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Optimization of Prosthetic Knee Joint Under Static and Cyclic Strength Tests

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ABSTRACT

Knee joint consists of different components, i.e. femur, tibia, patella and menisci which make it a complex structure, undergoing different critical loads in human body performing motions and physical activities. The present study focuses on the analysis of stress magnitude on knee joint and knee implant when these are introduced with different loads acting upon it with varying angles of inclination. 3-D model of the knee joint and knee implant were designed using 3-D modeling software i.e. CAD. These models were imported to ANSYS to get the specific results of stress magnitude using finite element analysis. This study has revealed that with a load range of 540N to 790 N and change in angle from 10° to 90°, the knee implant could be able to sustain a load of 540-640 N at an angle of 10°-50° demonstrating a stable stress value of 1.27E+08 – 6.11E+08 Pa. At steady state of the knee i.e. when the knee is at 90° position, stress value reaches to 1.28E+08 Pa.

Keywords : Knee Joint, Implants, Finite Element Analysis, ANSYS, Von-Misses Stress.

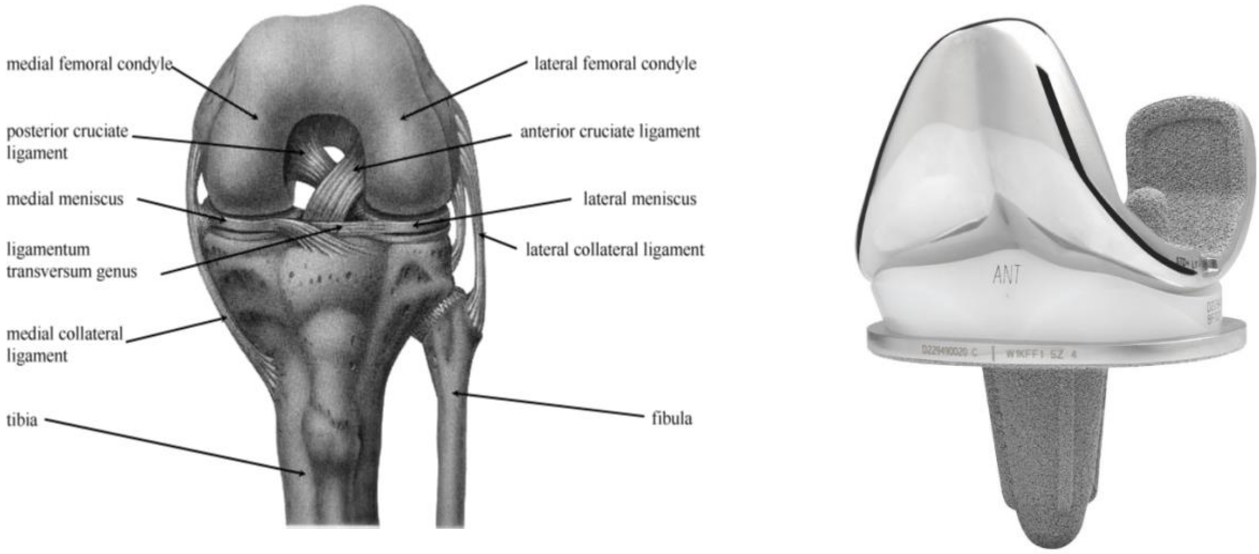

Fig . 1 Bio- Mechanical Knee Joint

I. INTRODUCTION

The knee joint is complex structure in the human body which undergoes critical loading simultaneously while performing different physical activities such as walking, running, in rotational motion, sitting, static positions etc. what we used to do in our day to day life. Major parts in a knee joint are femur, tibia, patella and meniscus. It has two articulation components one is in between the tibia

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and femur and another between the femur and patella. The knee joint is a pivot hinge joint. It permits extension and flexion of leg with that rotation in both internal as well as external part [1]. It's articular bodies are lateral and medial condyle were patella is present in the posterior region in between the lateral and medial condyle surfaces. Articular capsule of knee joints are the fibrous membrane and synovial membranes. Synovial membranes are those which are been attached near the cartilage of both tibia and femur. Cartilage is elastic thin tissue that acts as protection guard for bone and makes the joint surfaces. In knee joint there are two types of cartilages joint one is fibrous cartilage and other as hyaline cartilage. Fibrous cartilage has resistance to high pressure and has high tensile strength [2] . A meniscus is the articular disk present in the knee joint, having two components i.e. medial and lateral meniscus.

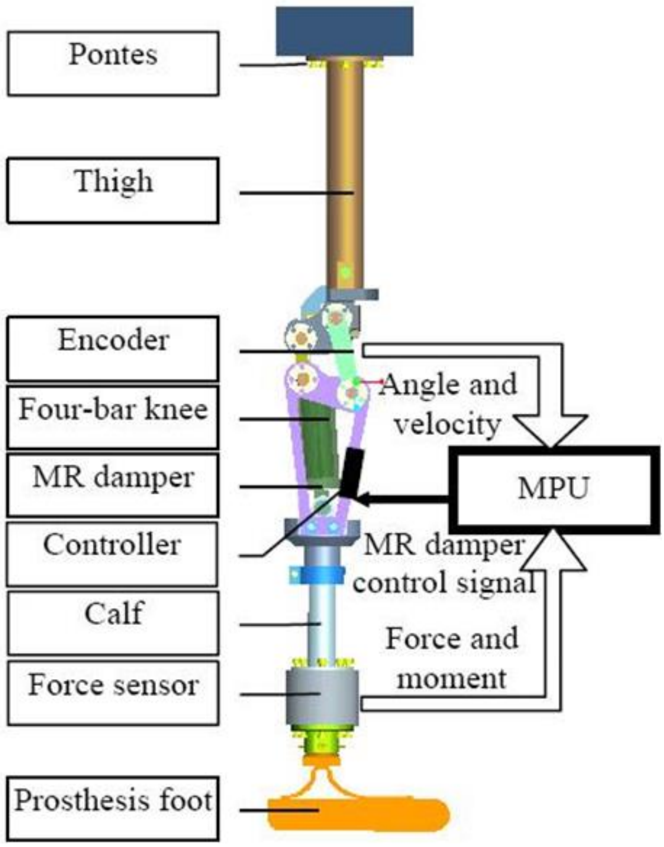

Fig. 2 Virtual prototype of IBL

Bionic design of IBL knee joint

The knee joint bears the largest weight and is the most complex joint of human body. Its main movement is flexion and extension. The structure of knee joint is directly related to the bionic characteristics and kinematic performance of IBL. The reasonable structure of knee joint can guarantee the stability in support phase and flexibility in swing phase. According to previous research of biomedicine [1], the human knee joint is composed of irregular shape of bones which are connected by ligament. The main bone structure of knee joint includes the femur, tibia and patella. Due to combined action of anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial ligament, lateral ligament, joint capsule and tendons, knee joint can move freely without dislocation.

The contact surface between femoral bottom and tibial top is irregular. During flexion and extension activity of knee joint, there are both rolling and sliding between the two contact surfaces.

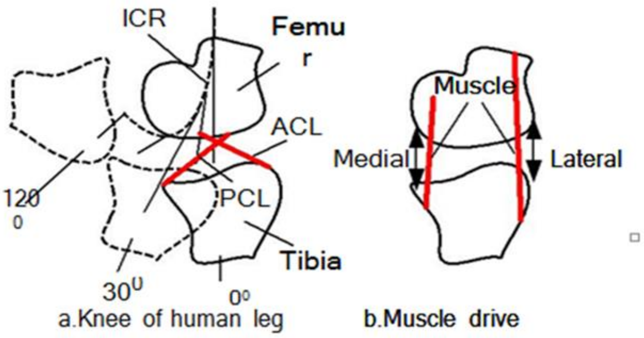

Fig 3. Bio- Mechanical ligament

The outstanding feature of knee joint is that its instantaneous centre of rotation (ICR) is not fixed and similar a "J" curve, as shown in Fig. 2. Thus, the length of thigh and calf is variable and the distance between foot and ground is increased.

Now most of the humanoid robots and artificial limb joints adopt single axis knee mechanism and motor driver. Its rotation centre is fixed and has obvious difference from that of human knee joint. Bionic knee joint should adopt multiple axis knee mechanism (4-bar, 5-bar and 6-bar). The 4-bar bionic knee is adopted in the design of IBL because it has simple structure, low cost excellent performance.

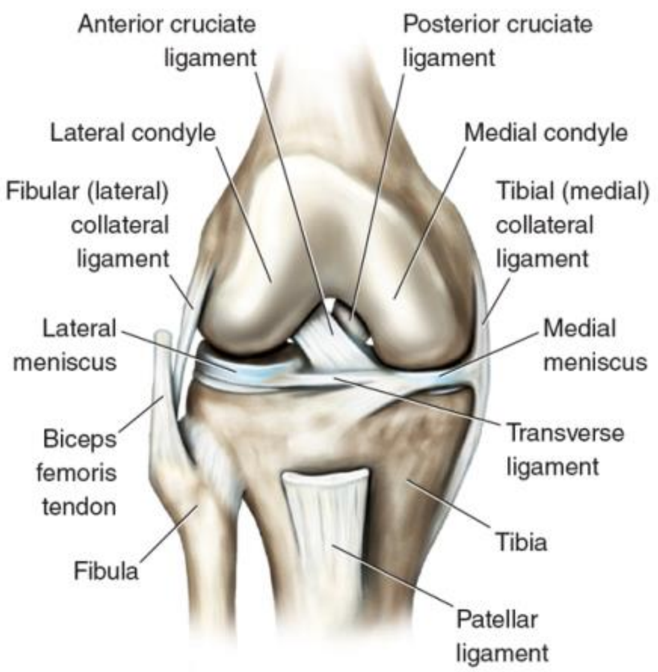

Fig 4. Human knee joint

Comparing with single axis knee mechanism, 4-bar closed-chain knee mechanism has many advantages such as "J" curve of ICR [7], higher foot clearance and good stability with GRF, as shown in Fig. 3. Virtual prototype of IBL knee joint is shown in Fig. 4.

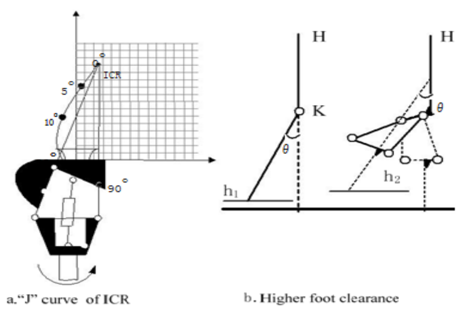

Fig 5. Advantages of 4-bar knee joint

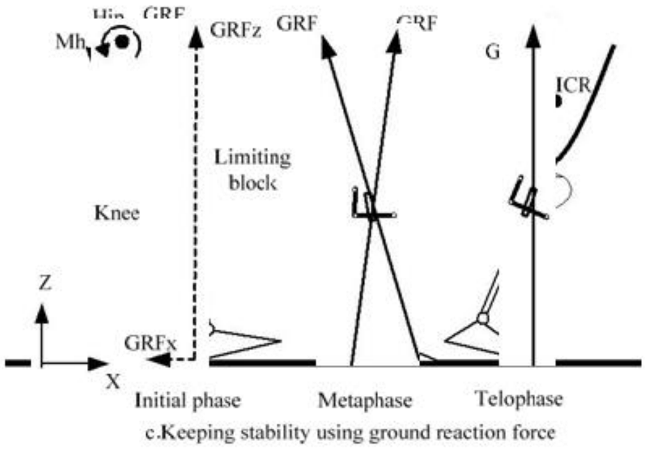

Fig 6. Virtual prototype of IBL knee joint

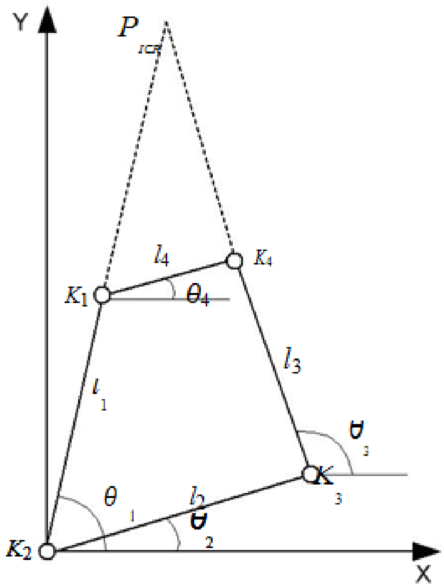

Fig. 7 Schematic diagram of 4-bar closed-chain knee mechanism

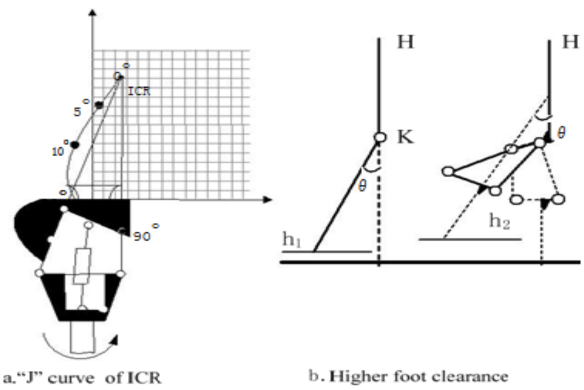

Fig 8. Advantages of 4-bar knee joint

Coordinate of point K_1

$$x_{K_1} = l_1 \cos\theta_1$$
$$y_{K_1} = l_1 \sin\theta_1 .$$

Coordinate of point K_3 :

$$x_{K_3} = l_2 \cos\theta_2 .$$
$$y_{K_3} = l_2 \sin\theta_2$$

Coordinate of point K_4 :

$$x_{K_4} = l_1 \cos\theta_1 + l_4 \cos\theta_4$$
$$y_{K_4} = l_1 \sin\theta_1 + l_4 \sin\theta_4 .$$

Table 1 : Properties of Biomaterial used for knee implant

Material	Density (g/cm3)	Elastic Modulus (MPa)
Cobalt-Chrome alloy	8.5	7-30
316L Stainless Steel	8.0	230
CP Titanium	4.51	200
Ti6Al4V	4.40	106
Bone	1550(kg/m3)	1×10^5

II. RESULTS AND DISCUSSION

Follow the steps as discussed in the above **section A,** and perform the static structural analysis of the knee joint without implant. In this static structural analysis of the knee joint without implant different loads were subjected i.e. 540 N, 590 N, 640 N, 690 N, 740 N and angle of the contact area as 10°, 30°, 50°,70°, 80°. And stress analysis was performed in both cases i.e knee joint without implant and knee implant.

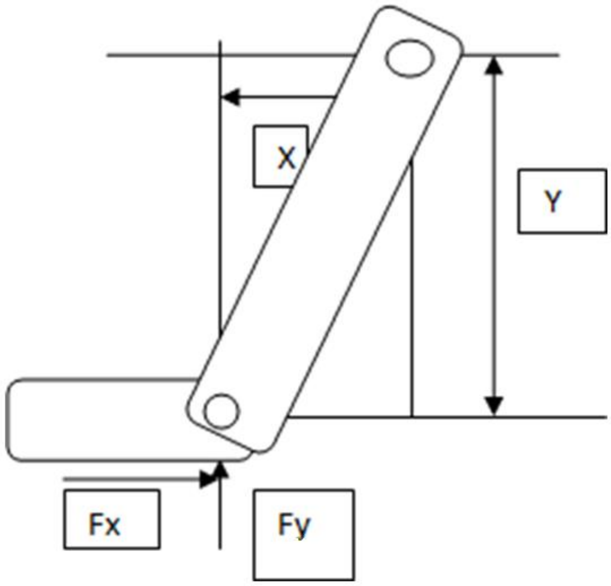

Fig 9. Forces applied to the knee joint

Initially, stress analysis was performed in knee joint with different load and angles without any implant with vertical forces. Results were recorded.

Stress analysis of Knee Joint Without / with implant stage

The load applied = 1400 N

Stress applied = Equivalent stress (Von-misses stress)

The stress magnitude of both full model and reduced model of the knee joint was calculated analytically and the data are represented in **table 2**.

Fx → Frictional Force
Fy→ Ground reaction force
X→ perpendicular distance along Fy
Y→ Perpendicular distance along Fx

	Reduced model stress (Pa)		
components	X	y	z
Femur	3.52E+05	2.53E+05	3.56E+05
Tibia	50556	12808	19523
Patella	3.28E+05	6.71E+05	3.65E+05

	Full Model Stress (Pa)		
Components	X	Y	Z
Femur	2.54E +05	9.22E+04	2.25E+03
Tibia	27743	16699	43771
Patella	2.13E +05	1.50E+05	3.11E+05

Table 2. Knee joint optimization based on genetic algorithm

III. OBJECTIVE FUNCTION

The degree of coordination between 4-bar knee mechanism and human body is better when the ICR trajectory similarity between 4-bar knee mechanism and human knee joint is higher. From this perspective, the square of coordinate difference between Static and cyclic strength testsIn this work, a guideline to conduct the static and cyclic strength tests on a prosthetic knee is adopted from the ISO 10328:2006 standard. Basically, the purpose of the static

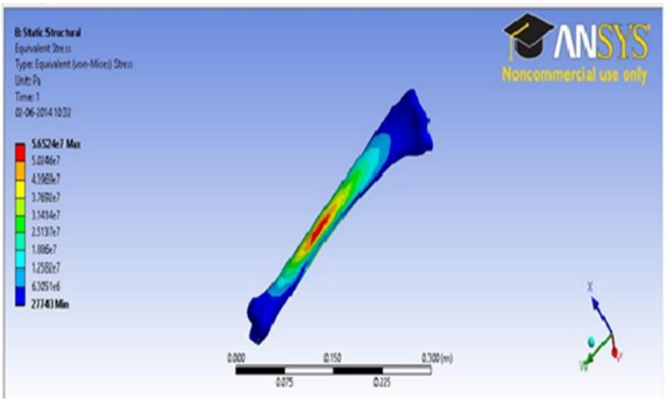

Fig 10. A (PATELLA) Model analysis of knee joint

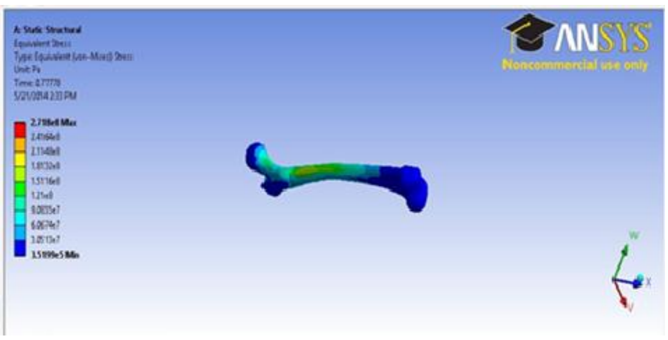

Fig 10 B. (FEMUR) Model analysis of knee joint

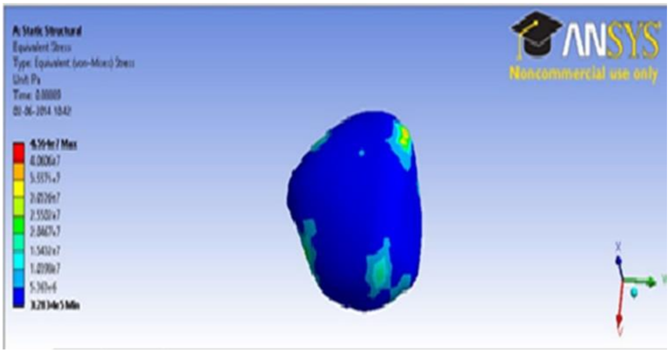

Fig 10.C (TIBIA) model analysis of knee joint

Figure 10 represents stress analysis of reduced/individual parts of knee joint, i.e. femur, tibia and patella respectively. In this figure mostly analysis part was being shown where the solution information was collected upon importing certain load and examining the equivalent stress magnitude. Here 1400 N force was applied to the parts of knee and stress magnitude was calculated in Pa as standard unit. Femur shows a maximum stress of 2.718e8 Pa and minimum stress of 3.5199e5 in the X- component. Tibia shows 155.03 Pa, maximum stress result and a minimum of 150.67 Pa in the x-component Patella shows a maximum stress value of 4.564e7 Pa and minimum value of 3.2834e5 Pa in the X-component . In the solution part we can see the maximum and minimum values of knee joint stress analysis. The outcome of the stress analysis of the individual components of the knee joint is represented in a table format.

Forces for different components of the knee joint with varying plane, i.e. X, Y and Z component and their stress analysis outcome is shown in table 3.

Table 3: Individual model stress analysis of knee

Reduced model Analysis	Components		
	1400(X-comp)	1400(Y-comp)	1400(Z-comp)
Femur(Pa)	3.52E+05	2.53E+05	3.56E+05
Tibia(Pa)	50556	12808	19523
Patella(Pa)	3.28E+05	6.71E+05	3.65E+05

Table 5 represents the stress magnitude result of individual parts of the knee joint after the analytical work was performed in ANSYS 13. In the above table individual part of knee joint stress magnitude is recorded. Stress value was recorded in the standard unit, i.e. in Pa when a force of 1400 N is applied to the specific models. Here stress result of all the three components by axis was obtained, i.e. X, Y and Z where same force was applied. The tabular data are then represented in the graph.- Von- misses stress of reduced model of the knee joint with specific loads in various vector components of plane shown on table 5 was graphically displayed in **figure 11**. It signifies the stress magnitude at each individual component of the knee joint.

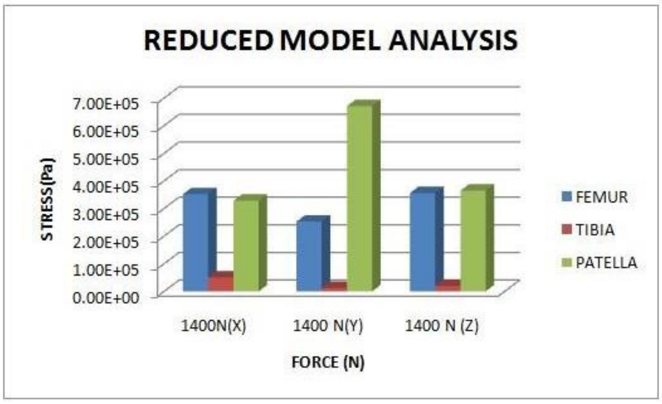

Fig 11 : Reduced model stress analysis

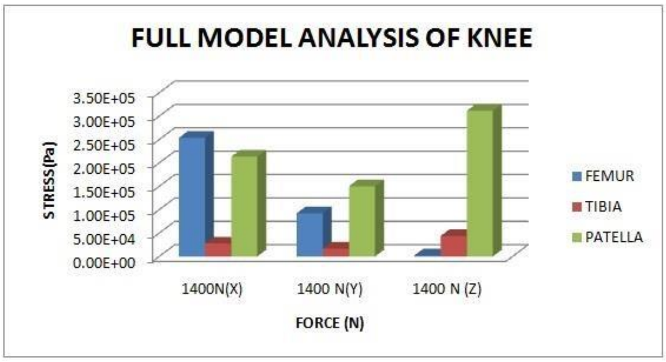

Fig 12 : Full model stress analysis of knee

Figure 12 is the graphical representation of the full model stress analysis of the knee joint. In the above graph we found that in the full model, stress analysis shows the lowest stress magnitude. Stress analysis of the menisci in full model was ignored because it doesn't affect that much when a load was being applied to the knee joint whereas patella a high range of stress magnitude under load of 1400 N with further increase in load leads to failure of the knee joint. Patella shows a higher bar graph in the Z-component having a stress value of 3.11e5 Pa.

From the above experimental study, we found that in reduced model knee components were analyzed separately, where we found out that the stress magnitude increases with load in all of the components as compared to full model stress analysis.

IV. Stress analysis of the knee implant

The equivalent stress analysis result of knee implant at a range of load from 540N to 790 N with changing angle of inclination from 10° to 90° were recorded and the data's are presented in Table 4.

Table 4 : Knee implant stress analysis result

	Von-Misses Stress (in Pa)					
Weight (in N)/Angle	10°	30°	50°	70°	80°	90°
540	8.90E+07	2.40E+08	2.93E+08	9.87E+07	4.08E+08	3.73E+08
640	9.84E+07	2.43E+08	3.54E+08	4.52E+08	4.63E+08	3.64E+08
690	1.09E+08	2.47E+08	3.48E+08	5.15E+08	5.32E+08	3.95E+08
740	1.14E+08	2.53E+08	3.47E+08	5.89E+08	5.95E+08	4.08E+08
790	9.36E+07	2.65E+08	3.49E+08	6.45E+08	6.53E+08	4.40E+08

Table 4 represents the stress analysis result of knee implant recorded in a tabular format upon force application in a wide range, i.e. 540N, 640N, 690N, 740N, and 790N with change in angles from 10°, 30°, 50°, 70°, 80°, 90°. And the equivalent stress was analyzed in standard unit format, i.e. in Pa. In this case, both stress magnitude was recorded only for the X - component. The above result is then plotted graphically.3D CAD model of the knee with implant

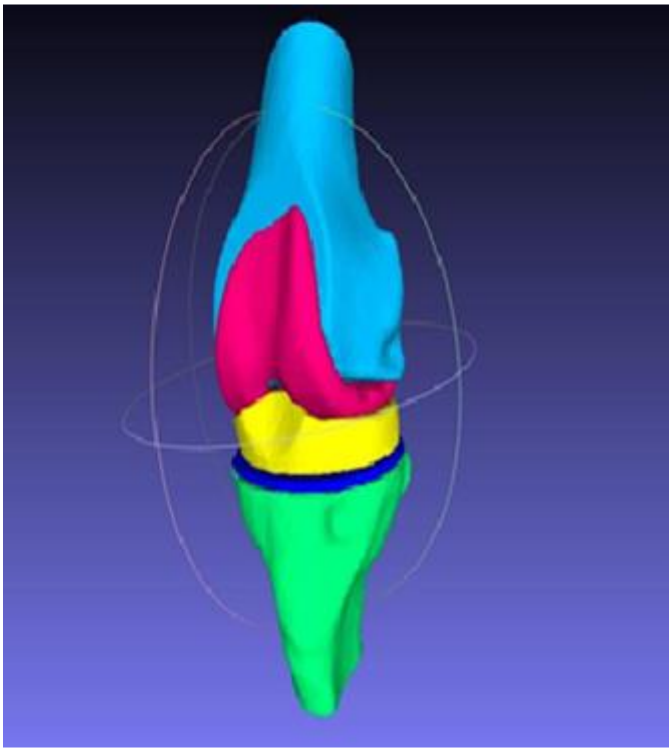

Fig 13 : Knee joint with implant

Figure 13 represents knee joint with an implant which was imported in meshlab for remeshing purpose. Meshlab can take model only in .stl format. Different color codes are representing different faces of the knee joint with an implant. Yellow face was the implant tibial tray whereas pink face was implanting metal surface of the femoral component. The model components are then exported in .stl format after the remeshing work is done.

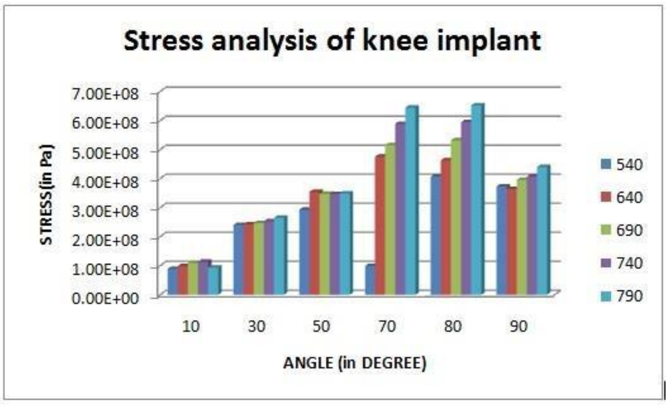

Fig 14 : Stress analysis of implant at different angles and load range

Weight(N)/Angle		Von-Misses Stress (in Pa)				
	10°	30°	50°	70°	80°	90°
540 N	6.69E+06	4.89E+08	6.56E+07	9.65E+07	3.25E+08	1.53E+08
640 N	7.32E+07	4.36E+08	6.89E+07	2.13E+08	4.26E+08	1.05E+08
690 N	6.25E+07	4.97E+08	7.47E+08	2.23E+08	4.21E+08	1.13E+08
740 N	1.16E+08	5.11E+08	5.20E+08	2.35E+08	5.57E+08	1.26E+08
790 N	1.27E+08	5.65E+08	6.11E+08	2.56E+08	5.64E+08	1.28E+08

Table 5 : stress analysis of knee joint with vertical forces

Table 5 represents the recorded data values of stress analysis of the knee joint without implant with varying load and angle. Stress magnitude was recorded in Pa unit when the force applied to the model is in Newton (N). The obtained data are plotted graphically.

Equivalent stress analysis of knee joint without an implant was performed in ANSYS workbench at various angles for different loads is displayed in

Fig 14 shows the analysis work of knee without implant where the solution part was performed. Where force was defined by vector, i.e. in only one component. Force was applied vertically with standard unit Newton (N) and stress magnitude is recorded in Pa. Force applied on the knee joint was 640 N and the resultant stress was found to be 1.28E+08 Pa at 90°. Similar analysis was performed with varying load and angles. Final results were recorded in tabular format.

Von-misses stress result for knee joint without an implant with changing angles at different loads was displayed comparative chart which is shown in figure 14.

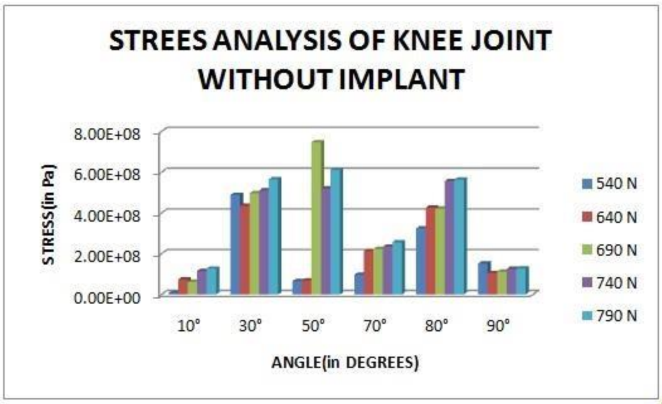

Fig 15 : Stress analysis of knee joint without implant with vertical forces

Figure 15 represents graphical interpretation of recorded values of stress analysis of knee joint with varying load from 540 N-790 N and varying angles. With vertical forces, we found out that at load of 690-790 N wearing affect become lesser at 10°, 70 °, and 90°. At 50° upon a load of 90 N stress value attains a high peak bar with 7.47E+08 Pa. As load increases wearing occur and while running and walking stress magnitude vary that causes injuries to the knee joint. Upon comparing both the results of stress analysis of the knee with implant and without an implant, we observe that beyond 50° implant starts tearing with gradual increase in the load. In 10°-50° flexion, knee implant posses less stress with a load of 640-790 N. At 90°, the knee implant was in steady state which cause less wear affect in the implant.

In this project work mostly stress analysis of the knee joint and its implant has been done. With a preliminary knowledge obtained after the study of force plate analysis for the determination of ground reaction forces and moment of the body, by performing certain physical activities on the force plate with the help of different individuals of varying height and weight. It was found that individual with maximum height and weight, i.e. individual 4 with height 5'11 and weight 74 Kg shows the highest peak range of medial-lateral force value of 1750 N and lowest moment of -35 Nm. After this, CAD model of the knee joint was designed and its reduced model and full model stress analysis were performed separately and the obtained stress magnitude results were compared. The final outcome of this study was that stress analysis of full model was observed to be lesser as compared to individual model of the knee joint. Patella shows maximum bar value in the Y - component of reduced model which was 6.7117e5 Pa and in full model analysis patella shows when the knee is in 90° position stress value reaches to 1.28E+08 Pa. When this study was compared with stress analysis of the knee joint without implant, it was observed that there is wide variation in the stress magnitude with the increase in load values with changing angles. At load of 690-790 N, wearing effect becomes lesser at 10°, 70 °, and 90°. At 50° upon a load of 690 N stress value attains a higher peak bar with 7.47E+08 Pa. From this we can conclude that knee implant can be designed in such a manner that it can uptake maximum load with varying angle of inclination.

V. CONCLUSION

The static structural analysis of the knee joint has a great significance, as these analytical results provide us a wider knowledge about the mechanical behavior of the knee. Performing stress analysis as a simulation method instead of intrusive methods is one of the important part of biomechanical study for different 3D models. The study reveals that the stress analysis work performed by X-ray images which help us to obtain a rough geometry of the knee joint. Analysis work was supported by ANSYS 13.0 which ensured that only desired and specific parts of the knee joint are involved in the designing and simulation of the model. Converting the specific geometry designed in CAD into Solidworks and Meshlab, and importing it in STL format can be used to validate the knee model along with finite element analysis. The material assignment was performed by Solidworks. For designing 3-D CAD model of the knee joint and knee implant, total CAD software operation was used, to examine the overall geometry of the designed model. It has been established that the angular stability of the knee implant can be improved through this analytical approach. Thus it has been demonstrated that this analysis paves the way for incorporation of different materials based on stress work.

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