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Load Bearing Capacity of Orthopedic Knee Replacement Implant

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Abstract: Before for the last 3 decades the orthopedic knee replacement implants were not in existence .But from the 3decadeskneereplacement has attained a good success rates. The knee joint is highly loaded during daily life. Detailed knowledge about loading of the knee joint is essential. Here , I am presenting the idea of studying the load bearing capacity of orthopedic knee replacement implant for different materials at three angles 0,45,90 degrees for the weights of 55,75,95,115 kgs. Equivalent (von-misses) and max principal stress acting for the corresponding loads are identified for the components of tibia, femur under both static and dynamic conditions by using ANSYS 15.0 and the design of knee implant is developed in CATIA V5R 20.

I. NTRODUCTION

Biomechanics is the study of the mechanical principles of living organisms, particularly their movement and structure. Biomechanics is closely related to engineering, because it often uses traditional engineering sciences to analyze biological systems. Some simple applications of newton mechanics and materials can supply correct approximations to the mechanics of many biological systems. Applied mechanics, most notably Mechanical engineering disciplines such
as continium mechanism analysis, structural analysis, kinematics and dynamics play prominent roles in the study of
Biomechanics Usually biological systems are much more complex than man-built systems. Numerical methods are hence applied in almost every biomechanical study. Research is done in an iterative process of hypothesis and verification, including several steps of modeling, Computer simulation and Experimental measurements. The present idea is under the sub field orthopedic biomechanics.

II. APPLICATION OF BIOMEECHANICS

The study of biomechanics ranges from the inner working of a cell to the movement and development of limbs ,to the mechanical properties of soft tissue and bones. Some simple examples of biomechanics research includes….

1) Investigation of forces that acts on limbs
2) The aero dynamics of bird and insect fight
3) The hydrodynamics of swimming in fish
4) Locomotion in general across all forms of life

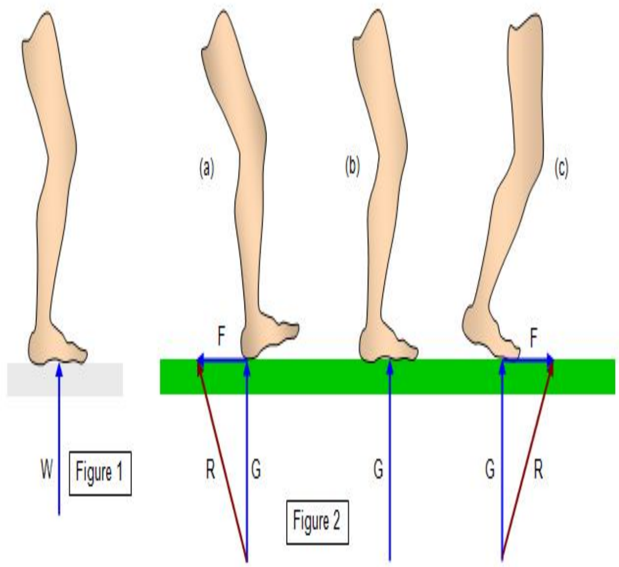
The biomechanics of human beings is a core part of kinesiology. As we develop a greater understanding of the physiological behavior of living tissues, researchers are able to advance the field of tissue engineering, as well as develop improved treatments for a wide array of pathologies. Biomechanics is also applied to studying human musculoskeletal systems. Such research utilizes force platforms to study human ground reaction forces and infrared videography to capture the trajectories of markers attached to the human body to study human 3D motion. Research also applies electromyography (EMG) system to study the muscle activation. By this, it is feasible to investigate the muscle responses to the external forces as well as perturbations. Biomechanics is widely used in orthopedic industry to design orthopedic implants for human joints, dental parts, external fixations and other medical purposes. Bio tribology is a very important part of it. It is a study of the performance and function of biomaterials used for orthopedic implants. It plays a vital role to improve the design and produce successful biomaterials for medical and clinical purposes.

III. KEY WORDS

Biomechanics, knee, implant, tibia, femur, coplanar forces, Equivalent (von-misses) stress, max principal stress.

A. Forces Acting On The Body While Standing And Walking

When we stand on the ground the ground will exert a vertical force (W) on us that just balances our weight as shown in Figure 1. This force is often called the normal reaction.



However once we try to walk or run some friction is essential as we can see from figure 2. The vertical force is G , and F is the frictional force that is acting opposite in the direction of motion. R is the resultant reaction. frictional force is related to the vertical force by the equation

$$F = \mu G$$

(1.1)

Where u is the coefficient of friction between our foot and the surface that we are walking on. This is actually between 0.6 and 0.75 for shoes and the floor.

IV. FORCE ANALYSIS OF KNEE JOINT

Static analysis is used to determine the forces and moments acting on a joint when no motion takes place or at one instant in time during a dynamic activity such as walking, running or lifting an object. A simplified technique is used such as a free body diagram and limits the analysis in one plane. The three principle coplanar force acting on the free body are identified and designated in the free body diagram. The various forces acting on knee joint in various motion are as follows

Fx - Ground To Foot Force
Fy - Friction Force
Fz = W - Ground Reaction Force
X – Perpendicular distance along Fz
Y - Perpendicular distance along Fy

Here there will be three force acting on the foot Fx , Fy, Fz during walking and running. Hence considering the moment about the joints the forces can be resolved and certain magnitudes of forces can be determined.
Here are the values of x, y, that are considered for a person of height 5 feet 6 inches.

X = 16 cm = 160mm

Y = 50 cm = 500 mm

Z = 10 cm = 100 mm

The resolution of forces can be understood by considering the figures 3 and 4.

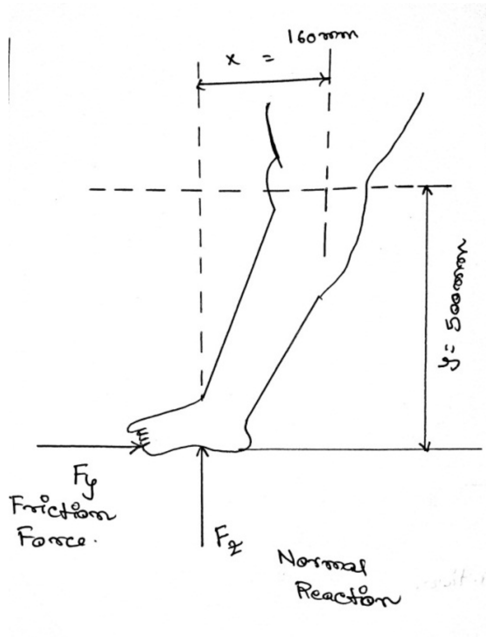


Fig. 3. Side view of leg while walking

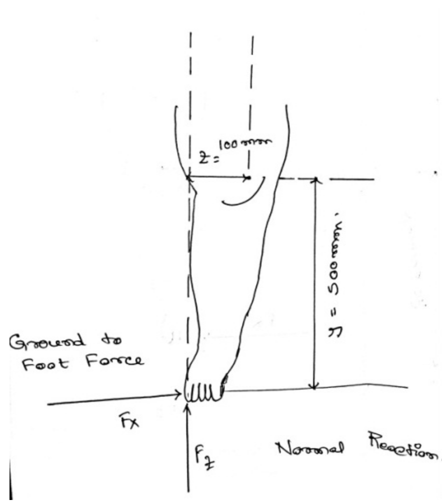


Fig. 4. Front view of leg while walking.

From Fig. 3. The moments taken at the joint gives Fy × y = Fz × x
(1.2)From Fig. 4 The moments are considered at the joint givesFz × z = Fx × y

(1.3)By using (1.2) and (1.3) the relavant values of Fy and Fx can be obtained.

For the person of weight 55kgs the normal reaction is given by

$$W = Fz = 55 \times 9.81 = 539.55 \text{ N}$$

(1.4)

On substituting the values of X and Y in (1.2) we get

Fy × 50 = 539.55 × 16

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Fy = 172.65
On substiting the values of Z and Y in (1.3) we get
539.55 ×10 = Fx × 50
Fx = 107.91N
Similarly for 60, 65, 70,75,80,85,115 kgs the relavant data is obtained and tabulated below.

TABLE 1
Calculated Values of Forces Based On The Weight While Walking

S.no	Weights kgs	(Fz) N	(Fy) N	(Fx) N
1.	55	539.55	172.65	107.91
2.	60	588.6	188.35	117.72
3.	65	637.65	204.04	127.53
4.	70	686.7	219.74	137.34
5.	75	735.75	235.44	147.15
6.	80	784.8	251.136	156.96
7.	95	931.95	298.224	186.39
8.	115	1128.15	361.008	225.63

When the body is in static which means no dynamic loads are going to be actes on that it defines the only standing posture. Hence the only normal reaction is going to be acted on the joint The values for static conditions are tabulated below.

TABLE 2
Value of Normal Reaction at Static Condition

S.NO	WEIGHT	NORMAL REACTION(Fz)
1.	55	539.55
2.	60	588.6
3.	65	637.65
4.	70	686.7
5.	75	735.75
6.	80	784.8
7.	95	931.95
8.	115	1128.15

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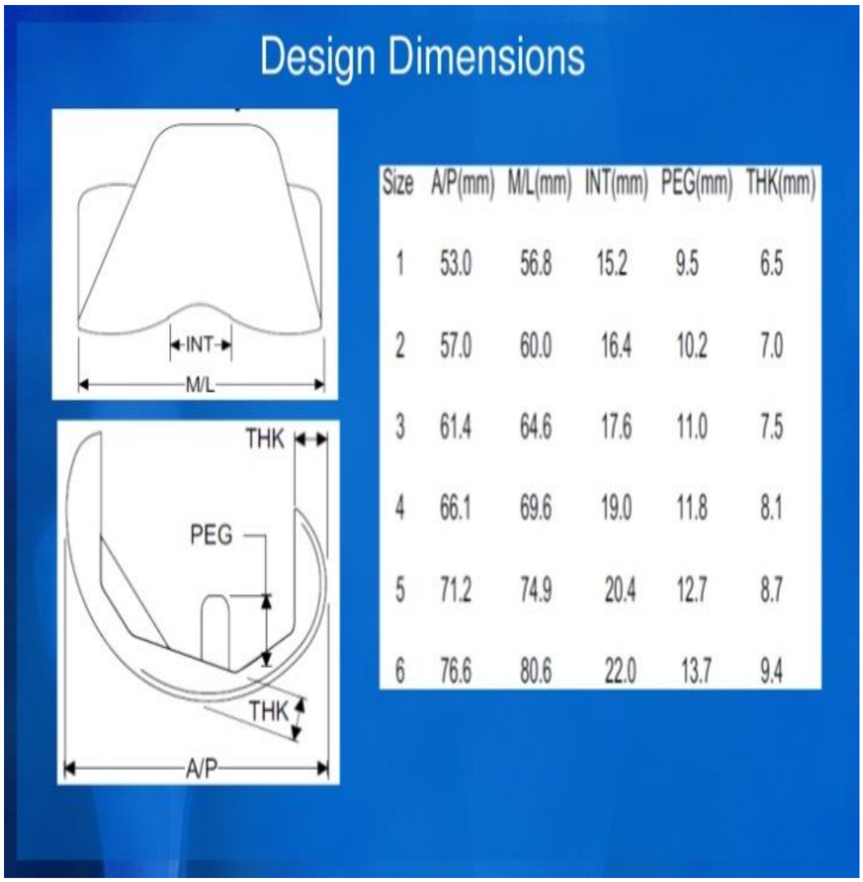
V. MODELLING OF KNEE REPLACEMENT IMPLANT AND BONE

CATIA (computer aided three-dimensional interactive application) is a multi-platform software suite for computer-aided design (CAD), computer-aided manufacturing(CAM), computer-aided engineering (CAE), PLM and 3D, developed by the French company Dassault Systèmes. CATIA enables the creation of 3D parts, from 3D sketches, sheetmetal, composites, molded, forged or tooling parts up to the definition of mechanical assemblies. The software provides advanced technologies for mechanical surfacing & BIW. It provides tools to complete product definition, including functional tolerances as well as kinematics definition. CATIA provides a wide range of applications for tooling design, for both generic tooling and mold & die.. Here we used the CATIA v5 R 20 version for the modeling of knne implant with bone.

The design considerations of knee femur implant are given in Figure 5.



Size	A/P(mm)	M/L(mm)	INT(mm)	PEG(mm)	THK(mm)
1	53.0	56.8	15.2	9.5	6.5
2	57.0	60.0	16.4	10.2	7.0
3	61.4	64.6	17.6	11.0	7.5
4	66.1	69.6	19.0	11.8	8.1
5	71.2	74.9	20.4	12.7	8.7
6	76.6	80.6	22.0	13.7	9.4

Fig. 5. Design dimensions

We designed the implant for the dimesions

A. Femur

A/P = 53.46mm
ML = 56 mm
INT = 20mm
PEG = 7.89mm
THK = 7mm

B. Tibia

Diameter = 57mm
Thickness = 20 mm

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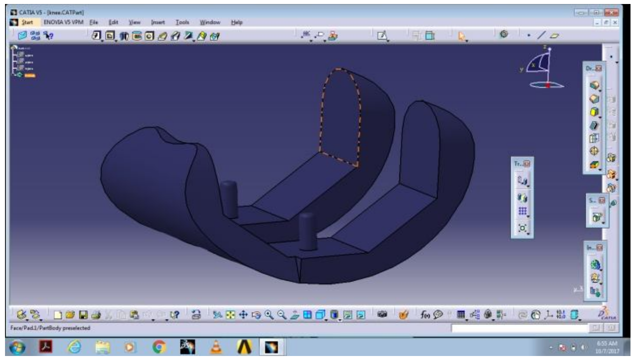

Fig. 6. Knee fumer

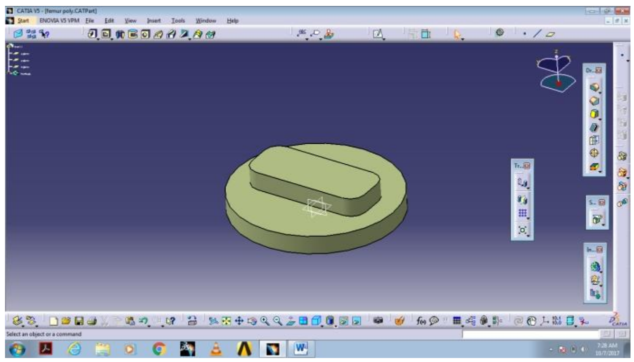

Fig. 7. Plastic surface

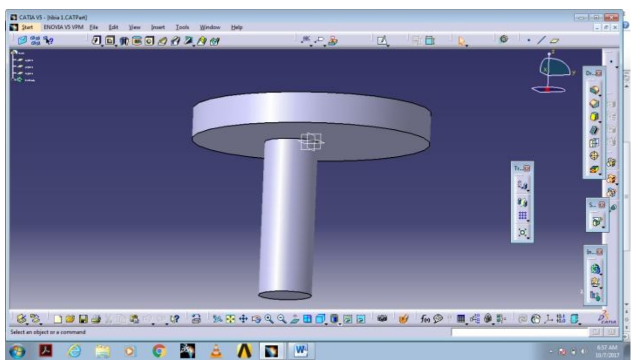

Fig. 8.Tibial plate

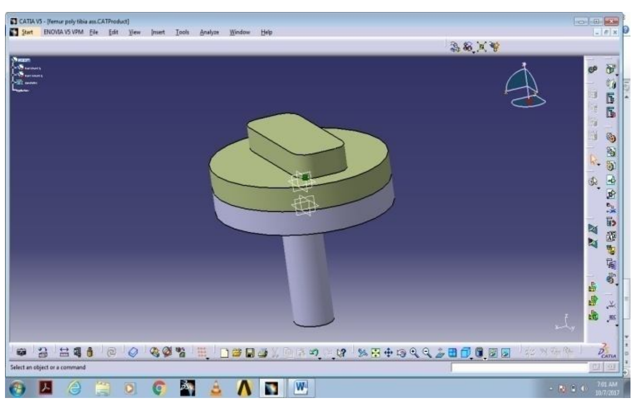

Fig. 9.Tibial plate assembly

The upper and lower bone models are also designed by using CATIA V5 R20 .the upper bone is assembled to knee femur where astibial to the lower bone. The total implant assembly with bone is shown for different angles 0 , 45 , 90

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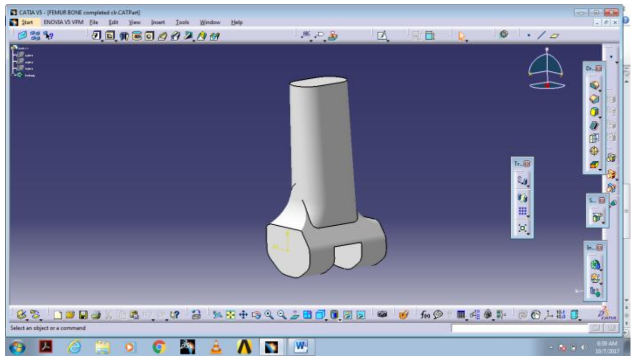

Fig. 10. Upper bone

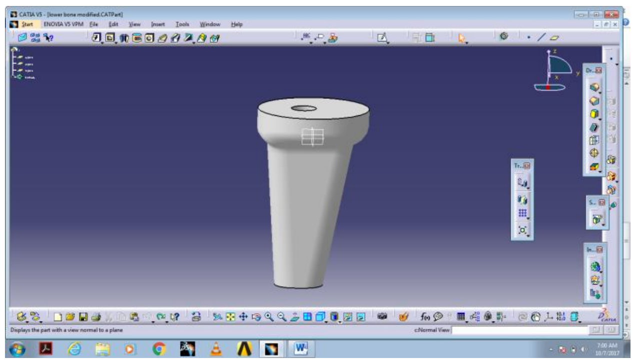

Fig. 11 lower bone

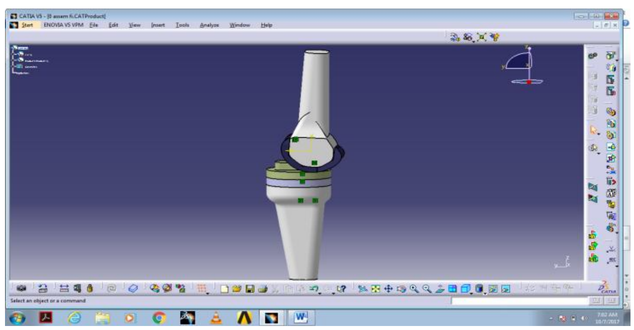

Fig. 12. Total bone assembly at 0 degrees

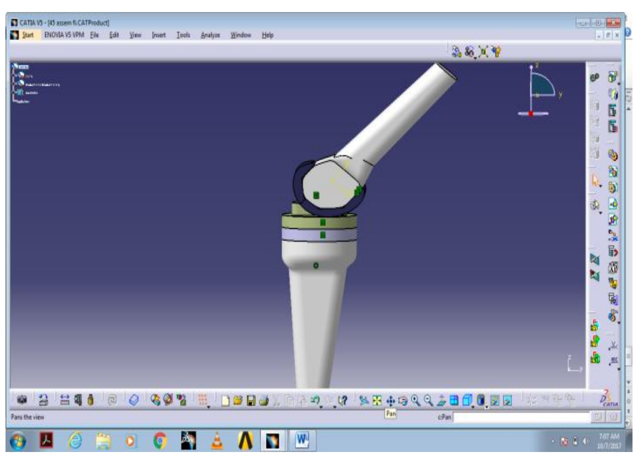

Fig.13. Total bone assembly at 45 degrees

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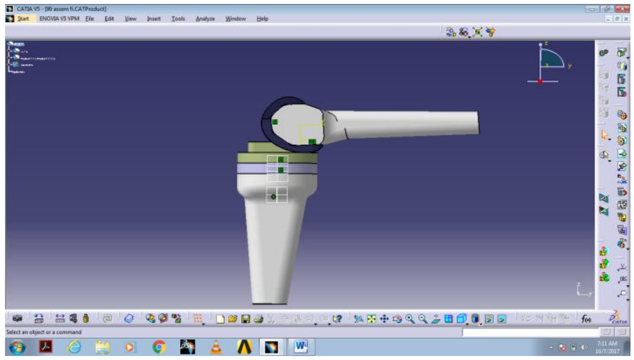


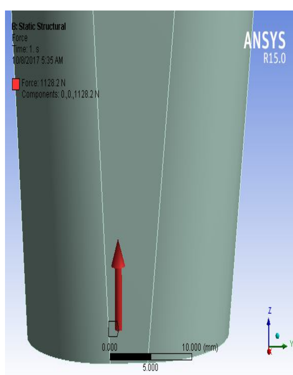
Fig.14. Total bone assembly at 90 degrees

VI. FINITE ELEMENT ANALYSIS OF KNEE JOINT

The finite element analysis is carried out in ANSYS 15.0 under the static structural analysis systems. For the finite element analysis of knee joint, the IGES format of the designs at 0, 45, 90 degrees are imported into the ANSYS 15.0 workbench. The solid element has three degree of freedom i. e translation in X, Y and Z directions The finite Element analysis is carried for different angular positions under dynamic conditions Some agents such as coplanar forces, fixed support, and theory of failures are to be considered.

A. Coplanar forces

The forces whose line of action lies on the same plane are called the coplanar forces. Here the normal reaction , frictional force , ground to foot force are three coplanar forces. While walking the lower bone is subjected to three coplanar forces , which are shown in fig 15, 16,17,18



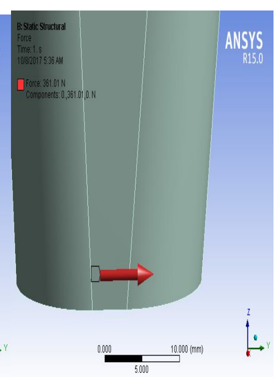
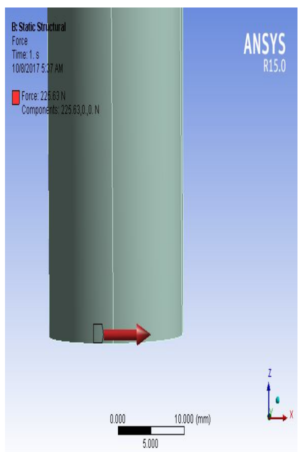


Fig. 15 Normal reaction Fz Fig. 16. Frictional force Fy



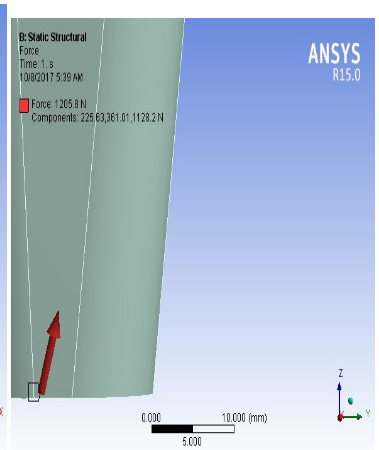


Fig. 17. Ground to foot force Fig. 18. Resultant coplanFy -ar force

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B. Fixed support

This boundary condition prevents one or more parts from moving or deforming. The fixed support is provided based on the application requirements , and loading definitions. Hence the femur and upper bone assembly is given a fixed support.

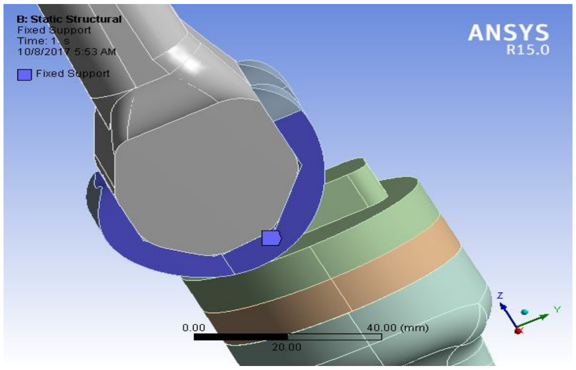

Fig.19. Fixed support for upper bone and femur

C. Equivalent (von-mises) stress

Von –mises stress is widely used by the designers to check whether their design will withstand a given load condition.

D. Distortion energy theory

The concept of Von mises stress arises from the distortion energy failure theory. Distortion energy failure theory is comparison between 2 kinds of energies, 1) Distortion energy in the actual case 2) Distortion energy in a simple tension case at the time of failure. According to this theory, failure occurs when the distortion energy in actual case is more than the distortion energy in a simple tension case at the time of failure. Distortion energy required per unit volume, for a general 3 dimensional case is given in terms of principal stress values as:

$$u_d = \frac{1+\nu}{3E}\left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]$$

(1.5)

Distortion energy for simple tension case at the time of failure is given as:

$$u_{d,sim} = \frac{1+\nu}{3E}\sigma_y^2$$

(1.6)

E. Expression for von mises stress

The above two (1.5) and (1.6) can be connected using distortion energy failure theory, so the condition of failure will be as follows

$$\left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]^{1/2} \geq \sigma_y$$

(1.7)

The left hand side of the above equation is denoted as von-mises stress

$$\left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]^{1/2} = \sigma_v$$

(1.8)

So as a failure criterion, the engineer can check whether Von Mises stress induced in the material exceeds yield strength (for ductile material) of the material. So the failure condition can be simplified as

$$\sigma_v \geq \sigma_y$$

F. Maximum principle stress theory

The theory states that the failure of the mechanical component subjected to bi- axial or tri- axial stress occurs when the maximum principle stress reaches the yield or ultimate strength of the material. It is best for brittle materials For tensile Maximum principle stress = yield or ultimate tensile strength For compressive Maximum principle stress = yield or ultimate compressive strength Analysis is carried out by considering the materials and their properties. The bone and plastic surface is considered to be with constant material . The femur and tibial plate materials are made to be in different combinations. The materials are selected in engineering data sources in project schematic and can be made to be edit. The combinations of Femur and tibial components includes Zr & Zr , Co Cr & Zrin which Zr, Co Cr are brittle materials.

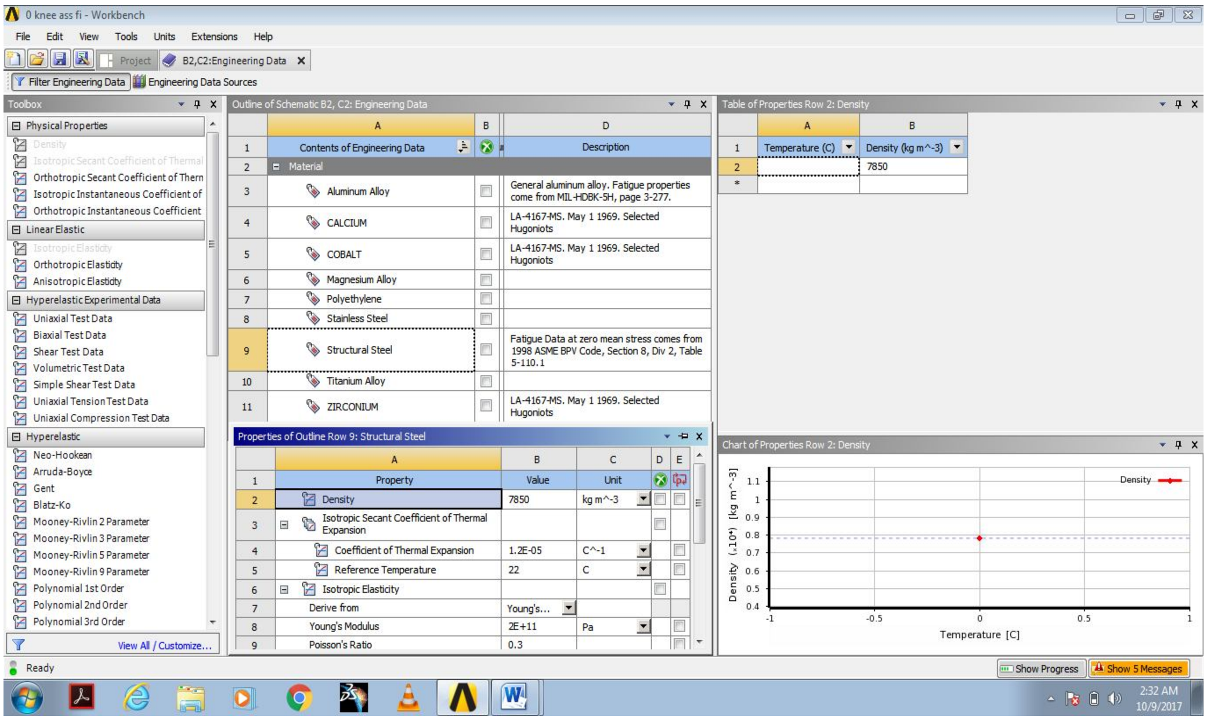

Fig. 20.Engineering data in project schematic

TABLE 3MECHANICAL PROPERTIES

S.N O	Properties / Materials	Density (Kg/ m3)	Youngs modulus (Mpa)	Poison'S ratio	Tensile yield strength (Mpa)	Compressive yield strength (Mpa)	Tensile strength ultimate (Mpa)
1.	Bone	1500	100000	0.45	-	-	-
2.	CoCr alloy	8500	230000	0.45	965	295	1200
3.	Zirconium	6505	68000	0.34	230	1200	330
4.	polyethylene	950	1100	0.42	25	0	33

TABLE 4

VALUES OF STRESSES (Mpa) ACTING ON FEMUR COMPONENT FOR THE COMBINATIONS

Weight Kgs	Materials (Femur &Tibial Components)	Equivalent (von-mises) stress			Max principle stress		
		0 Degrees	45 Degrees	90 Degrees	0 Degrees	45 Degrees	90 Degrees
55	Zr&Zr	34.092	12.12	22.975	37.335	7.2508	12.272
	CoCr&Zr	32.631	11.111	22.179	38.157	7.5185	14.242
75	Zr&Zr	46.491	16.529	31.331	50.913	9.8879	16.735
	CoCr&Zr	44.498	15.152	30.246	52.034	9.8439	19.422
95	Zr&Zr	58.889	20.936	40.633	64.49	12.525	21.198
	CoCr&Zr	56.364	19.162	38.312	65.91	12.469	24.601
115	Zr&Zr	71.287	25.344	49.118	78.067	15.161	25.661
	CoCr&Zr	68.23	23.232	46.377	79.785	15.094	29.78

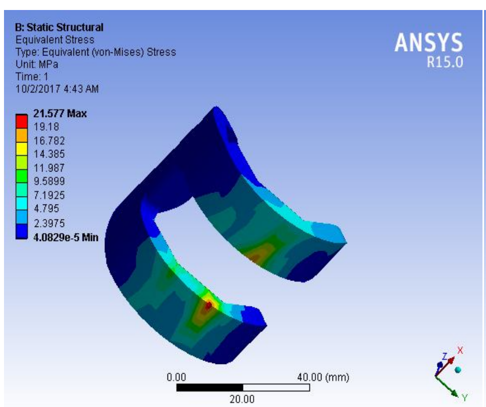

Fig .21. Femur component (Equivalent – stress)

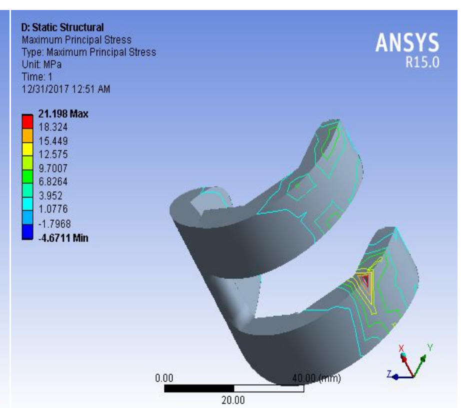

Fig . 22 . Femur component (Max principal stress)

TABLE 5 VALUES OF STRESSES (Mpa) ACTING ON TIBIAL PLATE COMPONENT FOR THE COMBINATIONS

Weight Kgs	Materials (Femur &Tibial Components)	Equivalent (von-mises) stress			Max principle stress		
		0 Degrees	45 Degrees	90 Degrees	0 Degrees	45 Degrees	90 Degrees
55	Zr&Zr	75.925	13.164	11.81	74.945	13.432	10.284
	CoCr&Zr	75.086	12.915	11.587	74.113	13.177	10.08
75	Zr&Zr	103.54	17.952	16.105	102.2	18.317	14.024

	CoCr&Zr	102.39	17.612	15.801	101.07	17.97	13.746
95	Zr&Zr	131.15	22.739	20.4	129.46	23.201	17.764
	CoCr&Zr	129.7	22.308	20.014	128.02	22.762	17.411
115	Zr&Zr	158.76	27.526	24.695	156.71	28.086	21.504
	CoCr&Zr	157	27.005	24.228	154.97	27.554	21.077

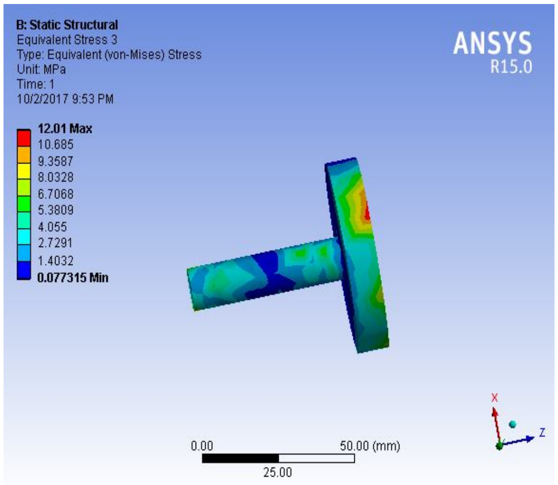

Fig .23 .Tibial plate (Equivalent – stress)

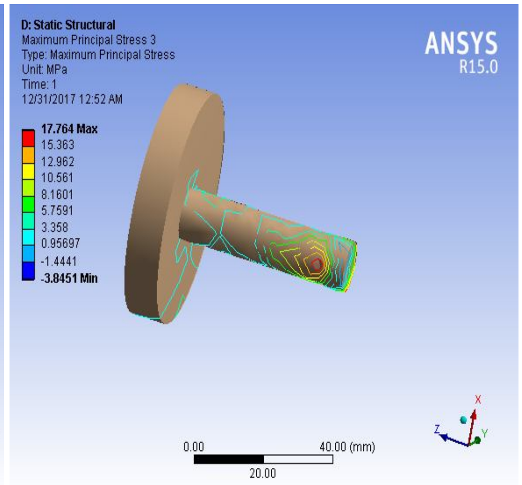

Fig . 24 .Tibial plate (Max principal stress)

VI. CONCLUSION

According to the theory of equivalent (von mises) stress and maximum principle stress the streses developed are less than the ultimate tensile strength or ultimate yield strength and ultimate compressive strength of the materials considered in the previous table. Hence we can conclude that the components manufactured with Zr and CoCr will have the less stresses induced in them when compared to other materials.And these materials can be well sustained to corrosion , fatigue etc.

A. Cobalt chromium

Cobalt-chromium alloys are hard, tough, corrosion resistant, bio-compatible metals. Along with titanium, cobalt chrome is one of the most widely used metals in knee implants. There is no consensus as to which material is better and more suitable. Although the percentage of patients having allergic reactions related to the use of cobalt-chromium alloys to is very low, one area of concern is the issue of tiny particles (metal ions) that may be released into the body as a result of joint movement. These particles can sometimes cause reactions in the human body, especially in case of those patients who have allergy to special metals like nickel.

B. Zirconium

Zirconium alloy is used in a new ceramic knee implant. The zirconium alloy is combined with an all-plastic tibial component, replacing the metal tray and plastic insert used in other knee replacements. It is believed that this new knee could last for 20-25 years, substantially more than the 15-20 years that cobalt chromium alloy and polyethylene implants are effective. The new combination can be lubricated, which results in a smoother and easier articulation through plastic.

Another important characteristic of this material is that it is biocompatible, meaning that people who have nickel allergies and cannot have knee implants made of cobalt chromium alloy (because nickel is an ingredient of cobalt chromium alloy). Zirconium alloy implants eliminate the risk to nickel-allergic patients because this new material contains no nickel.

C. Oxidized Zirconium

Oxinium oxidized zirconium is a new material used in knee implants since 2001. It is basically a transformed metal alloy that has a ceramic bearing surface. It contains zirconium and niobium alloy that was oxidized to convert the surface of the material into zirconia ceramic. The advantage of this metal is that just the surface has been changed, so the rest of the implant component is a high tensile metal. Although it is twice as hard as cobalt chromium alloys, it provides half the friction thus performs with higher quality and lasts for a longer time.

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