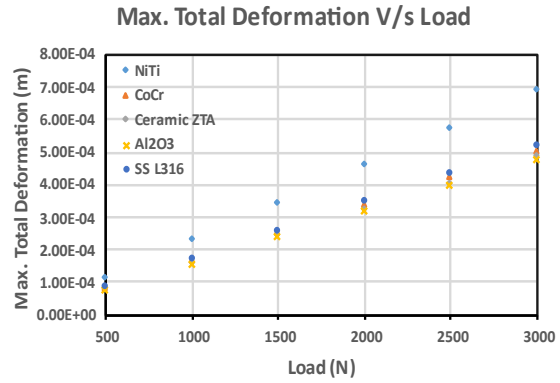


Fig. 9 Max. Total Deformation with load conditions

At each load conditions, von mises stress, maximum shear stress, maximum principal stress and total deformation are evaluated for selected materials. It is clearly seen that NiTi is most suitable material for femoral component when we consider von mises stress and maximum shear stress for load variations range from 500 N to 3000 N. Co-Cr alloys are most suitable material for femoral component when we consider maximum principal stress for load variations range from 500 N to 3000 N. Al2O3 is most suitable material for femoral component when we consider total deformation for load variations range from 500 N to 3000 N. The variations in range for maximum principal stress and total deformation for NiTi and other selected materials are very negligible as shown in fig. 6,7,8, and 9.

4. Conclusion

In conclusion, this study contributes to the understanding of femoral component behaviour in TKR by assessing different materials under varying loading conditions. The comparative analysis of stress distribution and mechanical performance allows for the identification of the most suitable material for the femoral component. The results obtained from this study provide crucial insights that can guide surgeons and clinicians in the selection process, ultimately improving the success rates and long-term functionality of TKR implants.

References

[1] Sudarsan Gautam D., Jagannadha Raju M.V., SasipalliVsrao, Modeling and Analysis of knee prosthesis, International Journal of Recent Scientific Research. Vol. 6, Issue, 9, pp.6493-6498, September 2015.

[2] Iliana Loi, Dimitar Stanev, Konstantinos Moustakas, Total Knee Replacement: Subject-

- Specific Modeling, Finite Element Analysis, and Evaluation of Dynamic Activities, *Frontiers in Bioengineering and Biotechnology*, April 2021, Volume 9, Article 648356.
- [3] Marjan Bahraminasab, B.B. Sahari, K.L. Edwards, FarzamFarahmand, Tang Sai Hong, Hamid Naghibi, Material tailoring of the femoral component in a total knee replacement to reduce the problem of aseptic loosening, *Materials and Design* 52 (2013) 441–451.
- [4] Marjan Bahraminasab, Ali Jahan, Material selection for femoral component of total knee replacement using comprehensive VIKOR, *Materials and Design* 32 (2011) 4471–4477.
- [5] Yong-Gon Koh, Jin-Ah, Paul ShinilKimc, Hyo-Jeong Kim, Kiwon Kang, Kyoung-Tak Kang, Effects of the material properties of a focal knee articular prosthetic on the human knee joint using computational simulation, *The Knee* 27 (2020) 1484–1491.
- [6] Marjan Bahraminasab, B.B. Sahari, K.L. Edwards, FarzamFarahmand, Tang Sai Hong, Manohar Arumugam, Ali Jahan, Multi-objective design optimization of functionally graded material for the femoral component of a total knee replacement, *Materials and Design* 53 (2014) 159–173.
- [7] JunJie Ni, Fan Liu, Gaolin Yang, Gun-Hwan Lee, Sung-Min Chung, In-Seop Lee, Cen Chen, 3D-printed Ti6Al4V femoral component of knee: Improvements in wear and biological properties by AIP TiN and TiCrN coating, *Journal of materials research and technology* 2021 ; 14 : 2322 – 2332.
- [8] J. Srinivas, Analysis of Materials for Tibia Tray component of Artificial Knee Joint, *International Journal of Innovative Research in Engineering & Multidisciplinary Physical Sciences*, Volume 2, Issue 2, April 2014.
- [9] G Mallesh, Sanjay S.J., Finite Element Modeling and Analysis of Prosthetic Knee Joint, *International Journal of Emerging Technology and Advanced Engineering*, Volume 2, Issue 8, August 2012.
- [10] Yuxing Wang, Yubo Fan, Ming Zhang, Comparison of stress on knee cartilage during kneeling and standing using finite element models, *Medical Engineering & Physics* 36 (2014) 439–447.
- [11] Yuxing Wang, Yubo Fan, Ming Zhang, Comparison of stress on knee cartilage during kneeling and standing using finite element models, *Medical Engineering & Physics* 36 (2014) 439–447.
- [12] Nithin Kumar KC, Tushar Tandon, Praveen Silori, Amir Shaikh, Biomechanical stress analysis of a Human Femur bone using ANSYS, *Materials Today: Proceedings* 2 (2015) 2115 – 2120.
- [13] C. Shashishekar1 & C. S. Ramesh, Finite element analysis of prosthetic knee joint using ANSYS, *Modelling in Medicine and Biology* VII.
- [14] Martin Kubicek, Zdenek Florian, Stress strain analysis of knee joint, *Engineering Mechanics*, Vol. 16, 2009, No. 5, p. 315–322.
- [15] Sadiq J. Abbass, Rana I. Abed, Mechanical analysis of hip & knee implants regarding different activities conditions and different materials, *Materials Today: Proceedings* 42 (2021) 2193–2201.
- [16] M. A. Kumbhalkar, Umesh Nawghare, Rupesh Ghode, Yogesh Deshmukh, Bhushan Armarkar, Modeling and Finite Element Analysis of Knee Prosthesis with and without Implant, *Universal Journal of Computational Mathematics* 1(2): 56-66, 2013.
- [17] Jason P. Hallorana, Anthony J. Petrellab, Paul J. Rullkoetter, Explicit finite element modeling of total knee replacement mechanics, *Journal of Biomechanics* 38 (2005) 323–331.
- [18] I.Vijayakanth, T.Lakshman Kumar, Design and structural analysis of knee joint using different materials with finite element method, *Open access international journal of science & engineering*, Volume 5, Issue 10, October 2020.
- [19] Yogesh Sanjay Pathare, Dr. Manish R Billore, The Design and Analysis of the Kneecap Model Using FEA, *International Journal of Mechanical Engineering*, Vol. 7 No. 4 April, 2022. Vol. 7 No. 4 April, 2022
- [20] Aadarsh S Chandran, Reena Trivedi, Bharat Modi, Rajesh Patel, Estimation of stress and strain of knee joint using finite element analysis, *Journal of Physics: Conference Series* 2021.
- [21] Deepak Kumar, Jitendra Bhaskar, Finite Element Simulation of Various Biomaterials based Knee Implants, *International journal of advance research and innovation*, Volume 8 Issue 4 (2020) 344-346.
- [22] Bhaskar Kumar Madeti, Chalamalasetti Srinivasa Rao, Finite element analysis for knee implants with suitable material combinations, *International*

journal of eExperimental and Computational Biomechanics, Vol. 4, Nos. 2/3, 2018.

- [23] YegireddiShireesha, Dr S. V. Ramana, P.Govinda Rao, Modelling and static analysis of femur bone by using different implant materials, IOSR Journal of mechanical and civil engineering, Vol 7, Issue 4, 82-91, August 2013.