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# Computational evaluation of the effect of femoral component curvature on the mechanical response of the UHMWPE tibial insert in total knee replacement implants

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## Abstract

Total knee replacement (TKR) surgery is done on individuals with end-stage osteoarthritis to restore knee function and alleviate joint discomfort. There have been recent developments in the design of customized implants based on patient-specific data obtained from MRI scans and subsequent image processing techniques. Here curvature of the femoral component plays an important role in effective implant design. Therefore the objective here is to investigate the influence of this curvature of the femoral component on the mechanical response of the bearing component. A 3D finite element knee implant model with a circular and an elliptical femoral component is developed and investigated for gait kinetics and kinematics. Responses such as contact pressure, stresses, strains, and wear produced on the tibial insert are estimated throughout the gait cycle. These findings suggest that the elliptical femoral component generates less contact pressure on the tibial insert than its circular counterpart. It is also inferred that too much variation in this curvature is not recommended as it may affect the patient's comfort level. In addition, the wear of the tibial insert is computed based on the contact pressure created by both knee implant models. Our study suggests an optimum value for the curvature and the comfort level of the patients over the existing knee implant designs.

**Keywords**: *Femoral component; Knee implant; Total knee replacement; Tibial insert; UHMWPE*

## 1. Introduction

For severe osteoarthritis of the knee, total knee replacement (TKR) is a common surgical procedure that reduces knee discomfort and restores mobility [1][2]. Ultra-high molecular weight polyethylene (UHMWPE) and cobalt chrome alloy (Co-Cr) are the most popular biomaterials used in knee prosthetics for decades. In India, around 1,20,000 TKRs are projected to be conducted annually [3]. TKR operations are increasingly being done on people of younger age. Traditionally, the advice is to postpone TKR as much as possible; however, the emphasis is now on enhancing functional ability and, therefore, standard of living, regardless of the patient's age [4]. This shift of thinking is partly due to the availability of higher-quality, longer-lasting implants and the increased public acceptability of TKR. Those younger who engage in greater physical activity where high flexion is culturally expected are more concerned about excessive knee flexion after TKA. Hence they are more likely to overload the prosthetic joint. As a result, they are at a higher risk of premature wear and failure. If the original TKR wears out or fails to work correctly, revision surgery is necessary. As a result, it is critical to enhance the life of mechanical joint replacements, especially in younger patients [5].

Clinical performance has improved as a result of advancements in TKA prosthesis design, including a greater range of movement and a longer implant lifespan. Several graded materials suggested in the literature may be utilised as implant materials for OA patients. [6,7]. However, TKA kinematics influences the joint's functioning and durability. Implanted knee kinematics are modified by conformity, loading circumstances, ligament integrity, and muscle function. Among knee conformity due to the curvature of the C0-Cr alloy component over UHMWPE, the tibial insert is the most crucial [3,8].

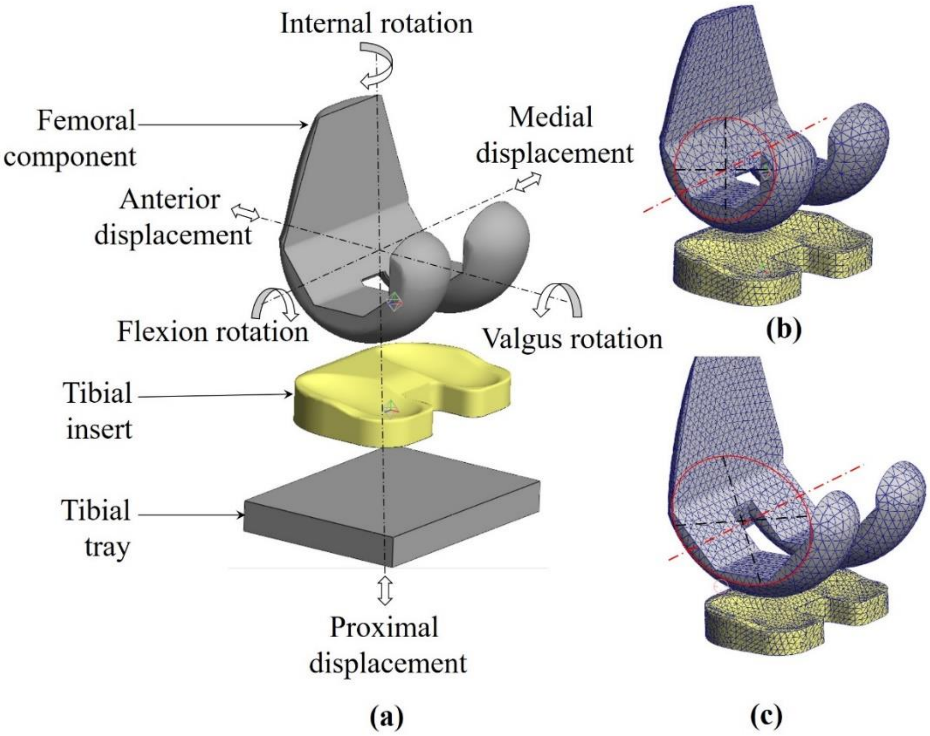

**Fig. 1.** (a) The 3D finite element model of the TKA; (b) Implant with circular design femoral component; (c) Implant with elliptical design femoral component

There are several TKR implants in the market, each with its design reason. Different implant designs strive to improve patient comfort by offering kinematics that is as similar to normal as possible. In this study, the femoral component curvature is hypothesized to influence knee kinematics and patient comfort. The wear on the tibial insert is stated to be influenced by relative sliding between the metal components as a result of the shift in maximum knee flexion caused by the femur's anterior-posterior placement on the tibia. Also, the wear of the UHMWPE tibial insert is hypothesized to be linked to the curvature of the Co-Cr femoral component. Conventionally the wear of the tibial insert is measured using a knee joint simulator for multiple millions of cycles passed over the UHMWPE insert. When compared to testing using a knee simulator, pin-on-disc wear tests reveal similar results of TKA while saving money and time [9]. The current study predicts the mechanical responses such as contact pressure, stresses, strains and wear of the UHMWPE tibial insert.

## 2. Materials and Methods

### *2.1. Computational Model*

The computational finite element model of the TKA used in this study is based on the design of a commercially available implant Scorpio NRG CR (Stryker, USA), as shown in Figure 1. (a). In this work, we modified the present design's femoral component curvature to circular and elliptical, as shown in Figures 1 (b) and 1 (c). Also, the fixed-bearing, cruciate-retaining type finite element TKA model is used for the present analysis. The Co-Cr metal components are modelled as a rigid body. The components are meshed with 10-node quadratic tetra elements with a femoral component average element edge length of 3.2 mm and a tibial insert average element edge length of 2.2 mm. The tibial tray contains 8-node, 5-mm linear brick elements.

A mesh convergence test is conducted in the study to ensure that the solution should not change when the mesh is refined. The optimum element length concerning the contact pressure generated on the surface is 2.2 mm, based on the tibial insert edge length of 4 models ranging from 1 to 4 mm in 1 mm increments. There is a total of 20155 elements in the tibial insert. The pre-processing and post-processing analysis is performed on FEBio Studio (University of Utah and Columbia University), an open-source finite element analysis software [10].

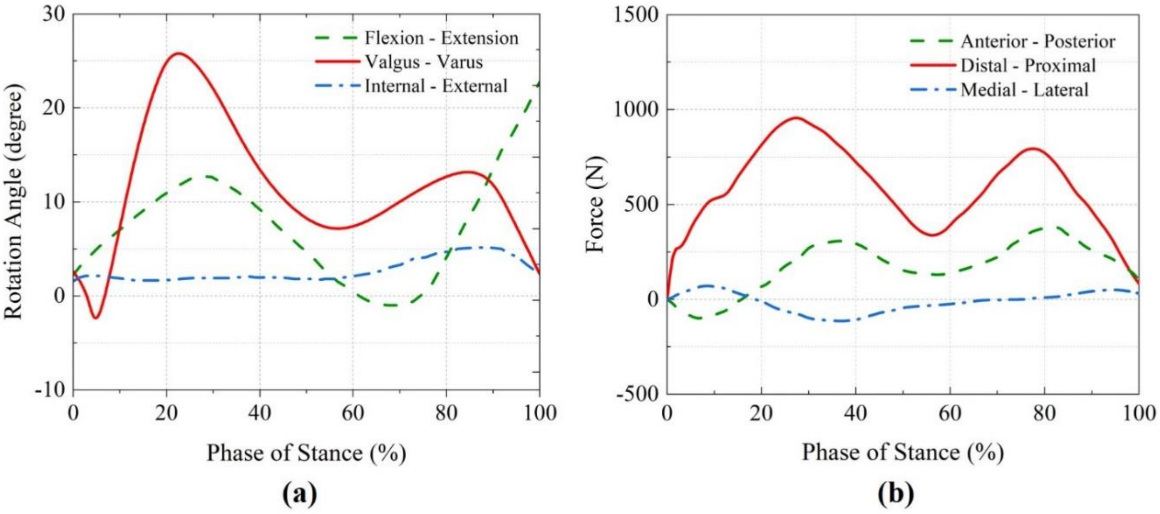

**Fig. 2.** The input gait data for the analysis; (a) The components of forces (N) act on the TKA in all three degrees of freedom during the gait cycle; (b) The rotation angle (degrees) in the sagittal plane, frontal plane and transverse plane respectively during the gait cycle [11,12]

### *2.2. Loading and Boundary Conditions*

An explicit TKA finite element analysis is performed to predict the knee joint movements and contact pressure on the tibial insert under gait loading conditions. The tibial tray and tibial insert are constrained in all directions, whereas the femur rotates in relation to the gait input data. In addition, all translational forces are applied to the femur component. The femoral component and tibial insert are designed to engage without friction. The master surface is the articular surface of the femoral component, whereas the slave surface is the tibial insert surface beneath it. During the gait cycle, the forces and rotations are applied to the centre of mass of the femoral component. The forces and rotations during the phase stance of the gait cycle are applied to the model, as illustrated in Figure 2.

The gait input data are taken from the literature and imported into the model for simulation [13–17]. The walking kinematics data are obtained from the subject (28-year male, 82 kg) who walked on a 10 m track at an average speed (1.7 m/s) [11]. Their study used 3D motion capture and anatomical marker systems to track walking and running data and converted them into knee kinematics data with commercial software.

### *2.3. Material Models*

The UHMWPE tibial insert is modelled as a linear isotropic elastic material, and the material constants are given in Table 1. The Co-Cr metal components are chosen as rigid bodies because their material constants are substantially higher than the tibial insert.

Table 1. The material constants for the components of the TKA implant

| **Implant Components** | **Mechanical properties** | | **Source** |
|---|---|---|---|
| Femoral component | Cobalt-Chromium (rigid) | Rigid body | |
| Tibial tray | | | |
| Tibial insert | UHMWPE (Isotropic elastic) | ρ=9.38x10-10 tonnes/mm3 | [18] |
| | | E=800 MPa | |
| | | ν=0.459 | |

### *2.4. Wear analysis*

Archard devised an equation for determining the linear wear depth from articulating surfaces between two moving metal surfaces [19,20]. The current investigation's wear calculation on the tibial insert uses equation (1).

$$\boldsymbol{H = K_w P S} \tag{1}$$

where $H$ is the linear wear depth, $P$ is the contact pressure, $K_w$ is the wear factor which can be calculated experimentally, and S is the total sliding distance for 1 lakh cycles. Co-Cr's wear factor of UHMWPE is calculated experimentally by a pin-on-disk tribometer (TRB 3, Anton-Paar, Austria). The wear track profile on the UHMWPE surface for a 1 million cycle is plotted with a profilometer. The wear factor or wear rate is calculated using equation (2).

$$K_w = \frac{V}{F_n * S} \tag{2}$$

where $V$ is the measured wear volume $388.9 * 10^6\ \mu m^3$, $F_n$ is the applied load 40N, and $S$ is the sliding distance of 1200m. The calculated wear factor is $9.05 * 10^{-6}\ mm^3/Nm$.

## 3. Results

The contour of the maximum Lagrange strain and contact pressure created on the surface of the UHMWPE tibial insert during a gait is shown in Figure 3. It is observed that the circular design has higher contact pressure and Lagrange strain compared to the elliptical alternative design. However, as shown in figure 4, the maximum values of mechanical responses are achieved during the first 20–30% of the stance phase. The contact pressure generated in the circular design is higher than in the elliptical design given in figure 4(a). Also, the principal and effective stresses have similar trends with respect to the contact pressure given in figure 4 (b-d). In addition, the elliptical design achieves a larger contact area on the articulating area than the circular design. The comfort of the patient decreases as the curvature flattens; however, the contact pressure reduces, which is observed in figures 4 (a) and 4(f).

The wear depth is calculated according to equation (1) concerning the maximum contact pressure generated for circular and elliptical designs, as given in Table 2. The comparison of maximum femoral translation over tibial insert is plotted in figure 5 for circular and elliptical designs. It is observed that the elliptical design has higher translation in all directions compared to the circular design. There is a 40 per cent difference in anterior-posterior translation between the two designs

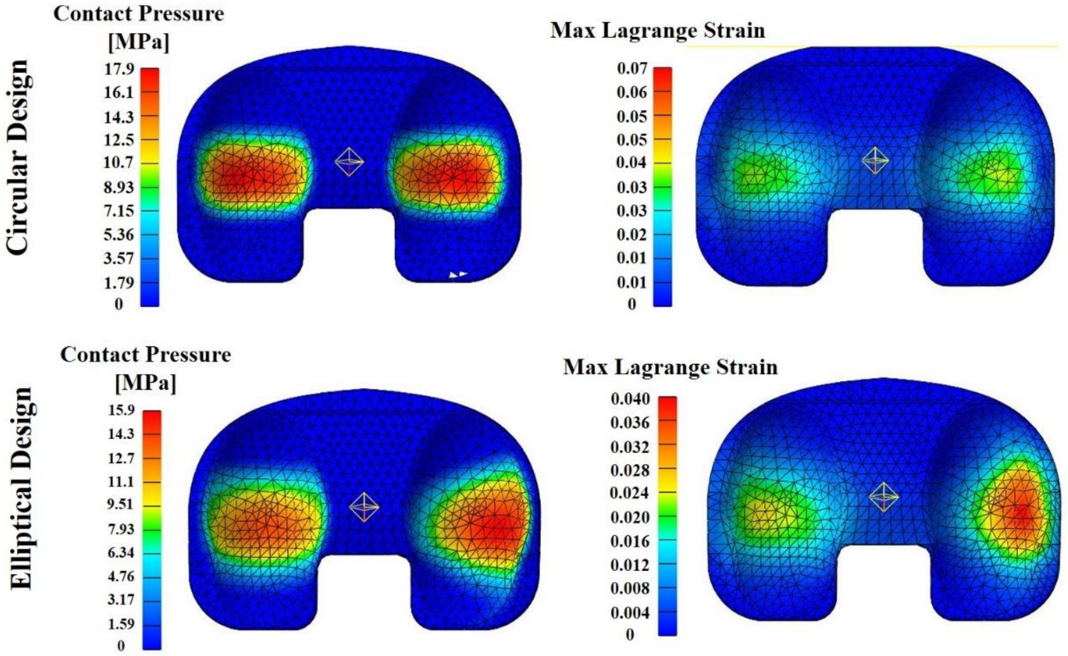

**Fig. 3.** Contours of maximum contact pressure and Max Lagrange strain generated on UHMWPE tibial insert during the stance phase of gait cycle.

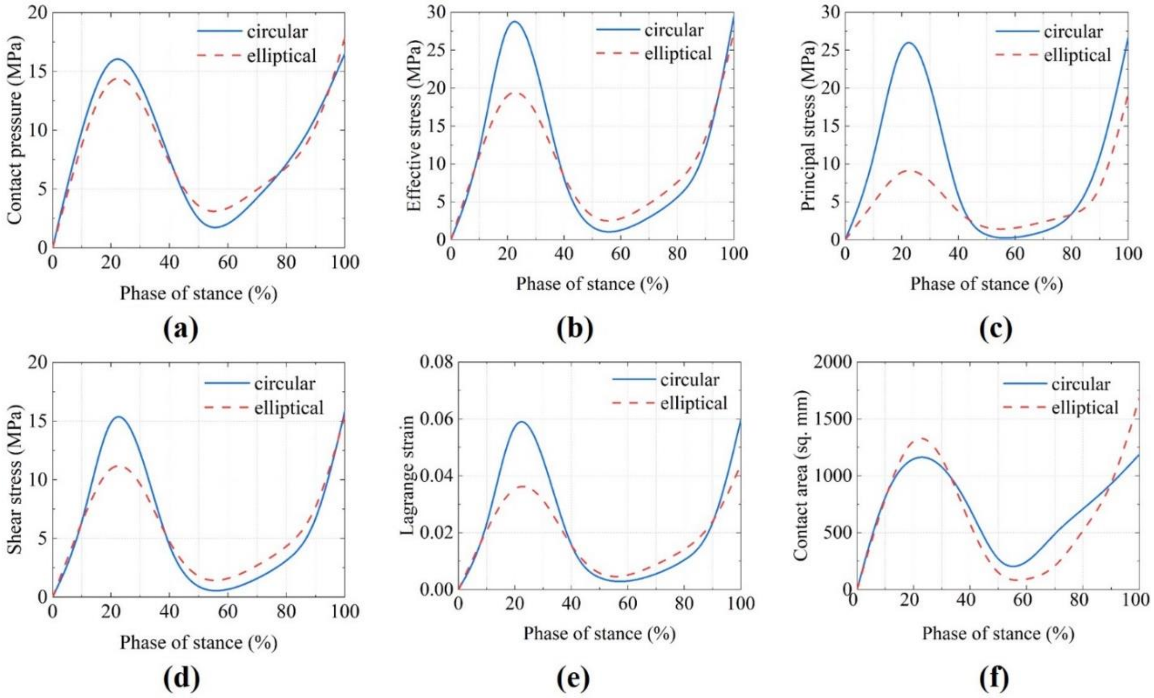

**Fig. 4.** The comparison of mechanical characteristics of UHMWPE tibial inserts on the influence of circular and elliptical femoral components during the walking gait; (a) the contact pressure generated on the tibial insert surface; (b-d) Effective stress, principal stress and shear stress; (e) Lagrange strain on the tibial insert surface; (f) the articulating area of contact during the gait cycle.

## 4. Discussion

The current work uses a knee implant geometry and data from all six degrees of knee kinematics. The effectiveness of the prosthetics and surgical success depends on the kinematic behaviour after TKA. According to a computational assessment of TKA design and subsequent wear analysis, the clinically observed anterior femoral translation is caused by a rapid decrease in the radii-of-curvature of the femur. As seen in figure 5, a shift from a smaller to a greater curvature radius caused the femur to translate posteriorly.

Table 2. The wear depth produced on the tibial insert during the gait cycle

| | **Circular Design** | **Elliptical Design** |
|---|---|---|
| Max. contact pressure (MPa) | 17.9 | 15.9 |
| Measured wear depth (mm) | 0.194 | 0.172 |

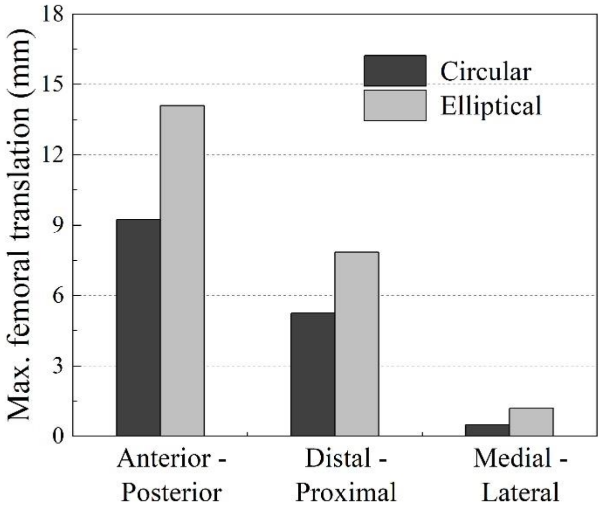

Fig.5. The comparison of the maximum femoral component translation during the gait cycle for circular and elliptical design

In reality, however, in vivo wear measurement in TKA is quite tricky. The results of the in vitro wear simulation have been quite predictive of the wear behaviour seen in clinical settings. It's a time-efficient and economical way to finish the equivalent of the last five years worth of clinical wear data [21,22]. As a result, computer modelling and simulation in this sector have grown more prevalent [21,23–25].

Experimental investigations are often carried out, despite being ineffective in terms of cost and time, and they can only study a restricted number of configurations and load circumstances [26]. However, experimental research is eventually required in order to have a complete understanding of the way materials behave. According to pin-on-disc testing, the amount of wear caused by UHMWPE decreases as contact pressure increases. Consequently, an implant with lower conformity with a constrained articulating area and high contact stress would experience less wear compared to an implant with a greater conformance [27,28].

It's uncertain if kinematic differences caused by patient characteristics and surgical technique exceed the impact of implant design [29]. Changes in reported kinematics were exclusively attributable to differences in articulating geometry since all geometric alterations to the implant geometry were analysed in the computational model under comparable boundary circumstances. In the future, researchers will investigate how these implants work under more physiological loading settings, as well as the in vitro variation that might be predicted.

## 5. Conclusions

The computational method used here successfully establishes the connection between the design of TKR implants and the mechanical responses of bearing materials. The model's sensitivity is shown by its ability to identify differences in kinematic patterns resulting from implant design changes to curvature. Now, it will be used to examine a variety of additional design aspects, including the reduction of UHMWPE tibial insert stress and the optimization of insert wear behaviour.

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