Contact analysis of Ti-Al-4V femoral implant in Total Knee Arthroplasty model at static loading

[1*]Amitesh Shrivastava, [2]Nitin Kumar Jain, [3]Rahul Salhotra,

[1,2,3]Department of Mechanical Engineering, National Institute of Technology, Raipur, (CG), India.
[1]amitesh1410.nitrr@gmail.com, [2]nkjain.me@nitrr.ac.in, [3]rsalhotra.mech@nitrr.ac.in

* Corresponding author-[1]amitesh1410.nitrr@gmail.com

Abstract
This paper aims to investigate contact analysis of the complex TKA knee joint on femur bone through numerical analysis of the 3D model of bone and implant components. A solid 3D model of the femur bone is created by utilising CT scan images, and the femoral implant and a spacer were designed to produce kinematic alignment.Misalignment of implant components under force can cause trauma, discomfort and instability, which further can be treated with re-examination and revision surgery. Our study analyses the effect of stress generated and the respective deformation at static loading conditions at full extension positions. Ansys program is used to process the 3D model created by providing a load of 1000N and contact boundary conditions. It is observed that the maximum stress in the bone component is generated adjacent to the contact surface and the maximum stress generated on the femoral component and plastic spacer were lower the yield strength. This study also favours the significance of spacer in shock absorption from the force and thus increasesthe life of the implant.

Keywords: Biomedical, Knee joint, Femoral implant, Knee arthroplasty,Finite element analysis

1. Introduction

The knee joint is regarded as one of the most complex biomechanical joints in the human body. It provides a simultaneous function of proving stability as well as allowing the body to move[1]. The knee joint executes flexion and rotation reality between the femorotibial and the patellofemoral joint[2]. In between femur and tibial menisci is present in a wedge shape which protects cartilages from degenerating by excessive axial stress generated by increasing the contact area between them [3]. Also, friction between the femorotibial joins is reduced by menisci and cartilages, and it also provides better sock intake and carrying capacity for the knee joint[4-5].

Post total knee arthroplasty (TKA) it is significant to understand the mechanical response of the implant placed for sustainability and reliability of the joint[6]. Numerous preceding articles have discussed that during routine activities such as walking, running and stair climbing, the compression force on the knee joint varies from 2 to 4 times self-weight [7].These forces even vary more and can reach more than 10 times while performing sports activity is involved[8]. These enormous forces acting on the knee joint are subjected more often to trauma and injury to the joint and also lead to tear of ligaments and meniscus and cause osteoarthritis. Therefore compared to other joints knee joint more often requires surgical treatment for its proper functioning.

Generally, TKA is suggested for the patients who have surpassed the conservative treatments and are now at the advanced osteoarthritis stage and left out as the most suitable solution[9]. The TKA is a surgical procedure under which the joint is replaced with an implant in order to restore its joint functioning and life of joint. Before performing TKA it is essential to know the regular activity of the patient to entrench the biomechanical parameters for using implant material and weight and to build a system for supporting bones[10].

2. Materials and Methods

A three-dimensional finite element model of the human femur with a femoral implant is used to investigate the effect of the implant while loading condition of knee joint structure. For the healthy working of the knee joint and its lifespan, biomechanical factors play an important role [11-12]. FEA can be effectively utilised for determining contact analysis of bone and implant[13-17].

2.1 3D model development

The CT scan images of the femur were utilised to generate a 3D solid. CT images were collected in DICOM file format. Collected DICOM files were utilised in Materialise Mimics and Materialise 3-Matic software for the creation of femoral components by performing segmentation and surface finish operations. For modelling of femoral implant and plastic spacer, Solidworks software package is utilised and is assembled. For simulation of the components, the Ansys software package is used.

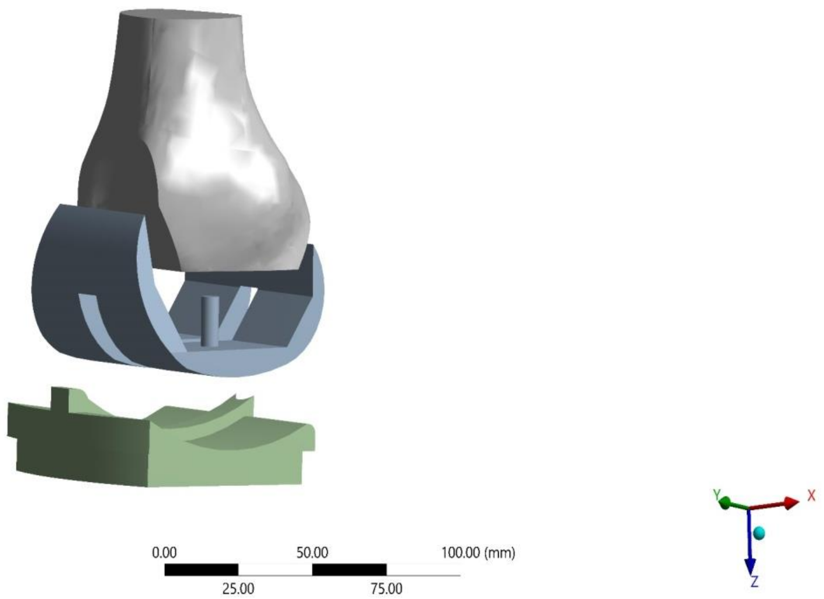


Fig1. 3D explode view of femur, femoral component and spacer, respectively in Ansys spaceclaim.

2.2 The material property

Human bone is a composite material that composes of hydroxyapatite and water. The property of bone varies from person to person and depends on age, gender, health etc.[18-19]. Therefore it is challenging to assign its particular property. In this study, we assumed bone to be homogeneous and isotropic in nature. The parameters utilised for assigning the properties are attributed form the previously reported information as shown in table 1 [20-24].

Table1 Material properties

Component	Assigned material	Young modulus E (GPa)	Poisson's ratio *v*
Femoral bone	Human bone	11.5	0.3
TKA femoral component	Ti-6Al-4V	110	0.35
Plastic spacer	UHMWPE	.463	0.46

2.3 Mesh property

For performing finite element analysis, generated mesh is of quadratic type and element are tetrahedral respectively. The used mesh property is more suitable to that of the complex geometrical components properties shown in table 2.

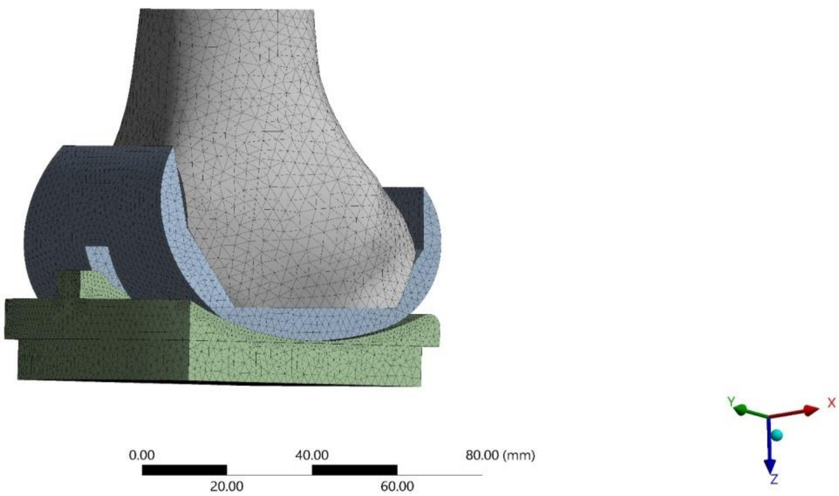


Fig2. 3D meshed model of the intact femur with femoral component and spacer, respectively in Ansys spaceclaim.

Table2. Mesh properties

Component	Mesh type	Element type	No. of Elements	No. of Nodes
Femoral bone	Quadratic	Tetrahedral	75099	106612
TKA femoral component	Quadratic	Tetrahedral	64409	98391
Plastic spacer	Quadratic	Tetrahedral	258037	370713

2.4 Boundary conditions

In the full knee extension position, a compressive load of 1000 N was applied on the centre axis of the femur[25]. The contact between the bone and Ti-Al-4V and plastic spacer is bonded type. The lower end of the plastic spacer is fixed to provide a reaction to it.

3. Results

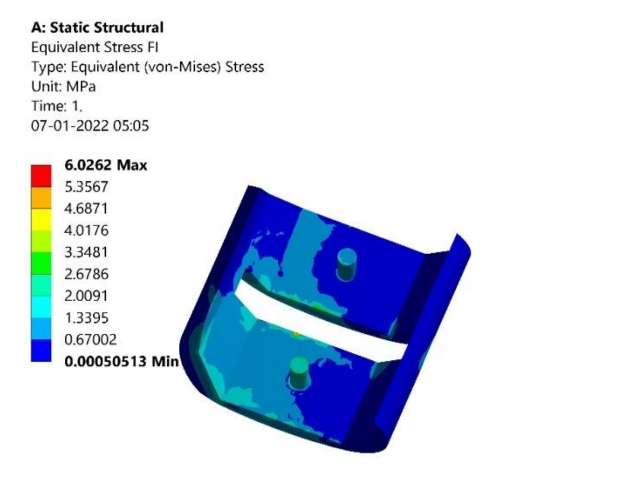
FEA analysis is performed as per the above-defined parameters, stress distribution, directional deformation, total deformation and directional deformation are calculated for each component and correlated variation is plotted graphically between them. These distributions can be better understood by graphical colour representation in the components.

3.1 Stress distribution

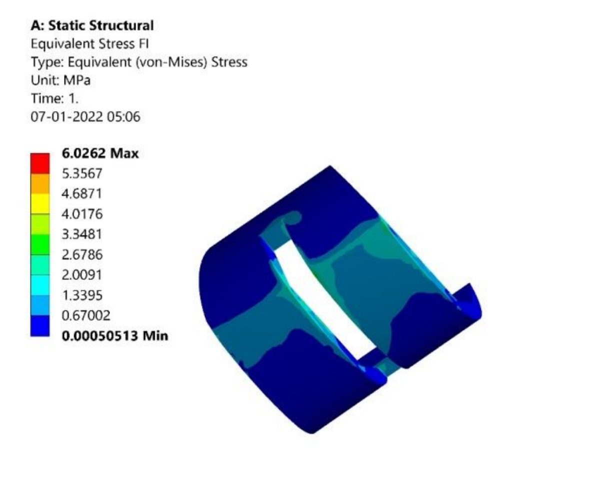
Assembled 3D model is processed under the above-mentioned conditions, and the stress generated is calculated on the components. Results related to stress generation are shown in.

3.2 Femoral implant component

Stress generated on the femur implant component is calculated under the compressive load of 1000 N, and von Mises stress is calculated. The maximum stress developed on the implant component by the compressive load is 6.03 MPa. The maximum stress is generated at the interface of bone and implant contact.



(a) Interior contact surface



(b) Exterior contact surface

Fig3. Distribution of von Mises stress in Femoral Ti-6Al-4V TKA component at full knee extension in Ansys workbench.

The maximum stress generated on the implant is quite lower than its yield point, which is 795 MPa and its ultimate strength of 860 MPa [26]. Therefore stress generated on the implant is very low and can perform effectively under the above condition.

3.3 Plastic spacer

The mechanical response of ultra-high-molecular-weight polyethene (UHMWPE) is studied by carrying out the analysis at the same parameters. From FEA results, the max von Mises stress generated on the plastic spacer component is 2.07 MPa. The maximum stress is localised on the upper surface of the plastic spacer at the contact between the femoral implant and the plastic spacer. It is observed that although the max stress is generated on the upper side of the spacer but drops significantly while distributing at the bottom. The developed stress is quite lower than its yield stress of 19.1 MPa, which says that it can sustain the above loading condition [27].

Fig4. Distribution of von Mises stress in plastic spacer component at full knee extension in Ansys workbench.

3.4 Femur bone component

Mechanical stress generated on the femur component is mostly at the contact between the femoral implant and bone section. The max von Mises stress on femur bone is 1.57 MPa and generated at the lateral side of the bone and is at the anterior segment, respectively. This clearly shows that the role of the plastic spacer is successfully accomplished in reducing the stress generation on the bone component.

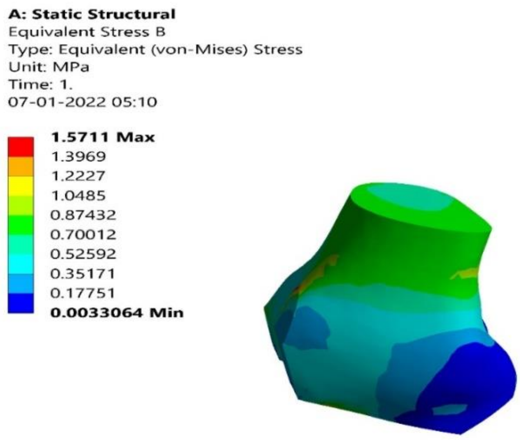
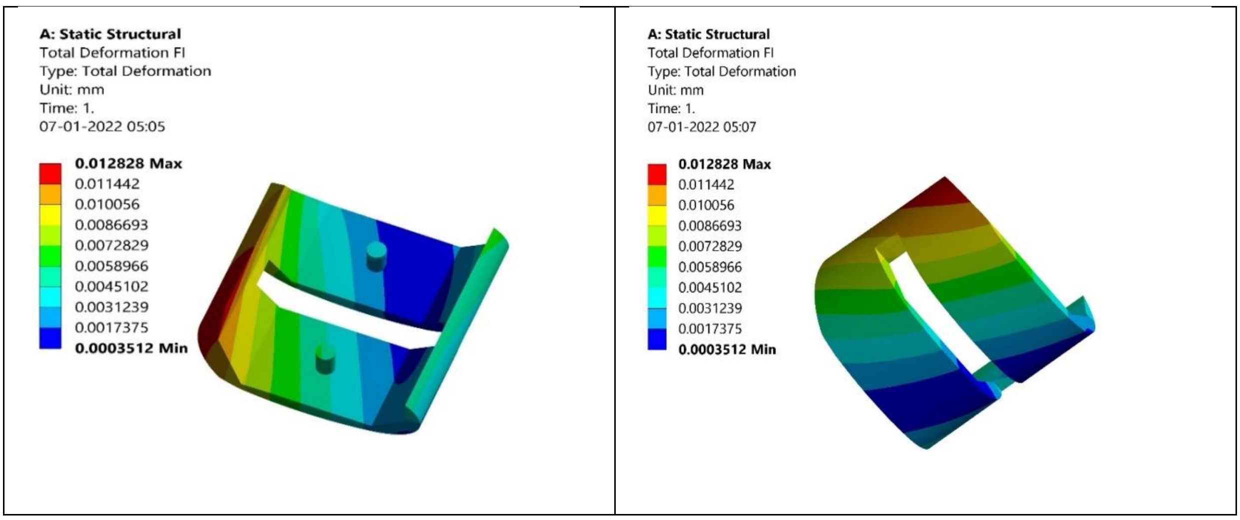


Fig5. Distribution of von Mises stress in femur bone component at full knee extension in Ansys workbench.

3.5 Deformation

The developed maximum stresses of 6.03 MPa that are generated on the femoral implant components tend to cause deformation in all the directions and directions along with force. The total deformation of the femoral component is 0.0128 mm, and the directional deformation of 0.0122 mm. The maximum deformation caused in the Ti-6Al-4V implant is at the anterior part of the implant and matches with the stress generation on the femur bone and Ti-6Al-4V implant, respectively. Similarly, the developed max stress of 2.07 MPa on plastic spacer contributes to the total deformation of 0.0093 mm and the directional deformation along the direction of force to be 0.0091 mm. The maximum deformation caused by a plastic spacer is on the upper surface of it, which lies between the interference between the femoral implant and a plastic spacer.



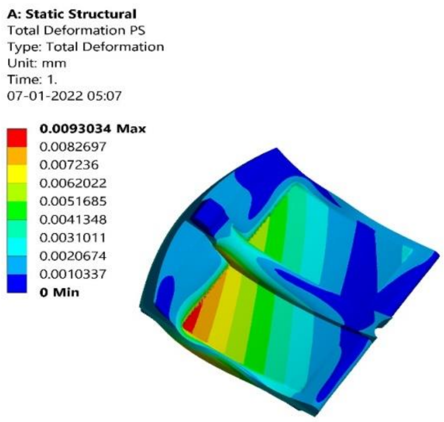
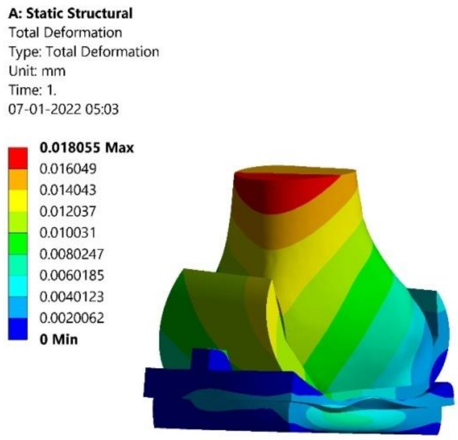
(a) Interior contact surface	(b) Exterior contact surface
	
(c) Plastic spacer and femoral contact surface	(d) Full intact view of TKA implant

Fig6. Total deformation in the femur, femoral component, spacer and intact knee joint, respectively in Ansys workbench.

4. Discussion

Knee surgery is prescribed for patients with serious trauma and functional limitations generally because of degeneration of the meniscus and ligaments. Knee surgery, in many clinical studies, is successful and satisfies the intended function after undergoing surgery[28]. However, some cases reported discussing about the failure of implants and worsening the condition of the knee joint further[29]. Several studies show different stress generation and criticality of knee implant subjected to sudden of gradual impact forces and the degree of the moment of knee joint affects bone as well as implant components [30][31]. Thus bone and implants are affected by the loading type of bone and implant and can cause trauma. Also, in some studies, loosening of the implant is reported, which adversely affects the life of the knee joint and implant components [32].

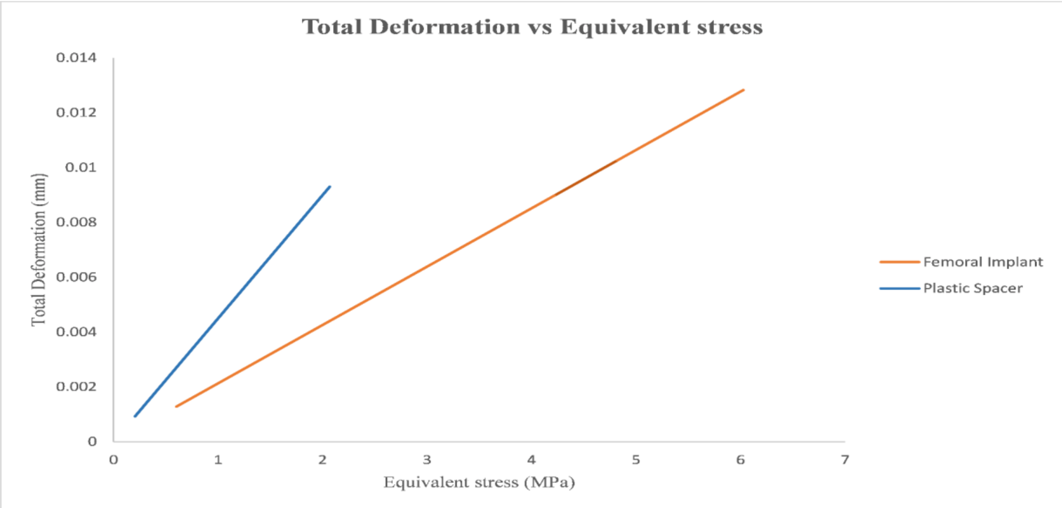


Fig7. Total deformation vs equivalent stress on femoral component and spacer, respectively.

The contact analysis using the numerical method is considered as one of the important tools for predicting the criticality of the joint and implant after surgical operation and helps in understanding the risk involved in it[33].Biomechanical studies conducted also show the predictability of rehabilitation time to achieve proper gait and reduction in trauma. The finite element method provides greater flexibility in calculating the response of biomechanical components and is cost-effective following that it doesn't harm the patient. Contact analysis and stress prediction is considered as an effective parameter for predicting the risk involved because of the interaction of foreign implant human biomechanical component[34].

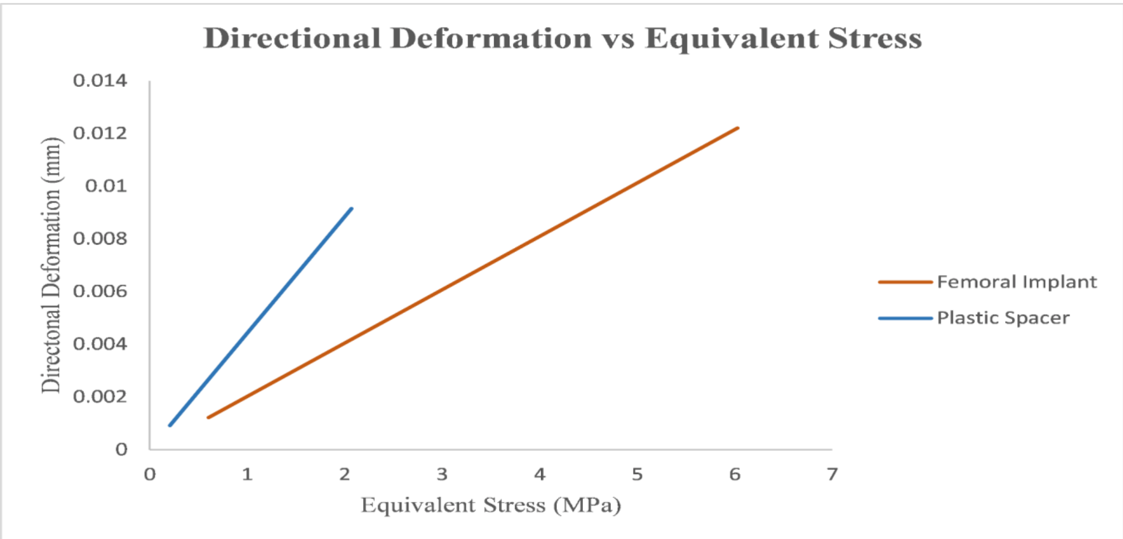


Fig8. Directional deformation vs equivalent stress on femoral component and spacer, respectively.

A histogram is plotted by utilising the maximum von misses stress generated in all the components, and the results show that the minimum overall stress is generated on the bone attached to the implant is 1.17 MPa, and the maximum stress is generated on femoral implant ids 6.026 MPa. Whereas the stress generated on plastic spacer 2.06 MPa plays an important role in shrinking the shock forces. On the other hand, metallic implant loosening tends to wear plastic spacer.

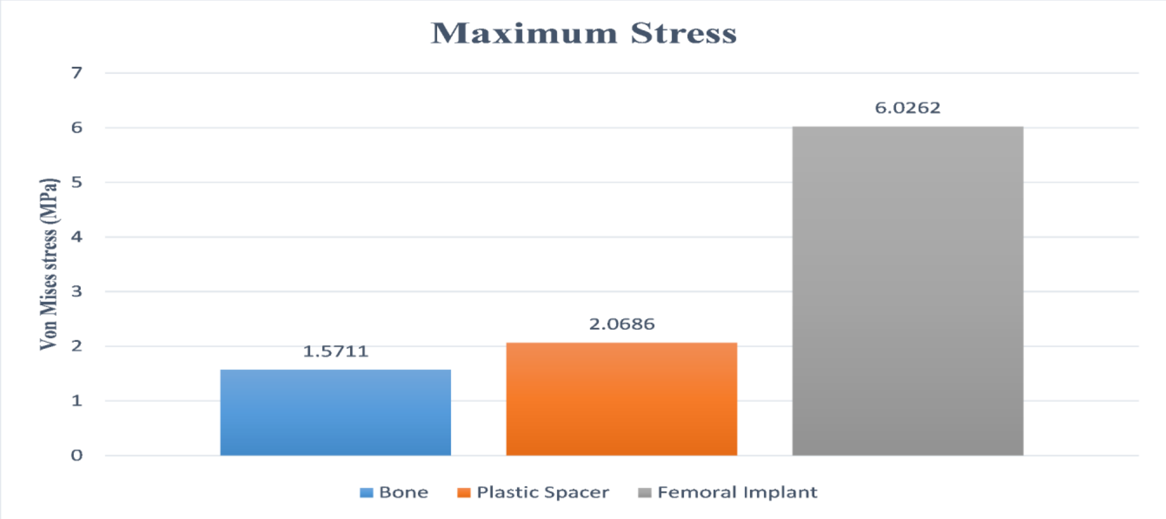


Fig9.Maximum stresses on the femur, femoral component and spacer, respectively.

So, the results in this study contribute to a better understanding of the biomechanical behaviour of implants at compressive loading conditions. This study shows the critical are of the implant in order to avoid the excessive load and movement conditions to avoid risks related to the implant. The provided biomechanical result of this study is useful in better understanding of the mechanical response of bone and implant. Moreover, in this study, static equilibrium is considered, and the effect of ligaments and muscles was not incorporated, which justifies the focus on implant behaviour. For this study, bone component material is considered to be homogeneous and linear elastic, and assumptions were made to understand the optimal implant design. Therefore, this study provides a qualitative assessment of implant biomechanical response during standing full flexion daily activity.

5. Conclusion

In this study, a realistic 3D model containing bone and implants is considered to investigate the biomechanical effect of compressive loading. Our result shows that the maximum stress in bone is propagated at the interface between the femoral implant and bone, respectively.

Also, this study shows a significant role of the plastic spacer in absorbing the sock generated and allows the minimum further transfer of stresses. Considering the application part of this study, a pre-surgical simulation can be performed for better optimisation of implant design as well as load transmission, which will benefit in less rehabilitation time and increase in the life of the implant and its functioning.

Declaration of conflict of interest statement

All authors declare that they have no conflict of interest

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