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FEA AND EXPERIMENTAL INVESTIGATION OFPROSTHETIC KNEE JOINT

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Abstract

This study has taught us how to assess the knee joint using a range of variables, yielding diverse outcomes. Furthermore, it elucidates the importance of the knee joint's stress capacity and the generation of various loading scenarios through these input variables. The primary focus of the research is on static analyses, enabling us to gain insight into knee capacity and the necessary stress conditions, which are vital for our understanding. Additionally, the study delves into the examination of kinematics within the experiment. The findings of the study indicate that mechanical testing methods are employed to assess the current state of the knee implant market.

Key terms: Finite element analysis, Circular Polariscope, Flexion angle, Sagittal radius, Knee joint, Tibial, and Femur.

I. Introduction

The human knee joint is a highly complex structure, essential for bearing the full weight of the body and facilitating movement. However, it is vulnerable to injuries, often resulting in severe damage and the development of osteoarthritis, leading to joint pain and mobility issues. Currently, total knee replacement (TKR) stands as a widely accepted and clinically effective treatment for alleviating severe pain caused by conditions like rheumatoid arthritis or knee joint injuries, while also restoring patients' physical capabilities. The TKR procedure and subsequent rehabilitation are frequently required. To reduce the necessity for knee replacement surgery, there is a pressing need for the development of improved knee implants [1]. The knee joint, the major joint of the lower limb, is designed to support the entire weight of the upper body while moving and maintaining the characteristic, upright bipedal position. It collaborates with the hip and ankle joints to support and move the body during a variety of action [2].

The knee, capable of withstanding compressive forces up to six times the body's weight during everyday activities, transfers the body's weight, inertia forces, and muscle forces to the ground.

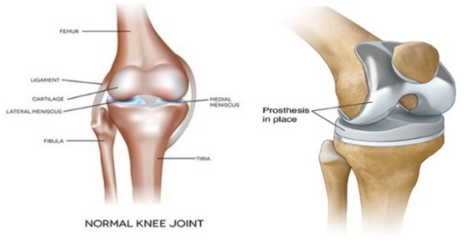

Fig 1. Normal knee joint and Artificial knee joint

This paper seeks to establish a clear understanding of key concepts and significant terminology pertaining to the knee joint. It also aims to investigate experimental stress analysis of a prosthetic knee joint using a polariscope. Additionally, it intends to analyze stress distribution within the prosthetic knee joint by applying desired material properties through Finite Element Analysis (FEA).

A. Prosthesis

In the field of medicine, a prosthesis is defined as an artificial device used to replace a defective or missing body part resulting from trauma, disease, or congenital conditions. There are primarily two categories of prostheses: craniofacial and somato (body). Craniofacial prostheses can be further categorized into two types: extra-oral and intra-oral. On the other hand, somato prostheses encompass various types such as limb prostheses and ear prostheses, which are used to replace defective body parts with artificial organs. [3]

B. Technique in Knee Replacement

Knee replacement surgery is a surgical technique that begins with a post-operative procedure and concludes with a surgical procedure. To see the narrowing that has occurred in between the joints of the knee, an X-Ray of the load-bearing of the knee joint is performed for the knee replacement of both the lateral and AP of the knee with 30° flexion of the knee is performed. MRI is used in conjunction with X-Ray imaging to see the impacts of the cartilage and its problematic places in order to carry out the replacement and incorporate exact implants in that region

II. Process of Constructing a Photoelastic Representation of an Artificial Knee Joint

To create a 2-D knee model, an initial step involves crafting a mold from Mseal epoxy compound. This mold is designed to shape the knee joint component's chamber, constructed from a 6mm thick epoxy resin plate, following specified dimensions. To prepare the epoxy resin, a smaller amount of hardener is mixed with it at a 3:1 ratio, though proportions may adjust for larger castings due to the heat generated. Both components are in liquid form and need to be mixed for around 120 minutes. Once thoroughly blended, this mixture is poured into the knee joint component's mold cavity, taking approximately 48 hours to fully solidify[9].

After the material has solidified, the photoelastic sheet is removed from the mold box to meet our specifications.

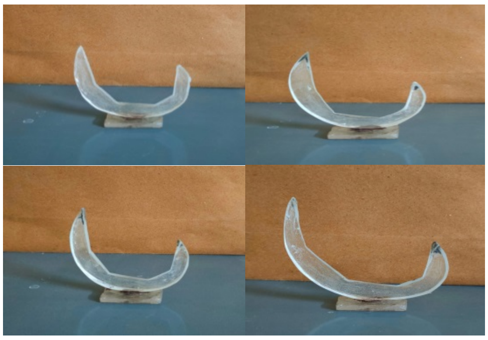

Fig 2. Photoelastic models for 40mm radius and different angles

III. Material Properties

In modern times, creating improved biomaterials for medical purposes is a significant challenge in materials science. Better artificial implants are in high demand. Additionally, biomaterials often exhibit hierarchical structures, and tissues demonstrate complex functionality with continuous transitions between structures and compositions[5].

Material Name	Epoxy Resin	Symbols	Unit
Density	1300	ρ	g/cm^3

Poisson’s ratio	0.34	ϑ	
Young’s modulus	3350	E	MPa

IV. Experimental Study

Conducting exploratory compressive tests and employing a limited component approach to analyze tibia bone arrangements and obstructions.

A. Photoelasticity: Photoelasticity is a whole-field technique for assessing stress and strain in materials by using a birefringent model of the structure to illustrate stress patterns resulting from external forces or inherent birefringence. This analysis is often conducted during the design phase to anticipate stress distribution and evaluate 2D stress systems, relying on Maxwell's stress optic law as its foundation.

The stress optic law is (σ)= $\frac{Nf\sigma}{h}$ ...N/mm^2

Where,

□= Stress in the model, N = Number of fringes in material, f= Fringe value, h = Model thickness

B. Polariscope: The polariscope is a piece of optical inspection equipment that is used to detect stress concentration in glass and other optical materials such as plastics and polyurethanes. A polariscope is made up of a light source and two crossed polarised lenses, similar to the ones seen in polaroids[10].

C. **Optical Arrangement in Polariscope Machine**

Table 1. Optical arrangement in a polariscope.

Machine setup	Polarizer and analyzer	Quarter wave plate	Background
Circular polariscope	Crossed	Crossed	Dark Dark
	Parallel	Parallel	Bright
	Crossed	Parallel	

D. Calculation of Stress

The stress optic law's equation is as follows:

$$(\sigma_1 - \sigma_2) = \frac{Nf\sigma}{h} \quad N/mm^2 \; \ldots\ldots\ldots\ldots(1)$$

Where,

σ_1 and σ_2= Maximum and lowest amounts of principal stresses in N/mm^2

f_σ = Value of the material's fringe in N/mm.

N = Fringe Order in the material.

Consider a round model (the knee model is supposed to be half of a circle).

$$f_\sigma = \frac{8P}{\pi DN} \quad \cos\alpha \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where,
P = Force applied to the model in Newton
D = Model's diameter in millimeters.
α = Angle of flexion
h= the model's thickness

For case 1,

The radius of the photoelastic model is 40mm, and the flexion angle is 30°.

$\mathrm{P} = 35\ \mathrm{KG} = 35 \times 9.81 = 343.35\mathrm{N},\ \mathrm{h} = 6\mathrm{mm} = 0.006\mathrm{m},\ N = 1.20,\ \alpha = 30°,$
$\mathrm{D} = 80\mathrm{mm} = 0.08\mathrm{m}$

$$f_\sigma = \frac{8\times35\times9.81}{\pi\times0.08\times1.20}\cos 30°$$

$$f_\sigma = 7.88 \times 10^3$$

Stress is now calculated as follows:

$$\sigma = \frac{1.20\times7.88\times10^3}{0.006} = \mathbf{1.57 \times 10^6 N/m^2}$$

VI. Finite Element Analysis (FEA) of Prosthetic Knee Joint

FEA is a simulation technique. It is employed in the solution of irregular, complex form geometries. The complete body is discretized into a small number of components, and a result is obtained by solving a differential equation. We employed Ansys analysis software for prosthetic knee joint analysis in this way.

A 2-D femur and tibia model was crafted in CATIA software, tailored to our specific dimensions and needs. This knee joint model featured dimensions of 40mm sagittal radius, and flexion angles of 15^0, 30^0, 45^0 and 60 degrees [7]. After importing the geometry into analysis software, material properties were assigned. The model was then meshed using quad elements or tetra mesh. Boundary conditions were applied, and the mathematical model was solved. The outcomes were examined in a general postprocessor for analysis.

The results of 40mm radius 15^0 flexion angle is shown below

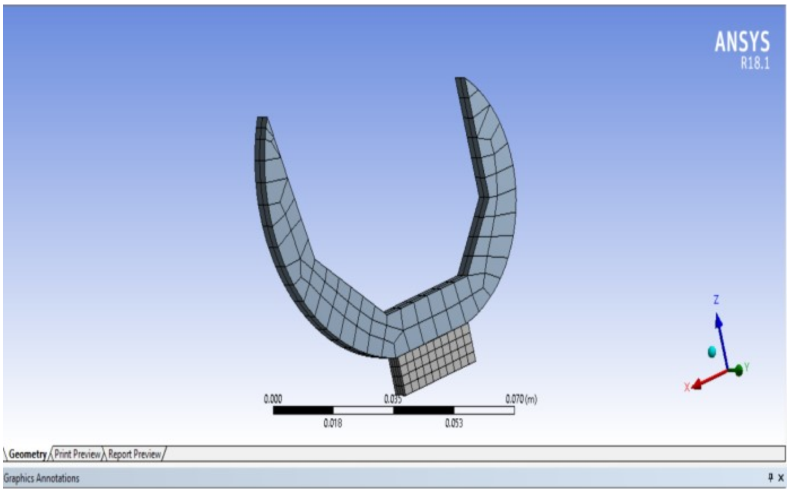

Fig 5. Meshing of model

V. Results and Discussion

An experiment is conducted using a polariscope machine. This experiment aims to determine the stress distribution on the model under different loading conditions, and the finite element analysis method is employed to calculate the Normal stress.

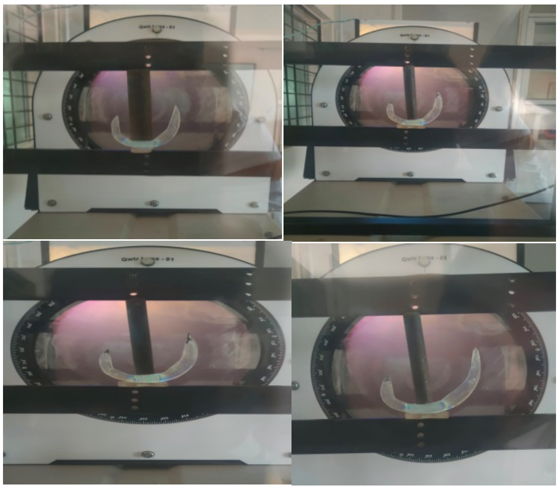

Fig 6. Stress distribution on photoelastic model for 40mm radius 15^0,30^0,45^0 and 60^0 flexion angles

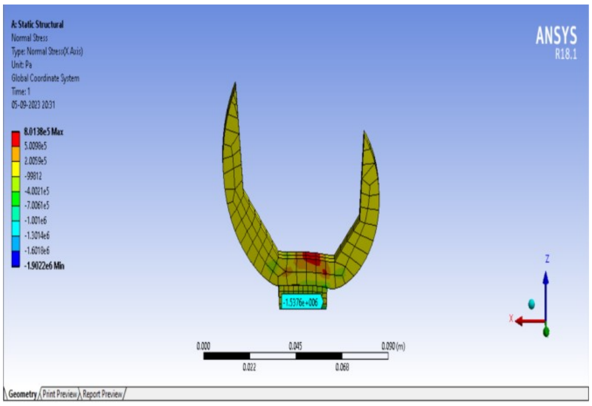

Fig 7. stress for 294N and 40mm radius, 15 degree flexion angle

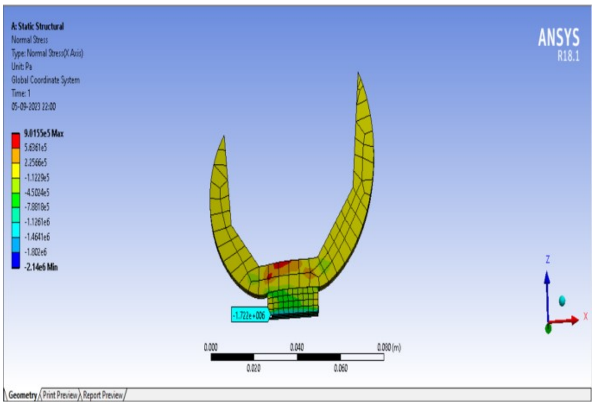

Fig 8. stress for 343.3N and 40mm radius, 30 degree flexion angle

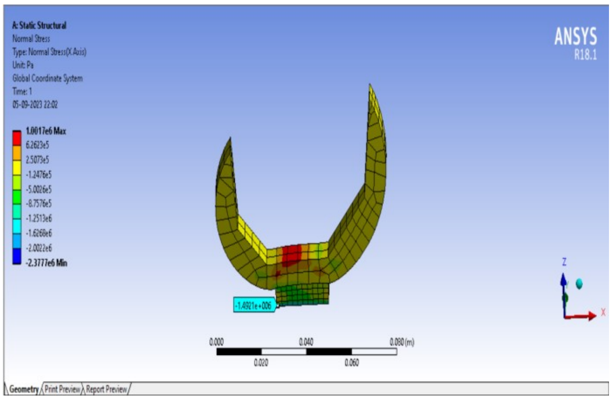

Fig 9. stress for 392.4N and 40mm radius, 45 degree flexion angle

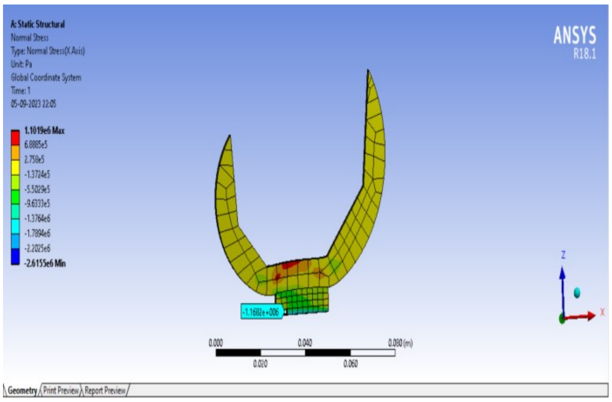

Fig 10. stress for 441.45N and 40mm radius, 60 degree flexion angle

The accompanying diagram depicts a stress analysis experiment on a knee model. Loads of 294.3N, 343.3N, 392.4N, and 441.45 were applied to various flexion angles (15^0, 30^0, 45^0, and 60^0 degrees). Stress fringes developed on the photoelastic model as compressive loads were gradually applied to it. The internal stress within the model can be determined by using the stress optic law equation based on these fringes.

The model is imported into the analysis program after FEA analysis. Choosing tetra or quadra elements and assigning material parameters such as young's modulus (E) = 3.32E3 MPa and poison’s ratio (ϑ) = 0.34 and density (ρ) =1.3 g/cm^3. The analytical software then solves the problem and returns the answer after applying boundary conditions to the model[9].

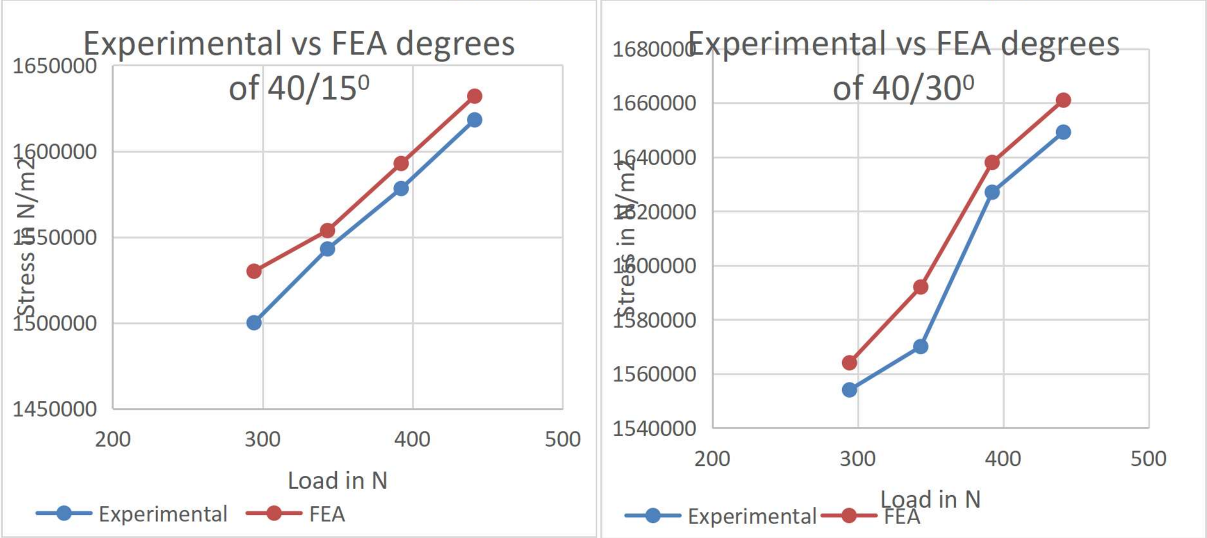

Fig 11. Stress for various loads is compared to experimental V/S FEA results (15^0 and 30^0 flexion angles and 40mm sagittal radius).

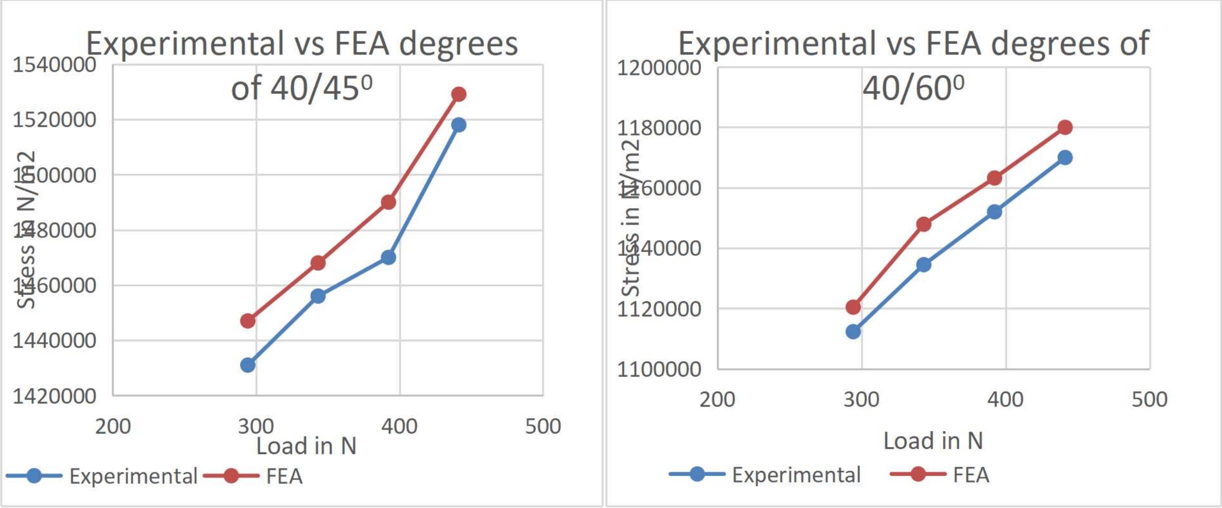

Fig 12. Stress for various loads is compared to experimental V/S FEA results (30^0 and 60^0 flexion angles and 40mm sagittal radius).

Figures 11 and 14 provide a comparison of Normal stress distribution to various loading conditions at 15 degrees of flexion. As the load increases, so does the stress. For both the 40mm radius, FEA stress exceeds experimental stress. When comparing figs. 10 and 13, the model must have less stress than the 40mm radius model.
Figures 11 and 14 show stress vs. load for 40mm radius at 30^0 degrees of bending. In comparison, stress is greater in the 40mm radius model as the angle increases.

Figures 12 and 13 illustrate Normal stress vs Load for radiuses of 40mm, respectively. When comparing the aforementioned figures, stress is greater in the 40mm radius model because the area is smaller than in the 50mm radius model.

VI. Conclusion

In conclusion, we find that the variance between the results from our experiments and those obtained through finite element analysis (FEA) is within an acceptable range. Our study delves into the stress distribution within a photoelastic model and its behavior under varying sagittal radii and flexion angles. Additionally, we observed that stress levels increase proportionally with the applied load on the model.

Acknowledgment

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