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RESEARCH ARTICLE

MODELING AND ANALYSIS OF KNEE PROSTHESIS

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ABSTRACT

In human body, knee joint consists of different components, i.e. femur, tibia, patella and menisci were subjected to different critical loads while performing physical activities. This paper describes the design and analysis of knee prosthesis. Geometric models of the knee implants were created from the data of CT/MRI images. These models were tested to get the specific results in terms of stress magnitude using finite element analysis software ANSYS. The von mises stress, total deformation, frictional stress and contact pressure between the implants has been analyzed for different biomaterials i.e. stainless steel, Co-Cr alloy and Ti alloy for femoral and tibial components. The obtained results are compared and concluded that, Ti6Al4V was the best implant material among stainless steel and Co-Cr alloy, when consider the von mises stresses.

INTRODUCTION

Knee joint is one of the most complex synovial joints. It supports the whole weight of the body. Also, it is the joint most vulnerable to both injury and development of osteoarthritis**.** Knee replacement procedures had been followed for almost 50 years in the surgical procedure called Total knee Anthroplasty

The Total knee Anthroplasty involves removing the articulating surfaces of the affected knee joint and replaces them with metal components either by cemented or cement less procedure [1]. The metal and the polyethylene components are all together called the artificial knee [2]. Artificial knee should satisfy certain design requirements, i.e., they should be ergonomical and biocompatible. The components of the artificial knee are femoral component, tibial component and polyethylene spacer. The femoral component and tibial tray are usually made of metals such as titanium-based alloys, stainless steels and cobalt chromium molybdenum (Co-Cr-Mo) alloys and the spacer is made of ultra-high molecular weight polyethylene [3].

The femoral component occupies its place around lower ends of the femur**.** The metal femoral component curves around the end of the femur (thighbone). It is grooved so the kneecap can move up and down smoothly against the bone as the knee bends and straightens. The tibial component lies on top surface of the tibia**.** The tibial component is typically a flat metal platform with a cushion of strong, durable plastic, called polyethylene. . During activation, stresses are developed at the interface of the joint, which in turn dictates the performance of the joint. The intensity of the stresses developed depends on several factors. To ensure the stress intensity, it is important to optimize the design of prosthetic knee joint. In this regard, FEM the most powerful numerical tool can be used to optimize the design [4], [8]. Most of the designs have not considered the femoral component and attached the polyethylene spacer directly to the bone. For additional stability, the metal portion of the component may have a stem that inserts into the center of the tibia bone. The spacer is also called as tibial insert and it replaces the cartilage and acts as shock absorber. Finite element analysis was performed on articular cartilage of different diameters and during squatting and normal walking activity and the von mises stresses were analyzed and the maximum stress is on the sides of artificial articular cartilage, this is due to the thickness differences between the sides and the middle [7].

Present paper deals with the modeling of knee prosthesis and finite element analysis of different stresses for knee prosthesis with materials of stainless steel, Co-Cr-Mo and Ti6Al4V. The paper discussed the different sections, section 1 presents the introduction. Section 2 presents the different bio materials and their mechanical properties that are adopted for knee prosthesis. Section 3 provides the geometric modeling of knee prosthesis with CAD software. Section 4 presents the finite element analysis of knee prosthesis and predicts the von mises

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stress, total deformation, frictional stress and contact pressure. Section 5gives the results and discussion along with the computational approach employed.

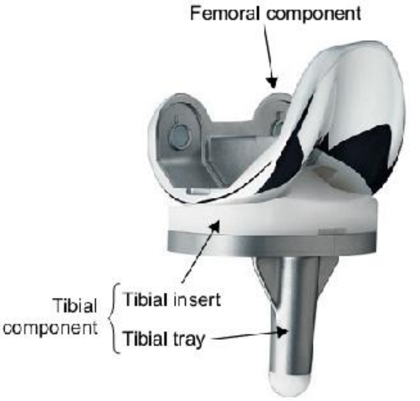


Figure 1 Components of Total Knee Replacement

Materials for Knee Implant

A biomaterial must fulfill two requirements before it can be used successfully in the human body. The first requirement is that it is capable of carrying out its prescribed function (e.g. load bearing) in the physiological environment. The material must also exhibit biocompatibility. This is a complex requirement that the interactions between the material and its biological environment must not prejudice its prescribed function. Problems of incompatibility arise because of the crudeness of the artificial model of living tissue, both biologically and mechanically. The three functions of load bearing, load transmission between implant and supporting tissue and motion define the requirements for materials used in joint replacement.

Table 1 Material Properties of Knee Prosthesis

Materials	Young's Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Ultimate Strength (MPa)
Stainless Steel (316 L)	200	0.3	290	580
CoCrMo alloy	210	0.3	450	720
Ti6Al4V alloy	110	0.33	825	1035
UHMWPE (Polyethylene)	1.2	0.46	20	40

Geometric Modeling of Knee Prosthesis

To achieve the 3D model of the knee implant, it was needed to have submitted real scanning elements. The CT images are used to measure the relevant parameters of knee including the width of the femoral condyle and the anteroposterior diameters of the lateral and medial condyle are the important parameters. From the measurements obtained from CT scan images and available literatures approximate size of the prosthetic knee joint was constructed using CAD software CATIA. Also in this phase: the so-called "solidification" of the model, consisting in taking into account the volume defined by the outer surfaces and the association of this volume of mass-specific material characteristics. In the case of the femur, more part bodies will be created, with several different characteristics that take into account in the actual structure knee implant. The knee implant consists of three different components they are the femoral component, tibial component and spacer are shown in figures 2 and figure 3.

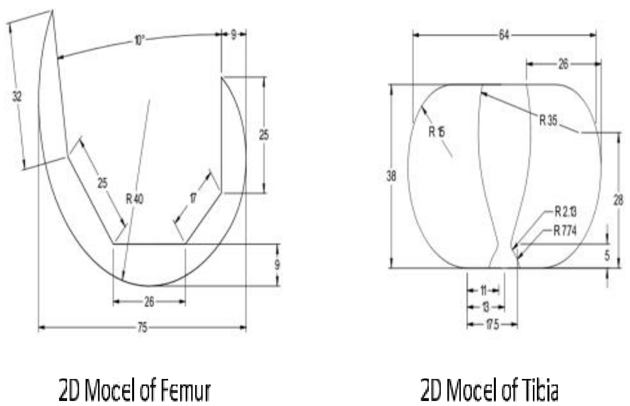


Figure 2 Dimensions of Knee Implant

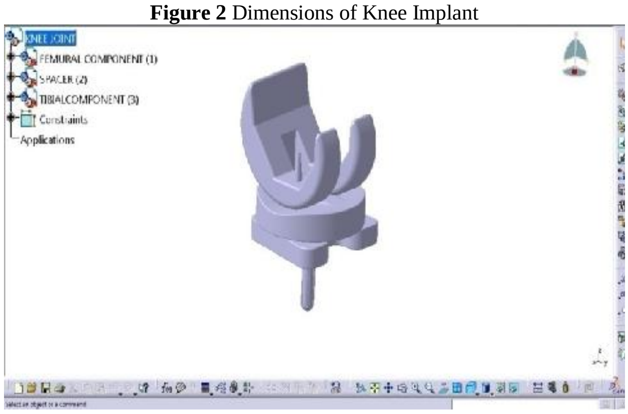


Figure 3 Assembly Model of Knee Prosthesis

Finite Element Analysis

The type of stress analysis used in the present study is the transient structural analysis (also called time-history analysis). This type of analysis is used to determine the dynamic response of a structure under the action of any general time-dependent loads. In Transient analysis, the load can be simulated with time dependent values, therefore in the present study we need to measure the knee contact force that applied on the head of the femur during a complete gait cycle for the activities included in my present study. These gait data which includes the knee contact force with the cycle duration have been used in my present study for a typical patient weight (100 kg) in order to calculate the stresses on the human femur bone. The activities included in my present study are illustrated. The finite element model of knee implant with volumetric mesh is imported in ANSYS. Since the knee implant model is nonlinear and highly heterogeneous in nature, model is first imported in finite element modeler. Human weight of 100 kg was considered and as per the Hip software the remote force of 341 N was applied at the inner surface of the femoral component and the moment load of 3.41N-mm is also applied on the femoral component. The two other implants of the prosthesis are rigidly fixed together and further carried to analysis and the constraint model was shown in figure 4.

RESULTS AND DISCUSSIONS

The finite element models of artificial knee prosthesis are analyzed to estimate dynamic behavior for the given loading and boundary conditions with three different biomaterials i.e. stainless steel, cobalt alloy and titanium alloy. The parts of the prosthesis are taken different combinational materials and the polyethylene spacer is used in three combinations to avoid metal to metal contact. The knee prosthesis is analyzed to predict the von mises stress, total deformation, frictional stress and contact pressure.

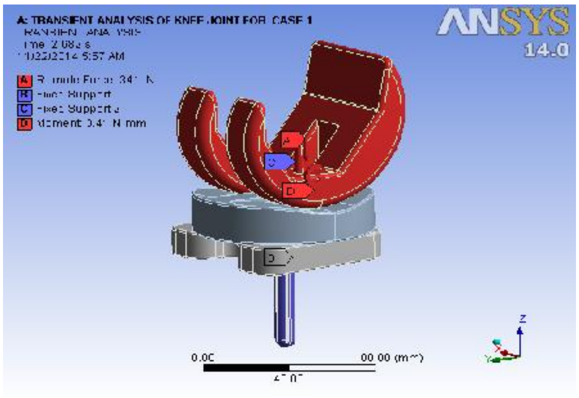


Figure 4 Constraint Model of Knee Prosthesis

Von mises stress

The von mises stress obtained from the transient analysis of the knee prosthesis on stainless steel, cobalt alloy and titanium alloy are shown in figures. From the results the obtained von mises stress for the materials stainless steel 17.4 Mpa, cobalt chromium alloy 16.91Mpa and titanium alloy 10.01 Mpa. While comparing the minimum von mises stress among the materials is for titanium alloy.

Total Deformation

The total deformation obtained from the transient analysis of the knee prosthesis on stainless steel, cobalt alloy and titanium alloy are shown in figures. 0.020312mm and titanium alloy 0.029178mm. While comparing the minimum total deformation among the materials is for stainless steel and the deformation is very less.

Frictional stress

The frictional stress obtained from the transient analysis of the knee prosthesis on stainless steel, cobalt alloy and titanium alloy are shown in figures.

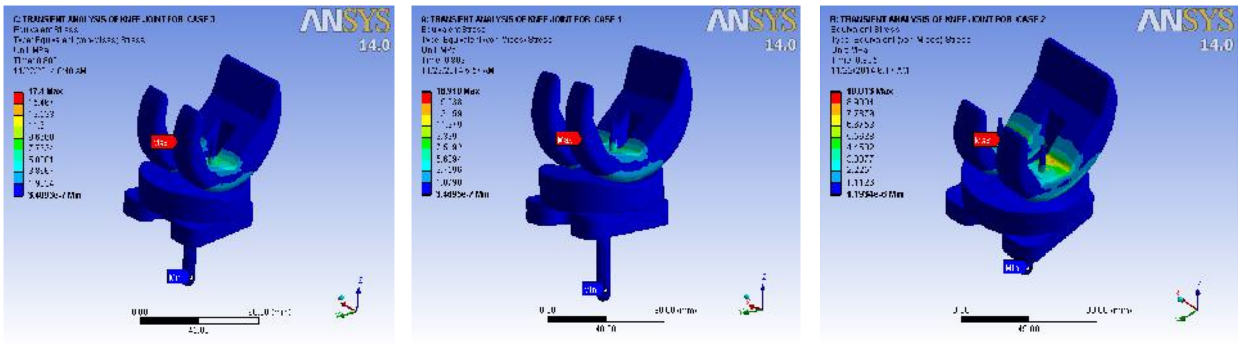
The frictional stress is also one criterion because the femoral component slides over the surface of polyethylene spacer. From the results obtained frictional stress for the materials stainless steel 0.28124 Mpa, cobalt chromium alloy 0.28645 Mpa and titanium alloy 0.3544 Mpa.

Contact Pressure

The contact pressure was developed in between the femoral component and the polyethylene spacer.

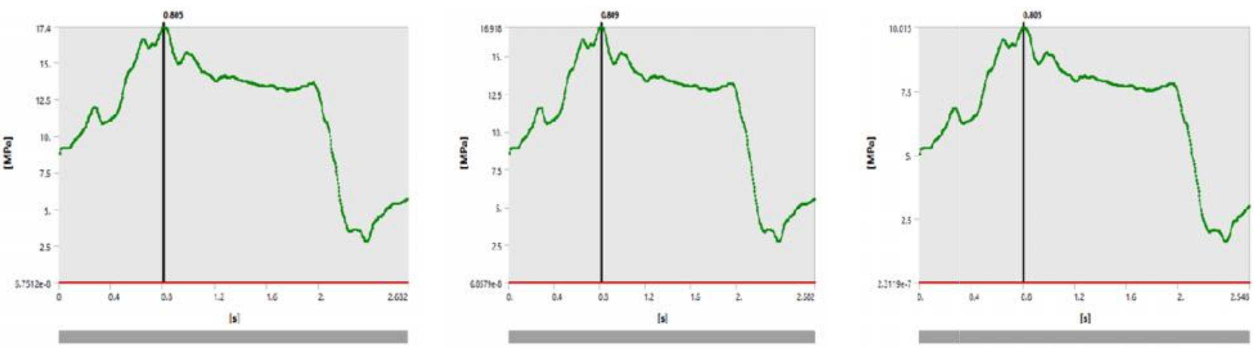
The contact pressure obtained from the transient analysis of the knee prosthesis on stainless steel, cobalt alloy and titanium alloy are shown in figures. From the results obtained contact pressure for the materials stainless steel 0.87644 Mpa, cobalt chromium alloy 0.89554 Mpa and titanium alloy 1.1476 Mpa.

The results of von mises stresses of different biomaterials were compared with gait cycle was clearly shown in fig.6.26 and corresponding von mises stresses maximum value obtained at time of 0.805 sec.



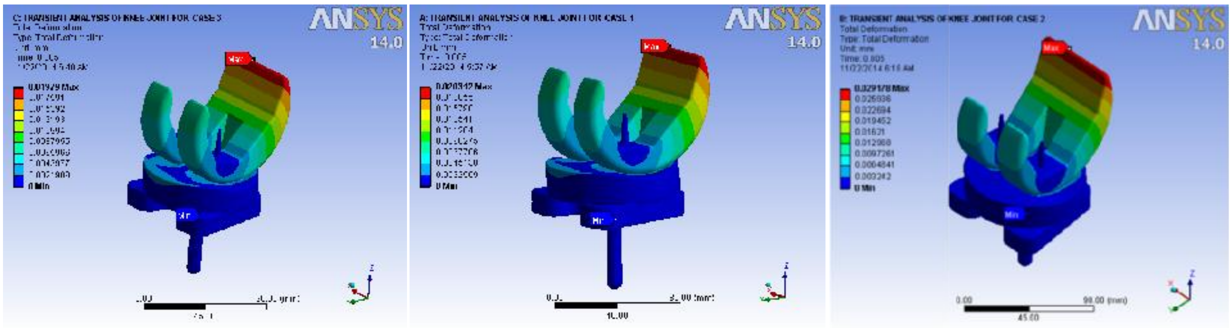
(a) (b) (c)

Figure 5 Von mises stress distribution of knee prosthesis for (a) stainless steel (b) CoCrMo and (c) Ti6Al4Vmaterials



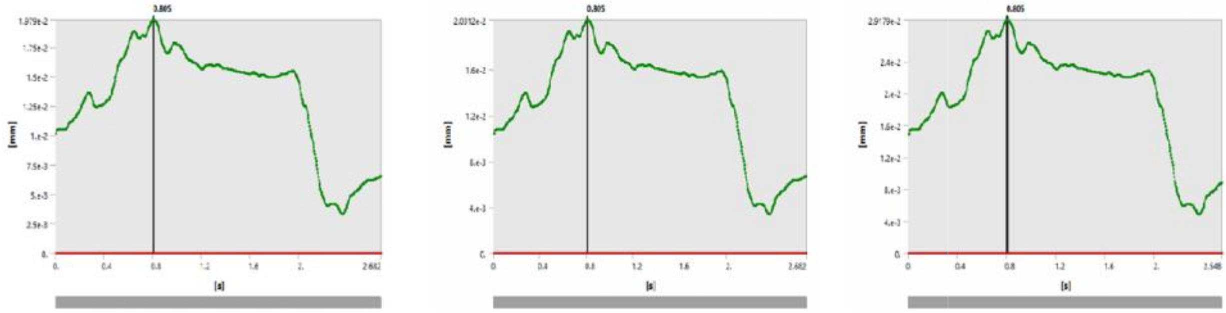
(a)Stainless steel (b) Cobalt chromium alloy (c) Titanium alloy

Figure 6 Comparison of von mises stress distribution for knee prosthesis of different materials



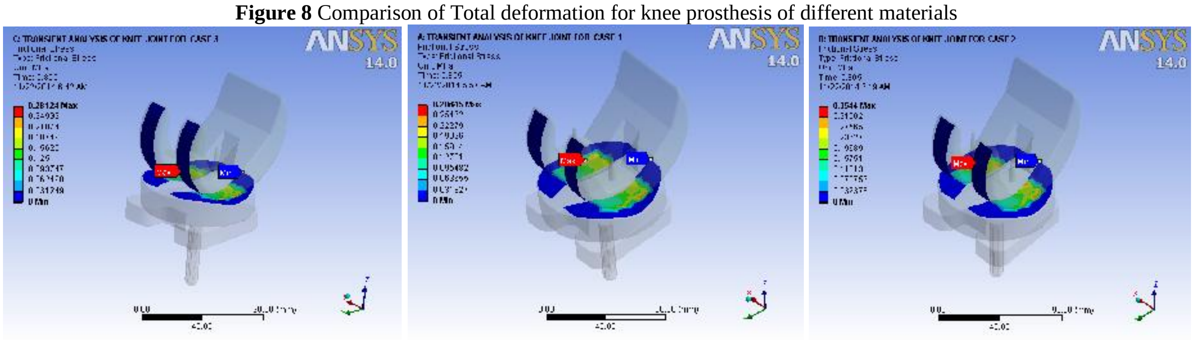
(a) (b) (c)

Figure 7 Total deformation of knee prosthesis for (a) stainless steel (b) CoCrMo and (c) Ti6Al4Vmaterials



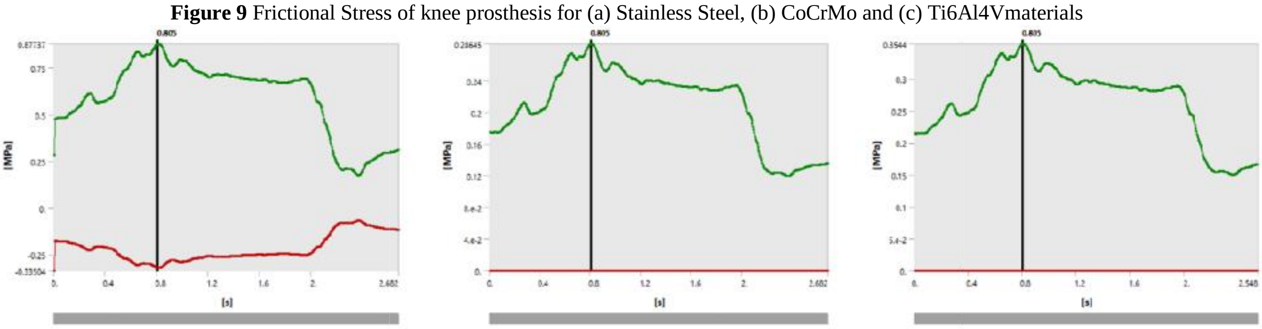
(a)Stainless steel (b) Cobalt chromium alloy (c) Titanium alloy

Figure 8 Comparison of Total deformation for knee prosthesis of different materials



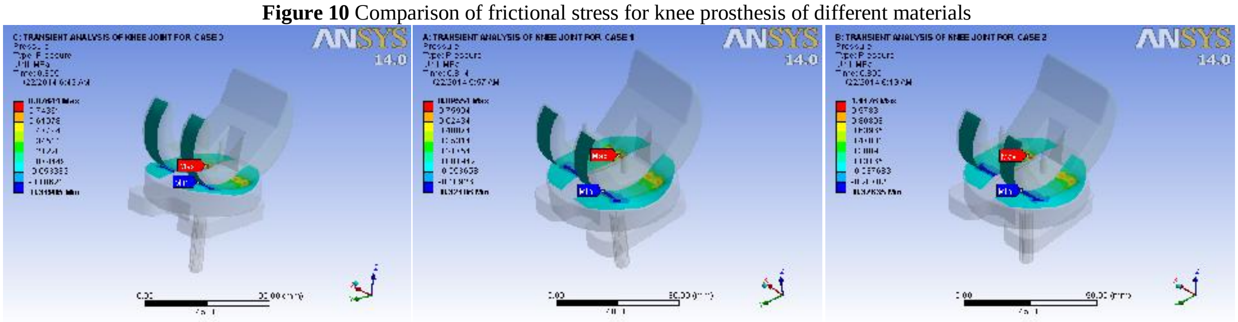
(a) (b) (c)

Figure 9 Frictional Stress of knee prosthesis for (a) Stainless Steel, (b) CoCrMo and (c) Ti6Al4Vmaterials



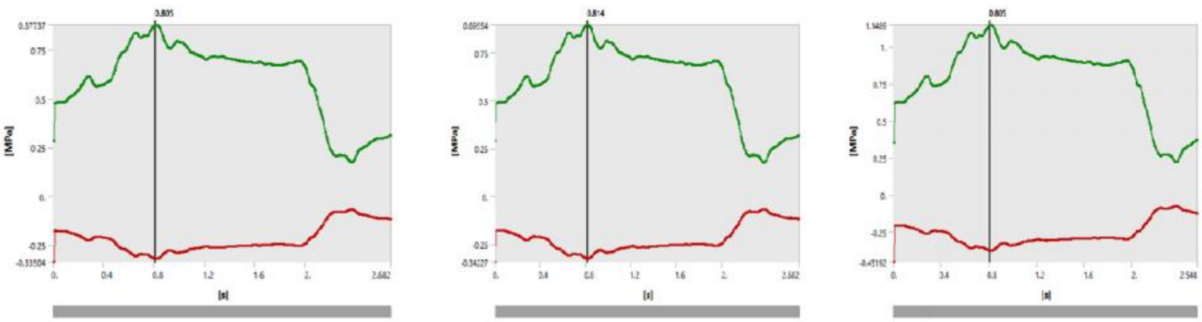
(a)Stainless steel (b) Cobalt chromium alloy (c) Titanium alloy

Figure 10 Comparison of frictional stress for knee prosthesis of different materials



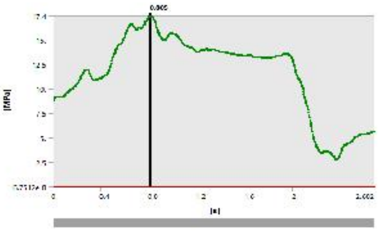
(a) (b) (c)

Figure 11 Contact pressure of knee prosthesis for (a) Stainless Steel, (b) CoCrMo and (c) Ti6Al4Vmaterials

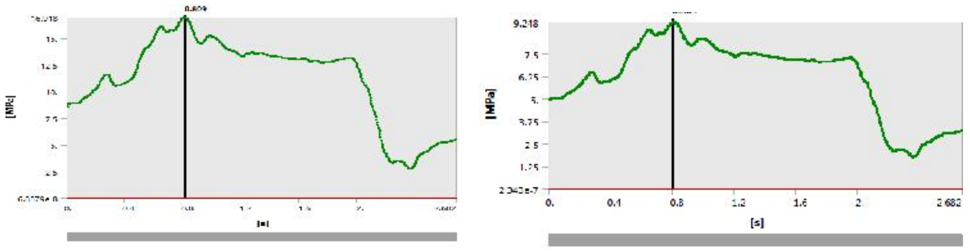


(a)Stainless steel (b) Cobalt chromium alloy (c) Titanium alloy

Figure 12 Comparison of contact pressure for knee prosthesis of different materials



(a) Stainless steel



(b) Co-Cr alloy (c) Titanium alloy

Figure 13 Comparison of Gait cycle with Graph representing Von mises Stress of Different Biomaterials

Table 2 Results for different bio materials

Material	Von mises stress (Mpa)	Total deformation (mm)	Frictional stress (Mpa)	Contact pressure (Mpa)
Stainless steel	17.40	0.01979	0.28124	0.87644
Co-Cr alloy	16.91	0.02031	0.28645	0.89554
Ti alloy	9.24	0.02732	0.73482	1.2247

This is because at that particular time one leg was in swing phase and other leg was in midstance phase and in this phase the total body weight acts on a single leg. And also the maximum values of all remaining parameters like total deformation, frictional stress and contact pressure are exhibit the same phenomenon for the other cases of Co-Cr alloy and Ti-alloy. So in each case the values in the graph gradually increases to midstance phase and slowly decreases after that phase.

CONCLUSION

In this present study, 3-D assembly model of knee prosthesis was designed in CATIA V5, transient analysis was performed to study the stresses and contact behavior of designed knee prosthesis for different combinations of biomaterials. The following conclusions are obtained from the analysis with different biomaterials.

- The minimum von mises stresses are obtained for titanium alloy when compared with other biomaterials. Titanium alloy being extremely light with less density and does not have any adverse effect on the patient and their movements.
- The minimum values of total deformation, frictional stress and contact pressure are obtained for stainless steel. The stresses generated in the knee prosthesis are well below levels that might cause failure of the material.
- Moderate values are obtained for all parameters of Co- Cr alloy.
- The maximum values of the stresses and other parameters are obtained at midstance phase of the gait cycle because at this phase the total body weight acts on a single leg. So in each case the values in the graphs gradually increase to midstance phase and slowly decrease after that phase.

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