International Journal of Advanced Mechanical Engineering.
ISSN 2250-3234 Volume 4, Number 7 (2014), pp. 721-727

http://www.ripublication.com

Study of Knee-Joint Mechanism before Implanting a Knee Prosthesis by Modeling and Finite Element Analysis of Knee-Joint Bones

Ashutosh Nayan Nautiyal[1], P.K.S. Nain[2] and Pramod Kumar[3]

[1]Pursuing M.Tech.in Mechanical (CAD/CAM) Engineering, Galgotias University, Greater Noida, UP, India
[2]Department of Mechanical Engineering, Galgotias University, Greater Noida, UP, India
[3]Department of Mechanical Engineering, Galgotias University, Greater Noida, UP, India

Abstract

Knee prosthesis has done a lot of advancement in the recent decade as this facilitates people to do various activities even after their old age or some injury. Knee-joint is a complex structure of the human body having a complex shape femoral condyle which moves over the complex shaped meniscus of the tibial bone and acquires various critical loads at various walking, moving and sitting activities. From a biomechanical point of view, clinicians need relevant knowledge in order to properly implant a knee-prosthesis. The purpose of this paper is to give people and clinicians a better understanding about the knee-joint mechanism and the loads & forces acting on it at different conditions. In this context, a three-dimensional model of femoral and tibial bones of knee-joint is made in Pro/E Wildfire 4.0 and finite element analysis of loads at different conditions and at different weights is done in ANSYS 15.0 software in order to evaluate the results in form of von-mises stress which can be used to make implant for knee prosthesis.

Keywords: Knee Prosthesis, femoral condyle, knee-joint mechanism, implant

Introduction

Bioengineering/Biomedical Engineering combines engineering expertise with medical needs for the enhancement of health care. It is a branch of engineering in which knowledge and skills are developed and applied to define and solve problems in biology and medicine. *Orthopaedic Bioengineering* is the specialty where methods of engineering and computational mechanics have been applied for the understanding of the function of bones, joints and muscles, and for the design of artificial joint replacements. Designing a prosthetic device to match the leg's capabilities is a serious challenge. Team of scientists, engineers, clinicians and designers around the world use different approaches and technologies to develop prosthetic legs that help the user regain a normal, active lifestyle.

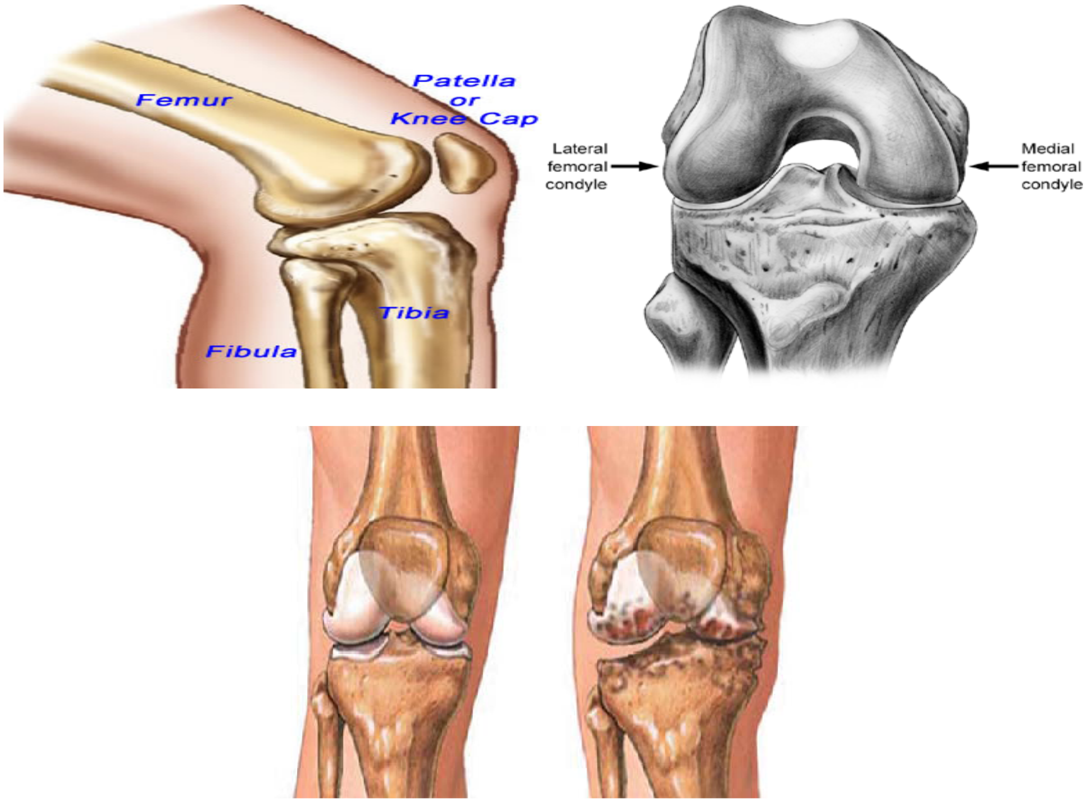


Figure-1: (a) Knee-joint parts (b) Femoral condyle & tibial plateau (c) Healthy knee and defected knee

Knee-joint is a complex structure of the human body having a complex shape femoral condyle which moves over the complex shaped meniscus of the tibial bone and acquires various critical loads at various walking, moving and sitting activities. In the tibiofemoral joint or knee-joint, the condyles of the femur articulate with the condyles of the tibia, but are asymmetrical (Fig 1). The larger medial femoral condyle is round, and the lateral condyle is longer, and wider at contact with the tibia. The medial tibial plateau is flat, but the lateral tibial plateau is convex. The meniscus provides increased stability by deepening the concavity of the tibia.

Knee prosthesis has done a lot of advancement in the recent decade. In 1995, Dr. J. De Vries carried out a strength-weakness analysis of 8 types of 4-bar linkage knee mechanisms and describes the kinematics of lower limb [1]. K. Oberg designed the polycentric linkage mechanism for different stance phase characteristics and incorporated different swing phase control mechanisms. The cosmesis of the available designs is acceptable but there is need for lighter and more compact designs [2]. In 2006, Yeh-Liang Hsu designed a Novel Total Knee Prosthesis using TRIZ theory with the ultra-high molecular weight polyethylene (UHMWPE) [3]. In 2008, Ernesto C. Martinez-Villalpando proposed a biomimetic active agonist-antagonist structure designed to reproduce both positive and negative work phases of the natural joint while using series elasticity to minimize net energy consumption [4]. In 2009, Kok-Meng Lee presents a method taking advantage of medically available MRI (Magnetic Resonance Imaging) data to derive the kinematics of a knee joint [5]. In 2011, Christoph Fiedler has done a mathematical study on the guidance of the tibiofemoral joint as theoretical background for total knee replacements [6]. In 2013, M. A. Kumbhalkar has done a comparative study on loads and stresses on knee joint with and without implant [7].

Procedure of Research

For replacement of defective bone structures we have to keep following parameters in our mind for a perfect design and comfort of the patient:

- Rotation – ease of changing direction
- Weight – maximizing comfort, balance and speed

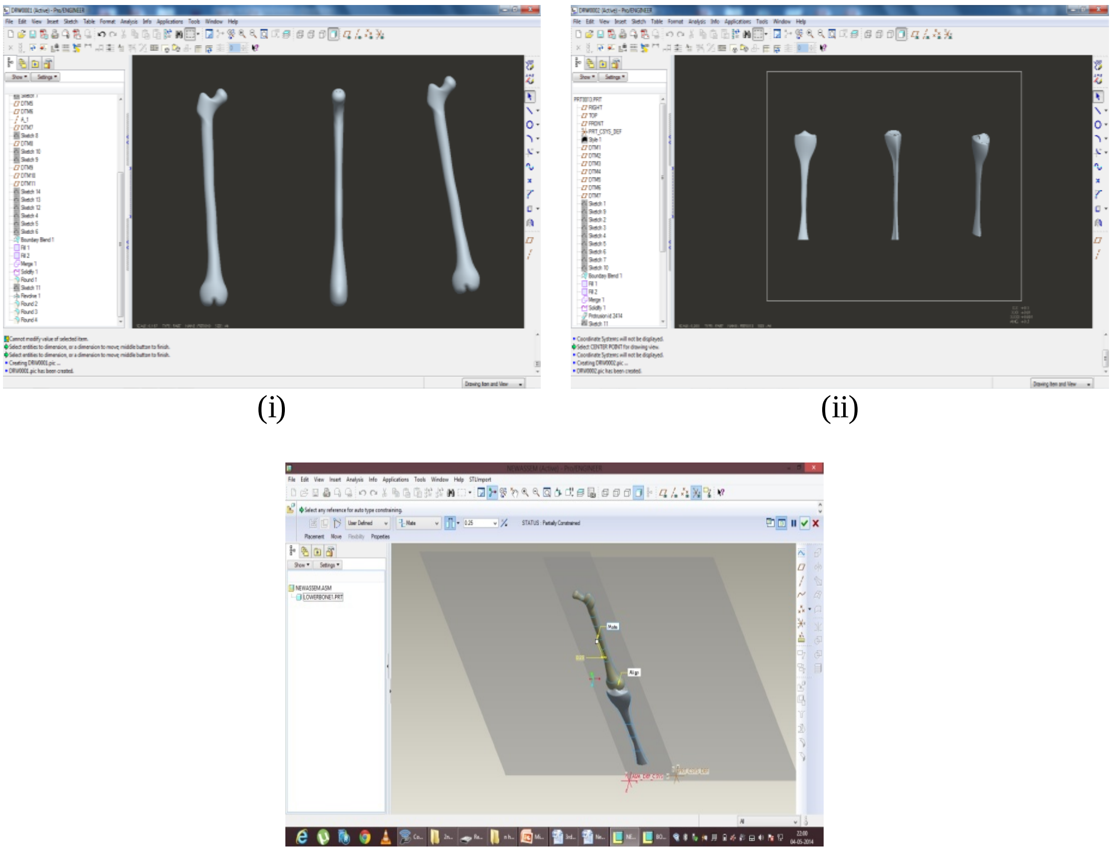
Thus by keeping the above parameters in mind replacement of the defective bone structures can be possible based on the following steps:

- Scanning or getting the dimensions & profile of the knee-joint: At first step we get the dimensions & profile of the knee-joint (both natural one as well as the defected one) by scanning or by manually which may be due to old age, some injury, accident etc.
- Modelling a three dimensional design of the Knee-Joint: We then model the original bones according to the dimensions and profile of it in any 3-dimensional modelling software. Here in this research work for replacement of defective knee-joint bone structures, I am using Pro-Engineer Wildfire 4.0 modelling software.
- Finite Element Analysis: Once the modeling of original knee joint is done we do several finite element analysis for calculating stresses at different points at different positions and angles & at several knee-joint movement conditions.

Then after getting the results in terms of von-mises stress of natural bones for several loading conditions we can make our model for knee prosthesis and can compare the results with the natural one.

Modeling of Knee Joint Bones

For modeling of natural human bones for knee joint in Pro-E Wildfire 4.0, a 3D design software first of all we need is the exact profile, shape and dimensions of the bones which is a tough job to get the accurate dimensions and profile of the bones. In modeling of the natural human bones for knee joint first we took the x-ray and CT scan of the knee but lack many dimensions. Then scaling of the image to some of the measured dimensions is preferred, for that I took various dimensions and pictures of the human skeleton and then import this picture into the Pro-E software and then by taking several points and coordinates as reference and by joining those points together over the picture one can do the 3D modeling of the natural human bones for knee joint as shown in figure 2.



(i) (ii)

(iii)

Figure 2: (i) Modeling of Femur Bone (Upper bone) of Knee Joint with complex shape femoral condyle; (ii) Modeling of Tibial Bone (Lower bone) of Knee Joint with complex meniscus, and (iii) Assembly of Femur & Tibial Bones of Knee Joint in Pro-E Wildfie 4.0

Finite Element Analysis of Knee-Joint

For the finite element analysis of the knee-joint, the IGES files of assembly of femur and tibial bones at various angles are imported to the ANSYS 15.0 software and various critical loads and weights are applied on it to see the results in terms of equivalent von-mises stresses.

For forces and moments on knee-joint static structural analysis is done in cases (i) when only vertical force due to person's weight is acting on a knee-joint by making the femur part fixed and applying a force in Y-direction for several weights and at different angles, (ii) when coplanar forces are acting in X, Y, & Z direction in tibial bone while walking and (iii) for joint reaction force during running or stair climbing [7].

Material Properties of Human Bone

Young's Modulus: 105 MPa Poission's Ratio: 0.45 Density: 1550 kg/m^3

Contact Type: No Separation Mesh Type: Coarse

Finite Element Analysis Results:

Table 1 for Case (i): When only vertical force due to person's weight is acting on a knee-joint (Upper femur part is fixed here and load is applied on the lower tibial bone part only in Y-direction)

Input Parameters		Output Parameters				
Weight (in Kg)	Force (in N) Fy = mg	Von-misses Stress at various angles (in MPa)				
		0^0	45^0	70^0	90^0	120^0
50	490	1.7835	1.5613	1.3949	2.0271	3.1061
60	588	1.9312	1.8735	1.6733	2.5028	3.6907
70	686	2.4720	2.1858	1.9557	3.2163	4.2750
80	784	2.9375	2.4980	2.2351	3.6184	4.8813

Table 2 for Case (ii): When the forces acting in all three Fx, Fy & Fz direction during walking (Again here femur part is kept fixed and three forces applied on the tibia)

Input Parameters				Output Parameters				
Weight (in Kg)	Force (in N)			Von-misses Stress at various angles (in MPa)				
	Fx	Fy	Fz	0^0	45^0	70^0	90^0	120^0
50	130.6	490	98.0	12.3712	11.946	14.3412	17.8163	19.317
60	156.8	588	117.6	14.1432	13.369	16.9310	21.0318	24.156
70	182.9	686	137.2	17.6830	16.727	20.2841	23.1128	27.932
80	209.0	784	156.8	19.7807	19.115	22.3107	26.3120	30.821

Table 3 for Case (iii): For joint reaction force when person is running or climbing stairs (this only acted when the knee joint is fully bended at 90^0 and 120^0, here femur part is kept fixed and body force 'Fy' is acted in Y-direction, joint force 'Fj' is acted is acted on the joint and condylar force 'Fc' acted on the femur condyle)

Input Parameters				Output Parameters	
Weight (in Kg)	Force (in N)			Von-misses Stress at various angles (in MPa)	
	Fy	Fj	Fc	90^0	120^0
50	490	2011.4	1606.3	135.3280	128.3100
60	588	2360.7	1857.2	162.0487	174.2340
70	686	2715.6	2113.7	243.7615	208.4187
80	784	3108.9	2448.4	389.1302	322.3713

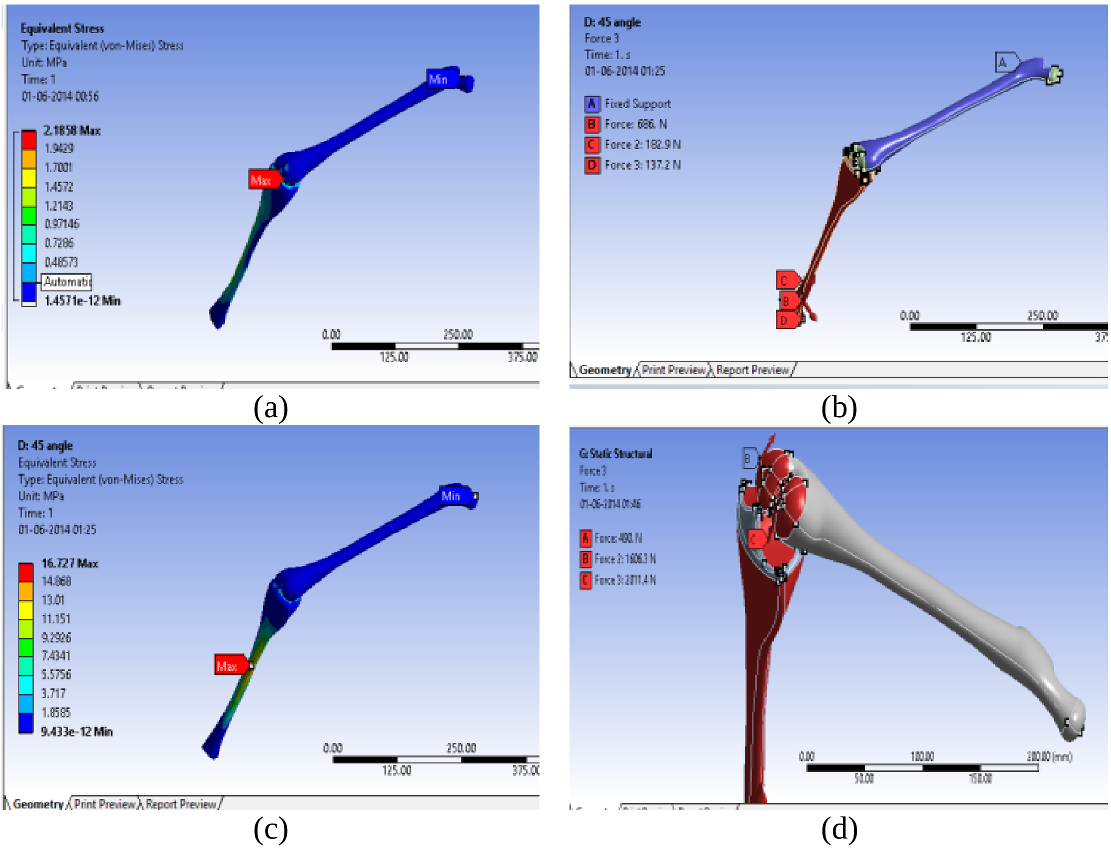


Figure 3: (a) FEA result as Von-mises stress for case (i) for 70 kg wt. at 45^0; (b) Loadings for 70 kg wt person at 45^0 for case (ii); (c) Ansys result for 70kg person in case (ii); and (d) Loadings for case (iii) at 120^0

Conclusions

The modeling and finite element analysis of knee joint of the complex femoral and tibial structure is carried out in Pro/E 4.0 and Ansys 15.0 for different loading conditions at various angles ranging from 0^0 to 120^0 for varying person's weights from 50 to 80 kg. From the analysis, it is shown that the von-mises stress increases continuously with increasing loads in case (i) from 1.7 to 4.8 MPa & case (ii) from 12 to 30 MPa and it increases more rapidly for case (iii) during stair climbing and running conditions when the knee is fully bend.

The loads and results can vary from person to person as the size of bones differs in each individual so the load and stress analysis is advisable before implanting knee prosthesis. Once this analysis is over one can make replacement or implant for knee joint prosthesis and compare the von misses stresses with the stresses achieved in analysis of natural bones without implant.

References

[1] Dr. J. De Vries; “Conventional 4-bar linkage knee mechanisms : A strength-weakness Analysis”; Journal of Rehabilitation Research and Development Vol. 32 No. 1, February 1995, Netherlands.

[2] K. Oberg; “Knee mechanisms for through-knee prostheses”; Prosthetics and orthotics International, 1983, 7, 107-112 Biomechanics Laboratory, College of Health and Care, Jönköping, Sweden.

[3] Yeh-Liang Hsu, Yung-Chieh Hung, Ju-Zhong Yin; “Design of a Novel Total Knee Prosthesis Using TRIZ”; *Journal of Medical and Biological Engineering*, Vol. 26, No. 4, December 2006, p. 177-185; recommended: (2007-08-02).

[4] Ernesto C. Martinez-Villalpando, Jeff Weber, Grant Elliott, Hugh Herr; “Biomimetic prosthetic knee using antagonistic muscle-like activation”; Proceedings of IMECE2008 ASME International Mechanical Engineering Congress and Exposition October 31-November 6, 2008, Boston, Massachusetts, USA.

[5] Kok-Meng Lee, Jiajie Guo; “Effects of Bio-joint Models on Compliant Exoskeleton Design”; 2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics; Suntec Convention and Exhibition Center, Singapore, July 14-17, 2009.

[6] Christoph Fiedler, Riccardo Gezzi, Karl-Heinz Frosch, Martin Michael Wachowski, Dietmar Kubein-Meesenburg, Jochen Dorner, Jochen Fanghänel, Hans nägerl; “Mathematical study on the guidance of the tibiofemoral joint as theoretical background for total knee replacements”; Acta of Bioengineering and Biomechanics Vol. 13, No. 4, 2011.

[7] M. A. Kumbhalkar, Umesh Nawghare, Rupesh Ghode, Yogesh Deshmukh, Bhushan Armarkar; “Modeling and Finite Element Analysis of Knee Prosthesis with and without Implant”; Universal Journal of Computational Mathematics 1 (2): 56-66, 2013 DOI: 10.13189/ujcmj.2013.010204.