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Modeling and Finite Element Analysis of Knee Prosthesis with and without Implant

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Abstract Biomechanics is the study of the structure and function of biological systems by means of the methods of "mechanics" which is the branch of physics involving analysis of the actions of forces. Knee joint is the complex structure of the human body acquires the critical loads in various moving conditions. This paper discusses the loads acting on the joint during different motions such as steady, walking and lifting. A 3d modeling software PRO/E is used to prepare a CAD model of knee prosthesis and evaluate the results in the form of stresses by applying the calculated loads in the finite element analysis software ANSYS. The stresses are evaluated by considering several cases of loading. The aim is to study and evaluate the loads and stresses acting on knee joint and compared with the implant results.

Keywords Knee Joint, Knee Implant, Biomechanics, Von-misses Stresses, Finite Element Analysis

1. Introduction

Geometric complexity and non-linearity of the materials of the knee make the analytical solutions of the mechanical behavior of the knee joint difficult. Within "mechanics" there are two sub-fields of study. Statics, which is the study of systems in a state of constant motion either at rest (with no motion) or moving with a constant velocity. Dynamics, which is the study of systems in motion in which acceleration is present, which may involve kinematics (i.e., the study of the motion of bodies with respect to time, displacement, velocity, and speed of movement either in a straight line or in a rotary direction) and kinetics (the study of the forces associated with motion, including forces causing motion and forces resulting from motion).

The knee joint is not only one of the largest, but also one of the most complex joint in the human body. It is able to withstand significant strain and injury risks in everyday and occupational life as well as in sports. However, people with anatomical problems such as bowlegs or knock-knees may experience pain. Normal age-related processes and excess weight, as well as physical inactivity, can lead to wear and tear on the joint. The X-ray and CT scan image of knee joint showing anatomy and injuries are shown in figure 1. X-ray shows the anatomy of knee joint (fig 1(i)) and the injury is shown in CT scan image (fig 1(ii)).

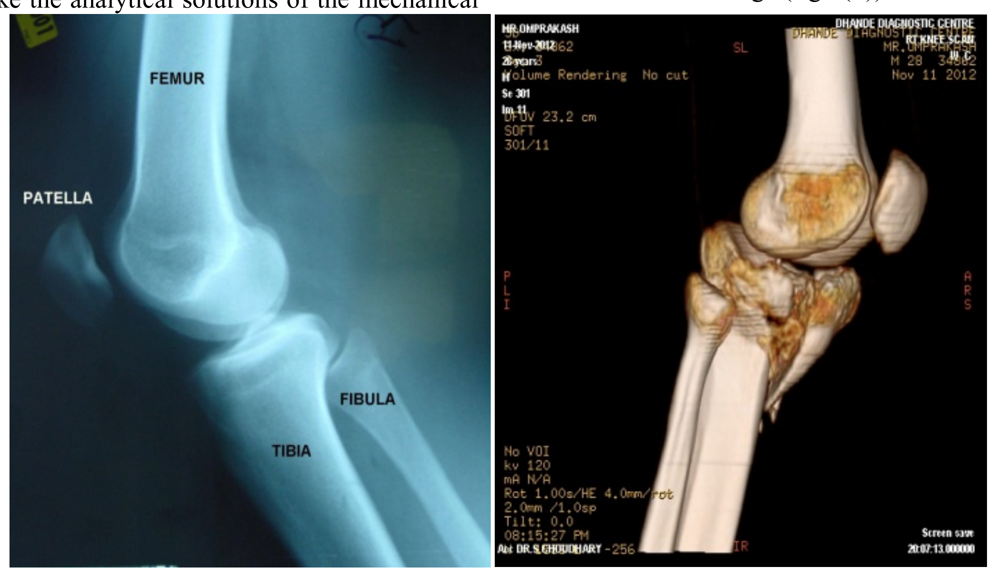


Figure 1. (i) X-ray of knee joint (ii) CT scan of knee joint

The round femoral knuckles or condyles lie almost flat on the tibial plateau, rolling or gliding every time the joint is bent or extended. This occurs only if the cartilage layer is intact, as it functions as a gliding surface that is continuously lubricated by the synovial fluid. The crescent-shaped lamellae or menisci, anchored outwards and inwards on the tibialplateau, surround the femoral knuckles and guide it through it. In addition, ligaments stabilize the joint; their inner (medial) and outer (lateral) sides prevent the femur and tibial plateau from bending outward or inward under normal conditions. The anterior and posterior cruciate ligaments provide additional stabilization, so that the tibial plateau is also anchored in place to prevent it from slipping too far to the front or back the joint capsule, whose inner side is covered by an inner articular layer, the synovial membrane, encloses the entire articular space. This synovial membrane secretes the joint or synovial fluid, which lubricates the cartilaginous areas and nourishes the cartilage itself. Not only do the menisci and ligaments stabilize the joint, but muscles also contribute greatly to stabilization. For this reason, specific strengthening of the muscles is generally the focus of rehabilitation measures.

In this paper the FE analysis of knee joint with and without implant is carried out in analysis software ANSYS12 by applying the calculated loads at various moving condition. The critical modeling of knee joint (tibia and femur) with exact shape and size is prepared in 3d modeling software Pro/Engineer 5.0. The analysis has been carried out for three different cases.

First, for the vertical force is applied at the bottom of tibia, then the analysis is carried out for vertical and frictional forces acted in x and z direction. Thereafter, the joint is analyzed for patellar tendon and joint reaction forces at various angles. At last the joint has been analyzed for knee implant and provide conclusion by comparing it with case-I.

2. 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 - Friction Force
Fy - Ground Reaction Force
Fz - Ground To Foot Force
X – Perpendicular distance along Fy
Y - Perpendicular distance along Fx
P - Patela Tendon Force
J - Joint Reaction Force
W - Ground Reaction Force
a- Perpendicular Distance along W
b- Perpendicular Distance along P

2.1. Free Body Diagram of Knee Joint

Case I: When the total weight of body is acting over a single knee joint in straight position.

In the first case, the two coplanar forces (Fx and Fz) acting on the foot are calculated by measuring the distance from the line of action of force from the ground by considering the vertical force Fy as a weight of the body.

The external force system acting on the tibia consists of the three ground-to foot forces (Fx, Fy, and Fz). Fx is the frictional force acting at the foot in the line of progression; Fy is the vertical component and Fz is the side-to-side ground-to-foot force. In the sagittal plane of the knee the turning moment Mz can be estimated from: $Mz = Fy \times X$ and $Fx \times Y$ (Fig. 2). The lever arms X and Y are calculated from the knee and the coordinates for the center of the pressure of the foot. In the coronal plane, Knee moment Mx is calculated from: $Mx = Fy \times Z$ and $Fz \times Y$.

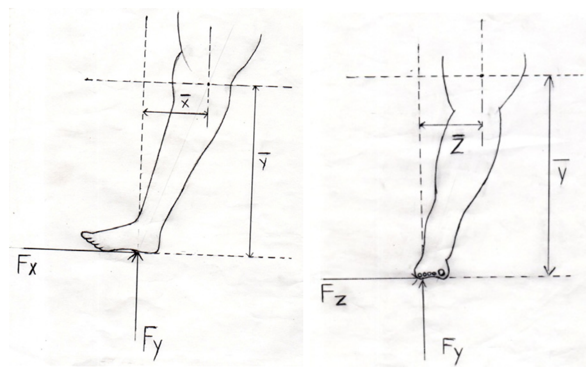


Figure 2. Free body diagram of knee joint for case-I

$Fx \times y = Fy \times x$
$Fx \times 53 = 588.6 \times 15$
$Fx = 166.57N$
$Fy \times z = Fz \times y$
$588.6 \times 10 = Fz \times 53$
$Fz = 111.05N$

The forces for different varying weight are calculated analytically for case-I and are shown in table 1.

Table 1. Force analysis for case-I

WT (Kg)	Fy (N)	Fx (N)	Fz (N)
55	539.55	152.20	101.20
60	588.6	166.58	111.05
65	637.65	180.46	126.31
70	686.7	194.34	129.56
75	735.23	208.23	138.82

Case-II: During walking or lifting, the leg is in inclined position and total weight of body acting on ankle.

For second case, an example illustrates the application of the simplified free body technique for coplanar forces to the knee. The techniques used to estimate the minimum magnitude of the joint reaction force acting on the tibio-femoral joint of the weight bearing leg when the other leg is lifted during stair climbing.

As per the literature studied the two main forces acting on joint during walking and stair lifting position are patella tendon force (P) and joint reaction force (J) with the ground reaction force (W) as per the weight of body. The forces acting on joint has been calculated from the vector diagram and the distance upto knee joint from vertical force is measured practically are shown in figure 3.

$\sum M=0$

$W\times A - P\times B = 0$

$W\times A = P\times B$

$P = 588.6\times16.5/5.156$
$=1883.52N$

$P = 12.8\times147.15 = 1883.52N$

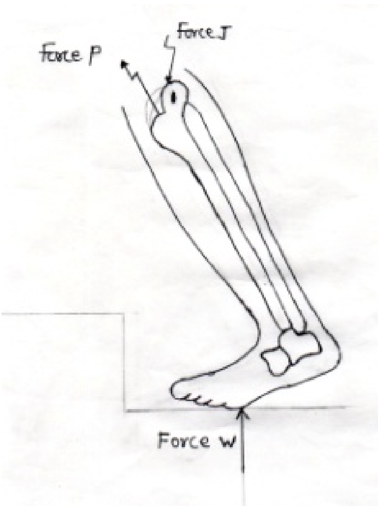
$J = 16.7\times147.15 = 2457.405N$

$W = 588.6N$

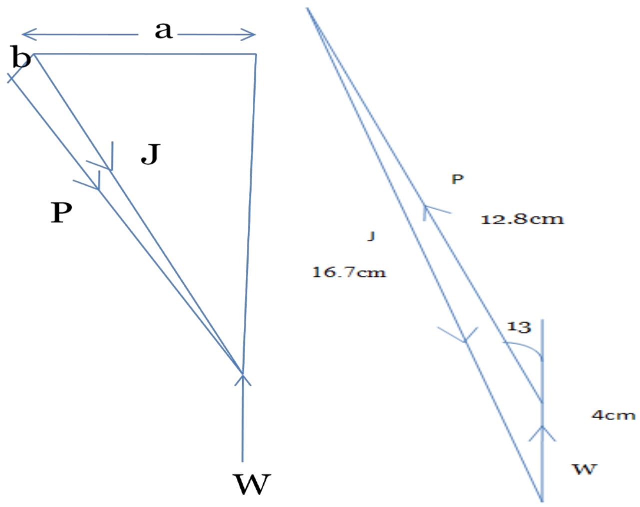
Similarly the forces for different varying weight are also calculated analytically for case-II and are shown in table 2.

Table 2. Force analysis for case-II

Ground Load (W)	Patellar Tendon Force (N)	Joint Reaction Force (N)
55 (539.95N)	1726.56	2266.11
60 (588.6N)	1883.52	2457.4
65 (637.65N)	2040.48	2648.7
70 (686.7N)	2197.44	2884.14
75 (735.75N)	2354.4	3090.15



(a)



(b)

Figure 3. (a)Free body diagram of knee joint for case-II (b) vector diagram

3. Modeling of Knee Joint with Bone

Pro/ENGINEER is a computer graphics system for modelling various mechanical designs and for performing related design and manufacturing operations. Pro/ENGINEER is a feature-based, parametric solid modeling system with many extended design and manufacturing applications. As a comprehensive CAD/CAE/CAM system, covering many aspects of mechanical design, analysis and manufacturing, Pro/ENGINEER represents the leading edge of CAD/CAE/CAM technology.

For the analysis of knee joint, three dimensional models are prepared by using 3-d modeling software PRO/E by using the dimension taken from the actual diagram of tibia and femur. For the exact dimension, component of the bone is collected from the medical representative and shape is drawn on A-3 size drawing sheet and measure by using scale. It is observed that the bone of man was in the range 25-40 year old. Pro/E model of knee joint with and without implant are shown in figure 4.

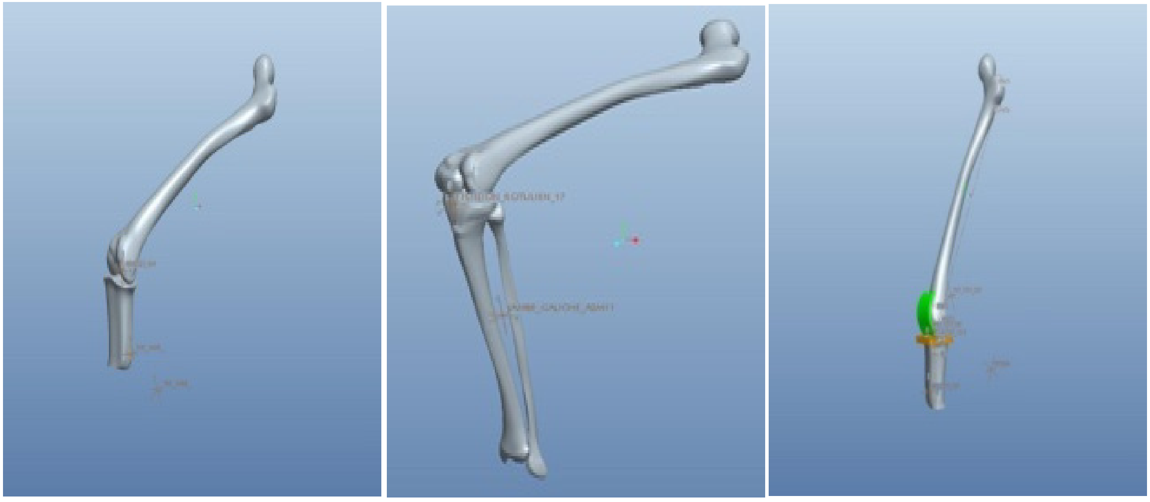


Figure 4. Pro/E model of knee joint with and without implant

3.1. Material Properties of Bone

The study of static mechanical properties of human knee joint (tibia & femur) by Kunwoo Lee1 [7] et al and titanium alloy for knee implant by By Gelareh Eslamian has been used as a reference in this papers. The mechanical properties are listed in table 3.

Table 3. Material Properties of Bone Material

Properties	Unit	Bone	Ti6Al4V
Density	Kg/m3	1550	4400
Young's Modulus	MPa	1 × 105	1.06 105
Poission's Ratio	-	0.45	0.29

4. Finite Element Analysis of Knee Joint

For the finite element analysis of knee joint, the IGES or STP file with femur and tibia is imported in ANSYS 12.0. The model is mesh with Solid 186 tetrahedral and Solid 187 hexahedral element with 17520 numbers of nodes and 7337 total number of elements. The solid elements has three degree of freedom i.e. translation in X, Y and Z-directions.

The finite element analysis of knee joint has been carried out for deferent loading condition and observed the stress level as per material property of bone. Analysis has been carried out for (i) vertical force (ii) 3-coplanar forces (iii) patella tendon force and joint reaction forces and (iv) forces on implant. All the results carried out using ANSYS 12.0 are shown in tabulated format. The boundary conditions for all cases are shown in figure 5.

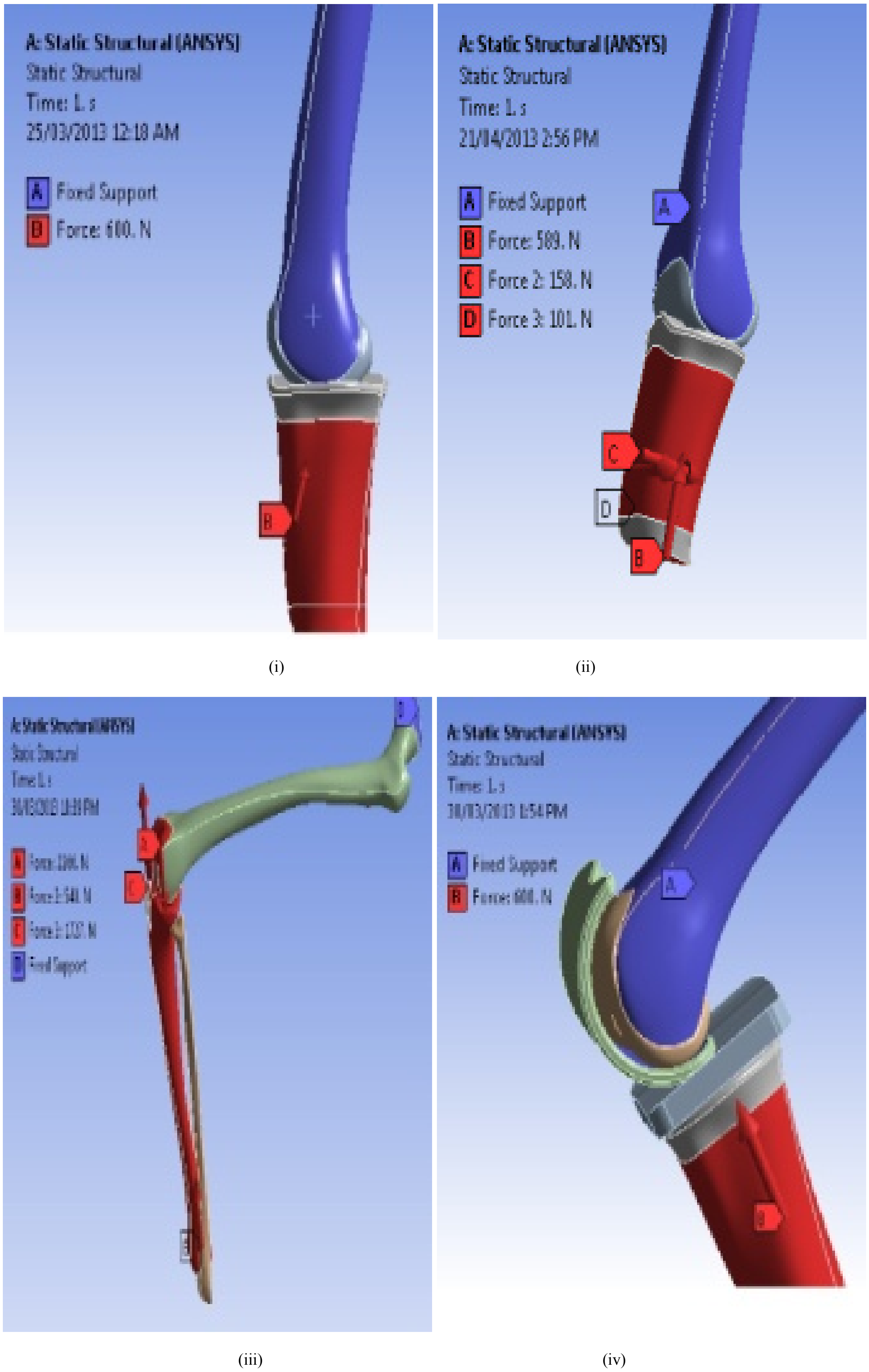


Figure 5. Boundary conditions for (i) vertical force (ii) 3-coplanar forces (iii) patella tendon force and joint reaction forces and (iv) forces on implant

4.1. FE Analysis of Knee Joint for Vertical Force

For the FE analysis of knee joint for vertical force in ansys12.0, the top surface of femur as taken as fixed and the vertical force is applied at the bottom surface of tibia as shown in figure 5(i). The stresses at various angles for 600N force are shown in figure 6. The results are also evaluated for varying weight and are discussed in conclusion.

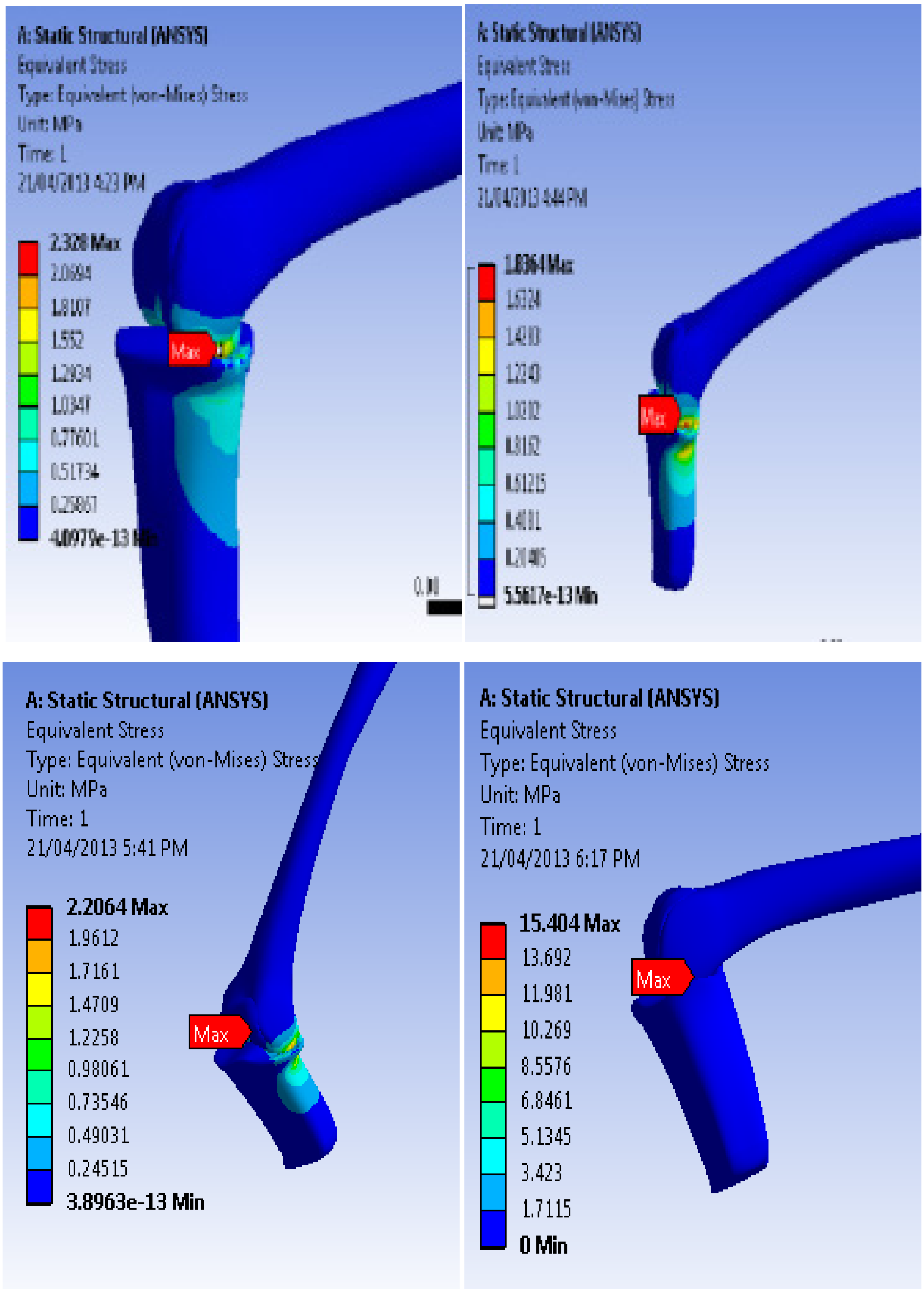


Figure 6. FE analysis of knee joint for 600 N vertical force for 10^0, 20^0, 50^0 and 90^0.

4.2. FE Analysis of Knee Joint for Three Coplanar Forces (Fx,Fy,Fz)

For the FE analysis of knee joint for three coplanar forces (Fx,Fy,Fz) in ansys12.0, the top surface of femur is taken as fixed and from table 2, the ground force(Fy) is applied at the bottom surface, the frictional force(Fx) is applied at front surface and the ground to foot force(Fz) is applied to side surface of tibia as shown in figure 5(ii). The von-misses stresses at various angles for varying weight are shown in figure 7.

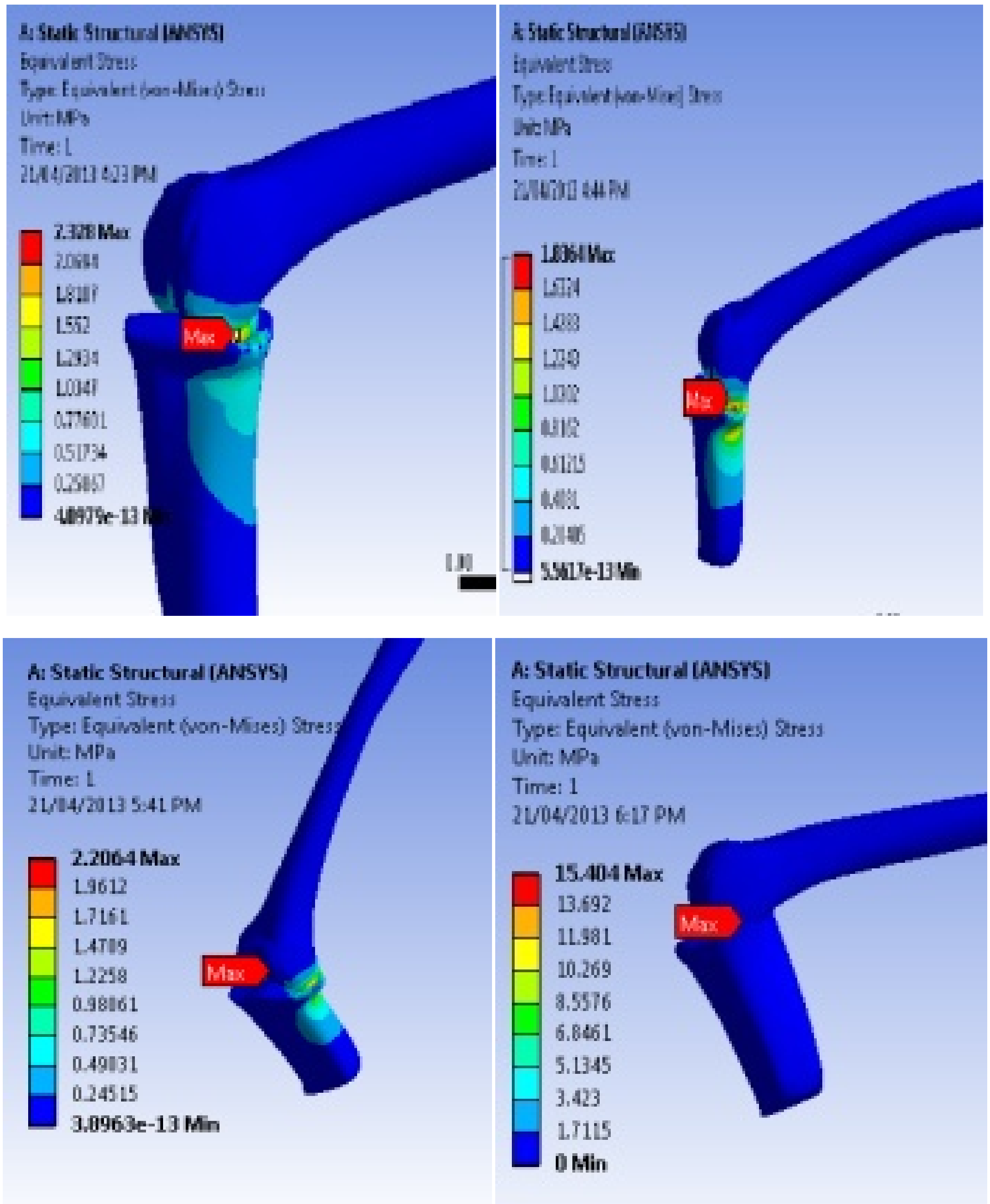


Figure 7. FE analysis of knee joint for three coplanar forces for weight of 60kg for 10^0, 20^0, 50^0 and 90^0.

4.3. FE Analysis of Knee Joint for Patellar Tendon and Joint Reaction Force

For the FE analysis of knee joint for patellar tendon force in ansys12.0, the top surface of femur as taken as fixed and the ground force (B) is applied at the bottom surface, the joint reaction force(A) is applied at joint and the patellar force(C) is applied on the patella along the condoler surface of femur as shown in figure 5(iii). The von-misses stresses for varying weight at 90^0 are shown in figure 8.

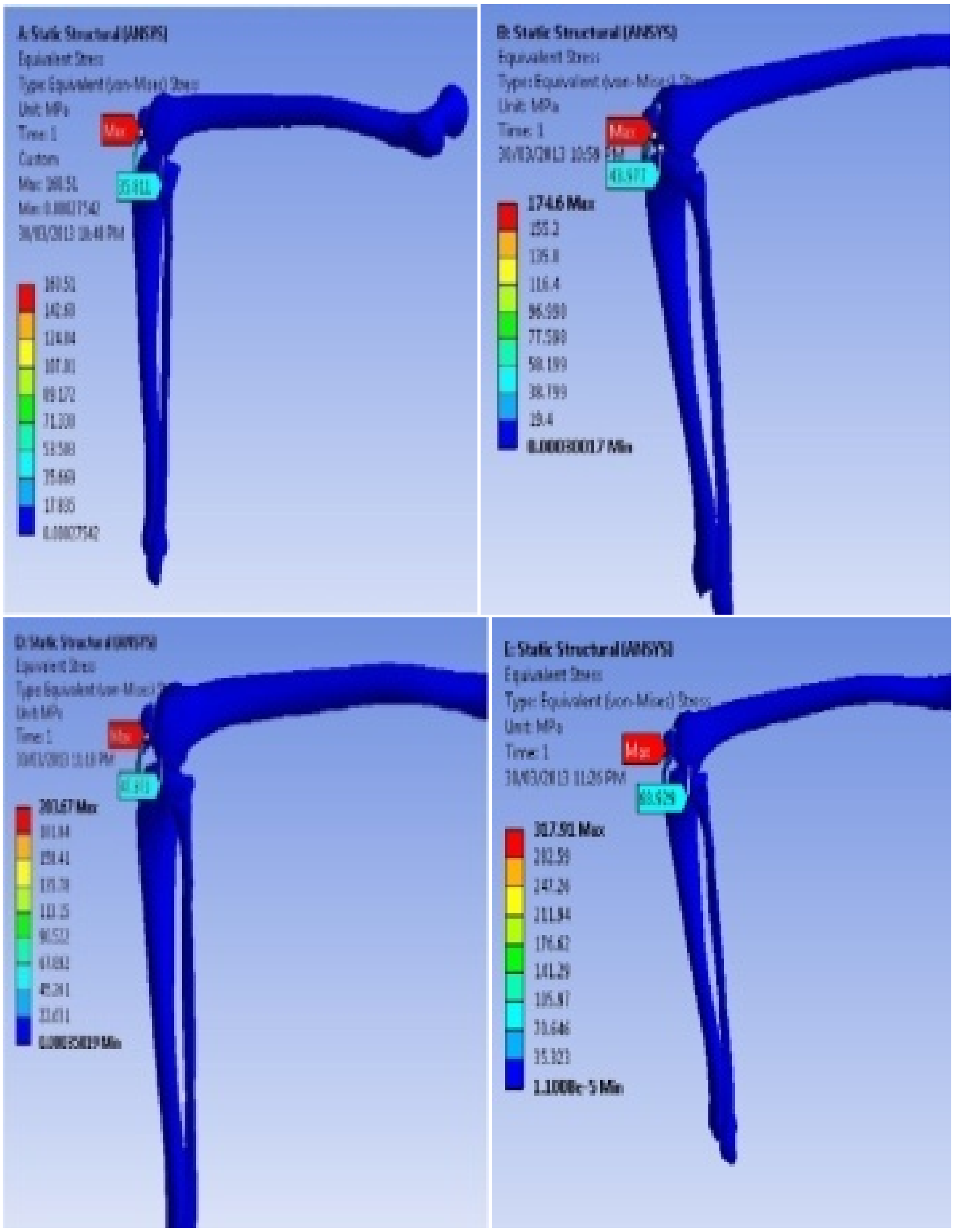


Figure 8. Von-misses stresses for patellar tendon & joint reaction forces on knee joint for the ground force of 55kg, 60kg, 70kg, 75kg at 90^0

4.4. FE Analysis of Tibiofemoral Joint with Implant

By assuming the disease or injuries of knee joint it is decided to do the FE analysis of knee joint with implant as one of the technique for total knee replacement. For the FE analysis of knee implant the same boundary condition (figure 5(iv)) is applied as that of the vertical forces and the result are find out and compared with the existing one. The von-misses stresses on knee joint with implant for varying weight at various angles are shown in figure 9 and the results are compared in table 4.

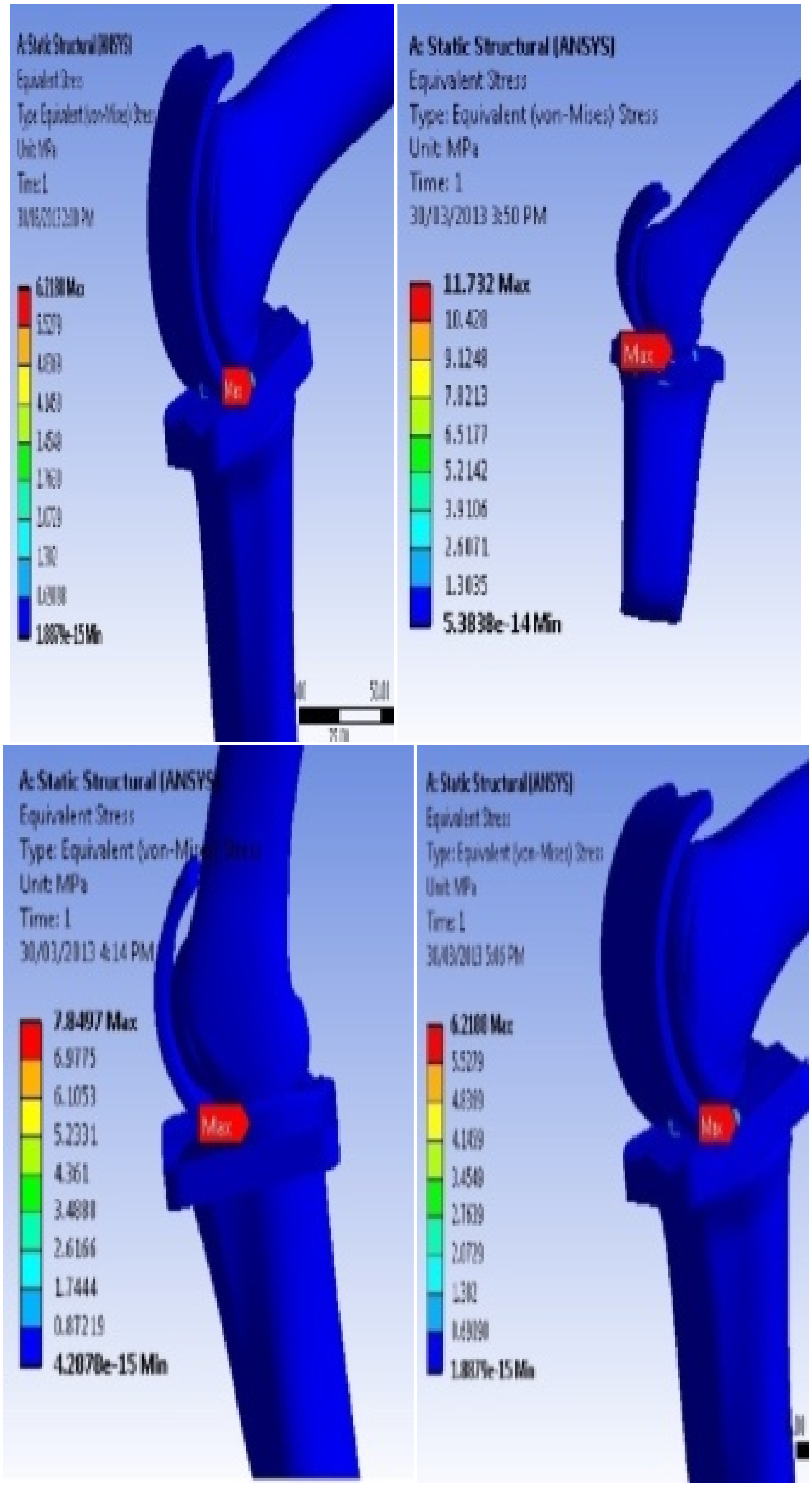


Figure 9. FE analysis of knee joint with implant for weight at various angles

Table 4. Comparision of stresses at different condition for knee joint with and without implant

Condition	Weight (kg)	Von-misses stresses at various angles (MPa)					
		10^0	30^0	50^0	70^0	80^0	90^0
Vertical Force without Implant	55	4.45	2.19	2.33	5.32	1.73	13.98
	60	5.19	2.18	2.72	6.2	2.02	8.66
	65	5.93	2.60	3.11	7.09	2.31	9.21
	70	9.88	2.93	3.5	7.98	2.59	10.36
	75	10.9	3.25	3.89	8.86	2.88	11.52
3-Coplanar Force without Implant	55	2.32	1.93	2.2	5.45	2.98	15.40
	60	2.71	2.25	2.57	6.36	3.49	17.82
	65	3.09	2.56	2.92	7.28	3.97	20.20
	70	3.49	2.89	3.30	8.19	4.49	22.93
	75	3.88	3.21	3.67	9.10	4.99	25.37
Patellar Tendon & Joint Reaction Force	55	Patellar tendon and joint reaction forces are acted during dynamic condition i.e. during running, so the stresses are found out only at 90^0.					160.5
	60						174.6
	65						201.7
	70						203.6
	75						317.9
Vertical Force with Implant	55	5.7	10.75	7.19	37.4	38.2	6.21
	60	6.21	11.73	7.84	43.7	44.6	7.25
	65	6.73	12.71	8.5	49.9	51	8.29
	70	7.25	13.68	9.15	56.2	57.4	9.32
	75	7.77	14.66	9.81	62.4	63.8	10.36

5. Result and Discussion

The finite element analysis has been carried out in ansys software and find out von-misses stresses for various conditions explain above are shown in table 4. From the result shown in table the von-misses stresses are continuously increases during steady conditions and for varying weight of 55 to 75 kg. The von-misses stresses is varying from 1.5 to 7.4 MPa which increases more during walking condition for the angle varying from 10 to 90 degree. But from the finite element analysis it is observed that the stresses are extremely changed for the dynamic conditions by considering patellar tendon force and joint reaction force for the varying weight at 90 degree.

By the study of method of total knee replacement, the implant is provided at the joint due to accidental injuries or diseases. The stresses has been found out which are more than the steady conditions, but safe up to certain limit i.e from 10 to 50 degree which extremely increases after 50 degree but safe at 90 degree. Table 4 shows the stresses at different loading conditions explained in FE analysis at various angels.

6. Conclusions

From the analysis, several conclusions are made which are listed below.

1. For the varying weight in steady condition the joint can easily sustain the body for the weight of 65 to 70 kg.

2. During walking i.e. from 3-coplanar forces it can be said that the joint start wearing as the stresses are increases compared with steady condition.

3. During dynamic condition i.e. for patellar tendon and joint reaction forces, the stresses are extremely varies because of running or extra work over joint as compared to walking condition which causes injury on the joint.

4. Because of injury the implant is one of the options for total knee replacement whose analysis shows the stresses are slightly increases for the steady condition but up to certain limit that is from 10^0 to 50^0, it means that the implant can occurred a pain or a damage of joint after 50^0.

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