International Journal of Technical Innovation in Modern Engineering & Science (IJTIMES)
Impact Factor: 5.22 (SJIF-2017), e-ISSN: 2455-2585
Volume 4, Issue 6, June-2018

A study on simulation of Human Knee Implant

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Abstract

Total knee replacement (TKR) is one of the successful surgical techniques, that contributes effectively in the case of cartilage damage helping removing the knee joint deformities and eliminating pain. The process thus enables walking by implanting an artificial metallic knee. Activities like walking, running, sitting, standing at the spot result in different loads acting on the knee joint. The present study focuses on the analysis of the magnitude of the stress and elastic strain considering critical loading conditions i .e. 2200N, 2500N, 3500N & 3000N at 0°, 20°, 40° &60° angles of flexion respectively. Tibio-femoral contact stresses of fixed bearing knee implant were analyzed using finite element analysis with software ANSYS WORKBENCH 15.0. The material used was ultra high molecular weight polyethylene (UHMPE) for tibial implant and 3 different alloys (cobalt-chromium, titanium and zirconium) under five different combinations being used for the femoral component and the tibial tray. Activities like stair climbing, squatting etc. are accomplished at higher flexion angles resulting in early polyethylene wear. The von Mises stress may vary depending upon degree of flexion, weight and material chosen.

1. Introduction

Knee joint being not a pure hinge joint, still provides movement with a complex set of translation and rotation. The bicondylar hinged joint allows six degree of freedom. Knee joint permits internal and external rotations along with extension and flexion of leg (Zaffagnini, S., et al., 2013). The two major articulations observed in the human knee are the one between femur and tibia and the other between femur and patella. Although the patient satisfaction rate is 90%, the number of patients requiring revision surgery is significant (D'Lima *et al.* 2001). Polyethylene wear and aseptic loosening are the most significant reasons for TKR revision. The wear of ultra high molecular weight polyethylene (UHMPE) is affected by elastic modulus of polyethylene, polyethylene component's thickness and conformity of articulating surfaces (Petty et al. 1999). Contact load and surface kinematics also influence polyethylene wear (Bie et al. 2004). Giat load also effect TKR performance, ligaments and muscles provide stability to the knee joint. There are four ligaments connecting femur and tibia. Stability at sides of the knee is provided by the medial condylar ligament (MCL) and the lateral collateral ligament (LCL).

Tibio-femoral motion is a combination of sliding and rolling at the contact surface between the femoral condyle and the tibia. Factors that mainly affect the motion between femur and tibia are the bony structure of the knee joint, muscles, tendons and ligaments. Hoppenfeld (1976) described the arc of motion of knee varies from 0° angle of flexion to 135° angle of flexion; also the internal and external rotation varies from 5°-10° in each direction. The external rotation of the tibia holds its significance to reach full extension of the knee as a small amount of external rotation on femur is required to reach full extension.

Total knee replacement is a successful surgical technique in the case of arthritis the knee pain caused because of it. The durability of the knee implant can be improved by choosing proper material and proper designing of the artificial knee implant. Complex movements (internal-external rotation, flexion/extension of the knee, anterior-posterior and medial-lateral translation) are observed in human knee causing complex stresses resulting in damage to the knee joint with time, leading to delamination and adhesive/abrasive wear.

Trying to conduct the realistic knee joint movement is hard using standard equipments. Thus a special tribo-system was constructed by researchers to mimic the patient's knee and it's functioning in everyday activities. Constructing tribo-system can be expensive and time consuming. For this reason finite element method (FEM) simulation proved to be a better method for the topic. Thus measuring contact stresses from measured TKA force proves to be very valuable since contact forces and stresses could be used to develop and validate wear simulation. There are two types of machines affecting knee simulation: force controlled and displacement controlled machines. Displacement controlled machines are easier to model as they manipulate the relative position of femoral and tibial component. Differences in implant alignment and soft tissue constraint may result in variation of generated forces. The Indian Standard Organization (ISO) has standards for knee wear, also ISO standards represent walking cycle.

Plenty of work has been done that traces the development of the artificial knee implant involving the researches resulting of the knowledge and development on the topics like thickness of tibial implant, composition of the alloy being used, polyethylene wear etc. The wear of ultra high molecular weight polyethylene (UHMWPE) is a major limitation to the success of artificial knee implant (Benjamin et al., 2005). Computational wear analysis involving wear and creep took considerable amount of time to reach a conclusion. While comparing the contact stresses and contact areas of fixed and mobile bearing total knee replacement (TKR) (Christina et al., 2002), concluded that the contact stress on the fixed bearing is greater than that of mobile bearing. Even the malaligned TKR components can result in poor functionality, increased wear and failure (Jeffrey et al., 2014). Aseptic loosening can also be a factor for increasing revision surgery of TKR. Thus the selection of optimal material plays an important role in TKR surgery (Marjan Bahraminasab, Ali Jahan 2011). For effective working of knee implant an important factor to be taken into consideration is fatigue strength including surface roughness and crystal orientation (Yuka et al., 2016).

Since the knee kinematics is a function of sliding, rolling and tractive rolling conditions. For determining a proper wear pattern on UHMWPE component proper kinematics is required. This can be accomplished by providing physiological forces, applying proper constraints on the fixtures and also the soft tissue restraints (Peter et al., 1997). The knee implant might have a risk at the time of high impact load occurring at the time of jogging, squatting etc. Thus high mechanical overload might result in aseptic loosening of the artificial knee joint and should be avoided for longer implant life.

Keeping in view, the main aim of the research is to compare the value of stress, strain and directional deformation on the knee implant for different alloying materials used for the femoral component and tibial tray with the help of finite element method.

2. Materials and Methods

In the present research 3D finite element model was analyzed to compare the various changes in mechanical behavior of the component depending upon the material type, body weight and angle flexion. The study analyses the simulation for a fixed bearing knee implant. The tibial implant is made up of polyethene and the femoral component and the tibial tray are made up of a combination of alloys as described in Table 1

Table 1 Materials used for Tibial Tray and Femoral Component

Denotation	Material For:	
	Tibial Tray	Femoral Component
C-C	Cobalt Chromium	Cobalt Chromium
T-T	Titanium	Titanium
Z-Z	Zirconium	Zirconium
T-C	Titanium	Cobalt Chromium
T-Z	Titanium	Zirconium

Simulation was done for four different knee joint positions such as 0°, 20°, 40° and 60° of flexion. Four different loads were applied on the femoral component fixing the tibial component and the tibial tray (Table 2).

Table 2 Loads applied on the Femoral Component at different flexion angles

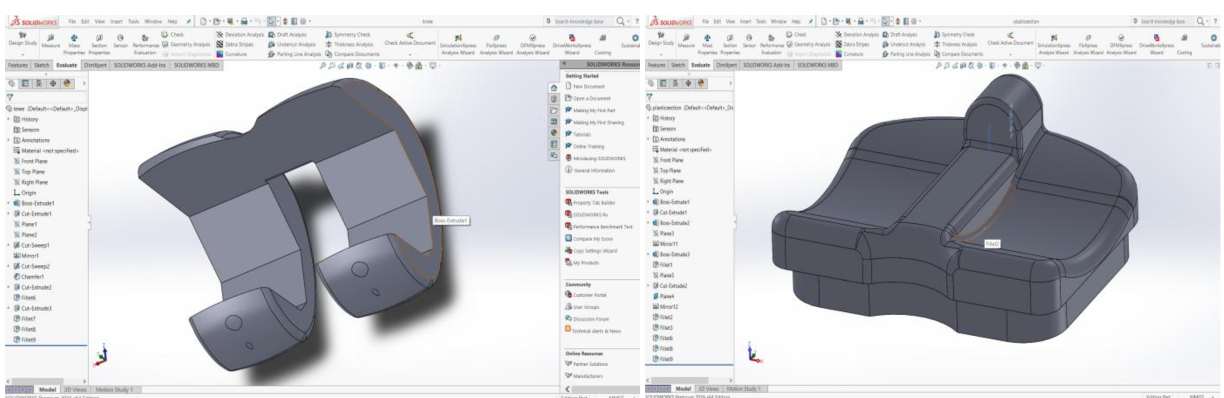
Flexion Angles	Load Applied
0°	2000 N
20°	2200 N
40°	3200 N
60°	2800 N

The material properties was required to be specified to the software for generation of various results needed for the research purpose. The specified material properties were provided in Table 3

Table 3 Material properties

Material	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio
Cobalt Chromium	8440	193000	.29
Titanium Alloy	4430	110000	.33
Zirconium Alloy	6440	97900	.33
Polyethylene	950	1100000000	.42

ANSYS WORKBENCH 15.0 was used for knee prosthesis model and finite element analysis (FEA). (Fig1). Tibial insert was fixed bearing type; the dual radius design was used for the sagittal curvature of the femoral component (Chadd et al. 2013) as dual radius of curvature helps easy femoral rolling on the tibial component. The designing of the femoral component is the most difficult while designing the knee implant which might contain two different steps, the designing of outer and the inner surface. The profile of outer surface is comparatively more important and to be taken into consideration as the contact of femoral component and the tibial implant is governed by the outer surface of the knee implant. Also the design of the tibial articulating surface it is subjected to two main requirements, namely to withstand the loading from the femur and implement the fixation on the tibial component. In order to fulfill these requirements, the size of the contact surface with the tibial components is designed sufficiently large so as to protect the joint from receiving excessive loading and enable normal knee motion.



(a) (b)

Fig. 1 Design of (a) Femoral Component (b) Tibial Insert in Solid Works

The final result displayed is dependent largely on mesh generation; the different type of mesh generated might alter the number of nodes and thus the finally the solution. The mesh being generated was advanced size function used on the curvature with medium relevance centre and max face size of 3.5 mm. The analyzed model consisted of numerical consideration while the effects of muscles and ligaments were not taken into consideration. For the simulation only axial force was taken into consideration while the effects of torsion and flexion forces were not taken into consideration.

Several body assumptions are introduced for FEA simulation:

- Elasticity module of thetibial implant is 1000MPa;
- Lower area of tibial implant is attached to fixed area of tibial component;
- Femoral component is rigid body
- Tibial component is rigid body.

The contact between the femoral component and the tibial component corresponds to a rigid body deforming a soft body.

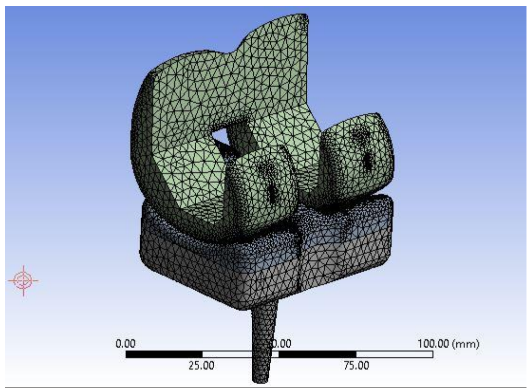


Fig. 2 Total knee endoprosthesis FEA model

The loading conditions described in Table 2 was applied on the combination of materials as described in Table 1 and the results were being compared to conclude that what combination of material shows the best behavior for the given mechanical properties.

3. Results and Discussion

Stress v/s time graph drawn for cobalt chromium alloy comparing the results at the four angles of flexion was shown in Fig.3 depicts increasing stress values w .r.t. time and angles , and the overall stress for 60̊ angle of flexion shows comparatively larger change than other angle of flexions. Thus the knee is more vulnerable to wear at higher angle of flexions.

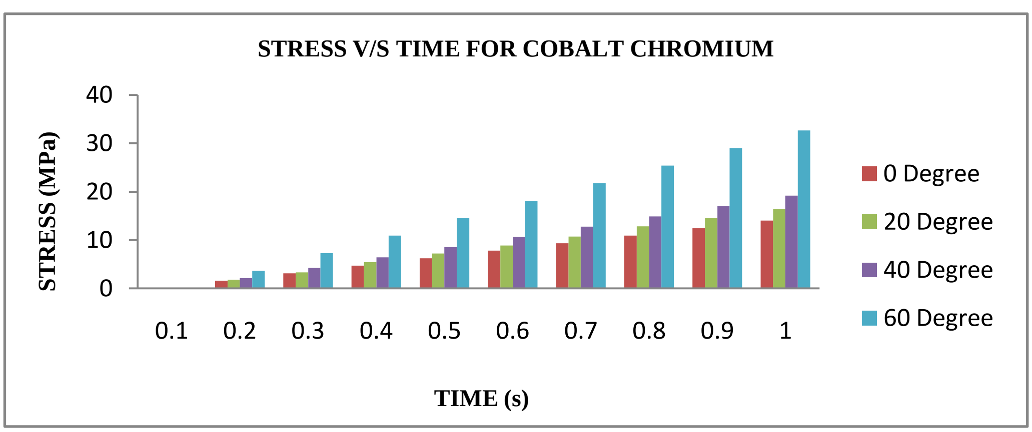


Fig. 3 Stress V/S Strain Graph for Cobalt Chromium Alloy

Von Mises stress v/s time graph shows different trends at different angle of flexion. While it shows measurable difference in the stress values at smaller flexion angles and very small difference in the stress values at larger flexion angles. C-C shows the highest stress values and Z-Z shows comparatively lower stress values.

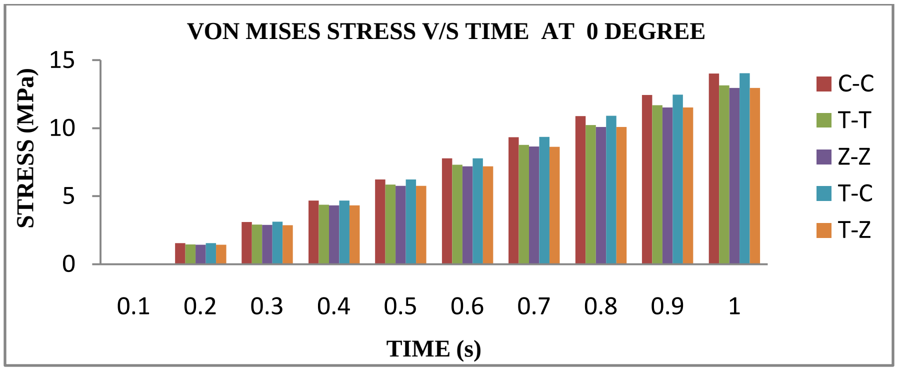


Fig. 4 Von Mises stress v/s Time at 0° angle of Flexion

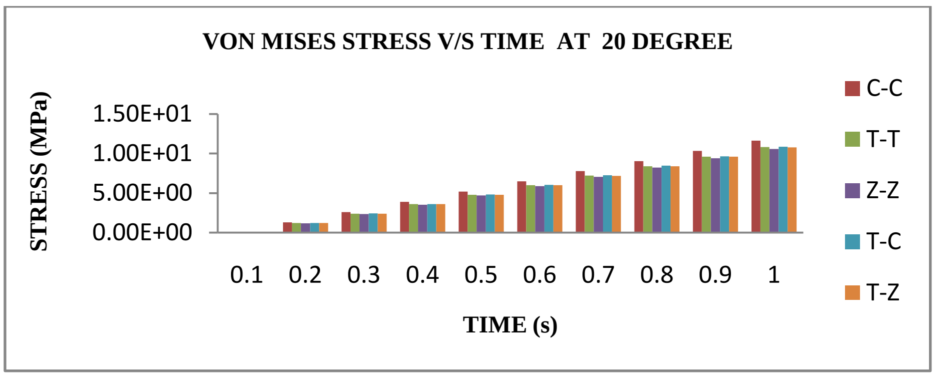


Fig. 5 Von Mises Stress v/s Time at 20° angle of Flexion

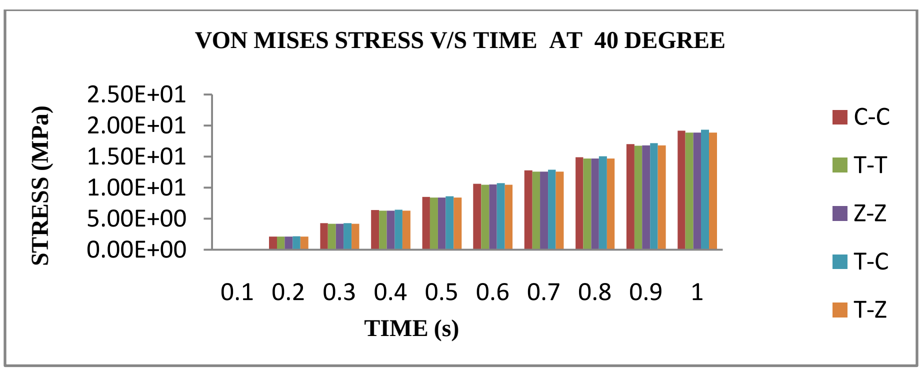


Fig. 6 Von Mises Stress v/s Time at 40° angle of Flexion

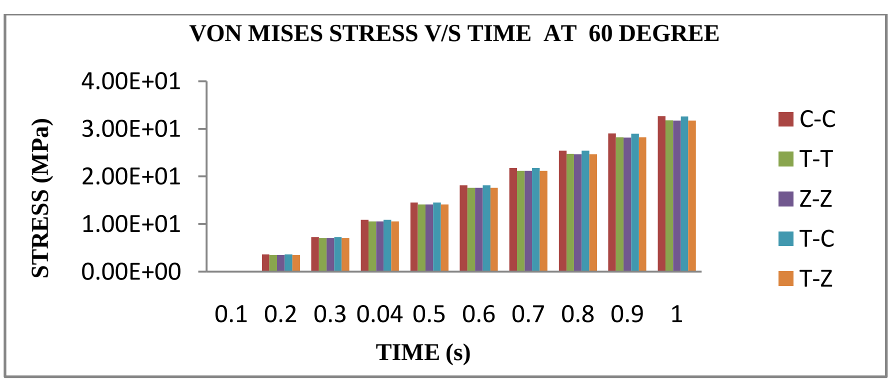


Fig. 7 Von Mises stress v/s Time at 60° angle of Flexion

The value of elastic stain is found to be increasing with time for all the four angles of flexions. But the change in the value of elastic strain with respect to the materials being considered is very small. Thus all the materials show a similar behavior as observed in the graphs.

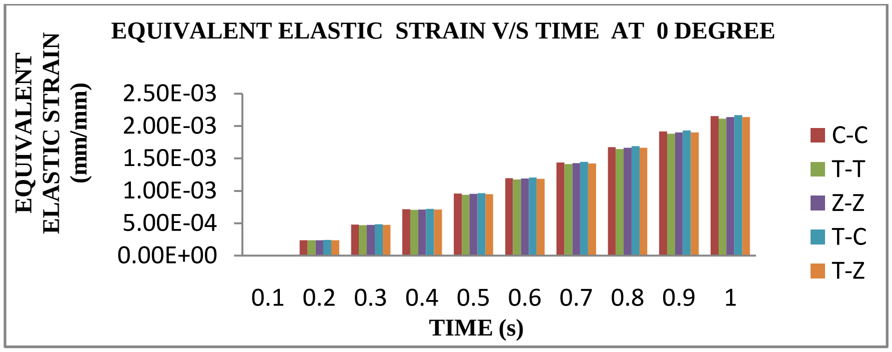


Fig. 8 Equivalent Elastic Strain v/s Time at 0° angle of flexion

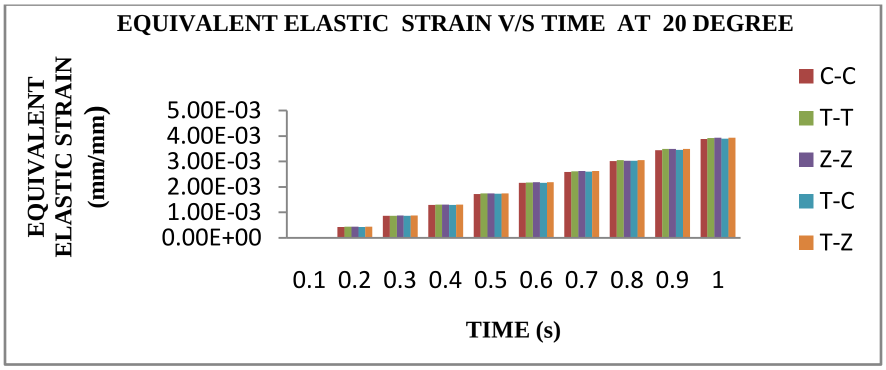


Fig. 9 Equivalent Elastic Strain v/s Time at 20° angle of flexion

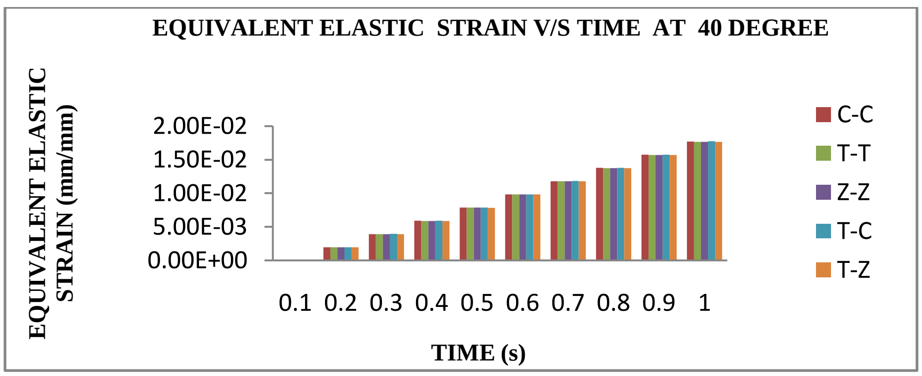


Fig. 10 Equivalent Elastic Strain v/s Time at 40° angle of Flexion

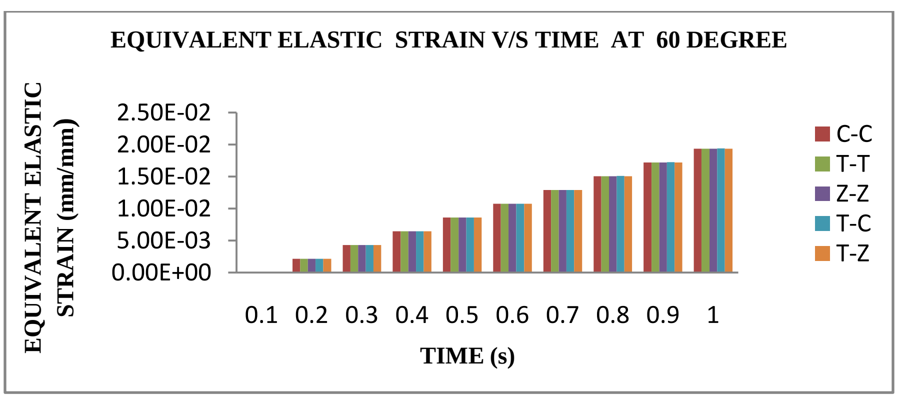


Fig. 11 Equivalent Elastic Stress v/s Time at 60° angle of Flexion

4. Conclusion

The present research investigated the effect of critical loading at different flexion angles for cobalt chromium alloy, titanium alloy and zirconium alloy being used at the femoral component and the tibial tray and the polyethylene at the tibial insert and stress results were being computed for the complete implant and the tibial implant. Based on the study and analysis the following conclusions are drawn as follows:

- Von Mises stress values increases with increasing time and angle of flexion thus increasing the tendency to wear of polyethylene tibial implant.
- Exercises like jumping, jogging, squatting, stair climbing etc. can result in early polyethylene wear.
- The contact area in 0° angle of flexion is approximately twice the contact area at 20° angle of flexion. Normally at higher flexion angles the contact area decreases and subsequently the Von Mises stress increases.
- Elastic strain shows increasing trend values with time but almost similar values with respect to the material.

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