Finite Element Analysis of a Novel High Flexion Knee (Ti – UHMWPE) used in Total Knee Arthroplasty

S Sivarasu, M Lazar

Abstract

The application of Finite Element Modelling in Medical Applications has been evolving as the field of high importance especially in the development of medical devices. The Total Knee Arthroplasty [TKA] has been in existence for over 6 decades till now. The generic artificial knee implants used in the TKA have the restriction in its range of motion with around 90 degrees. A new design allowing flexion extension range of over 120 degrees was designed with a view to facilitate partial squatting and the same is used for the analysis purpose. The loading conditions of 10 times the body weight are considered. The finite element analyses of the designs were carried out based on standard biomaterial used in orthopaedic implants. In this paper we have discussed the results of analyses of an artificial knee with Ti alloy. The results of the analyses were used in identifying areas of extreme stresses within the design and the spot prone for higher deformation. Based on these results slight modification on the designs was carried out. The results are also verified whether the body is within the linear deformation levels. As the results obtained were very satisfactory the models have been recommended for prototyping.

BACKGROUND

The joint replacement surgeries are doubtlessly the gift of science and technology for human welfare. The history of joint replacement begins way back in the late fifties. Initially from the Hip, then to Knee and now shoulders, ankle elbow and almost all the joints are replaced nowadays.

The knee replacement procedures had been followed for almost 50 years in the surgical procedure called the Total Knee Replacement [TKR] or the Total Knee Arthroplasty [TKA]. Here the cartilages and the bones surface which are degenerated by arthritis are removed and replaced with the metal components either by cemented or Cementless procedures [1]. The metal and the Polyethylene components are all together called the Artificial Knee [1].

A thin layer of bone is removed from the damaged surface of the femur (thigh bone) using special instruments which remove the correct thickness of bone. The removed bone is then replaced by a thin layer of metal, approximately the same thickness as the bone which was removed. In a similar fashion the upper end of the tibia (shin bone) is removed and is replaced with a wafer of plastic. The back part of the knee cap (patella) may also be resurfaced with a piece of plastic. This procedure is called Total Knee Arthroplasty [TKA].

CURRENT STATUS OF ARTIFICIAL KNEE

The components in the artificial knee are,

- The Femoral component
- The Tibial component
- The Patellar component
- The PE Insert

The design of each components of the artificial knee is shown below.

Up to three bone surfaces may be replaced during the total replacement of the knee: the lower ends (condyles) of the thighbone, the top surface of the shinbone, and the back surface of the kneecap. Components are designed so that metal always articulates against plastic, which provides smooth movement and results in minimal wear. As Shown in Fig.1
The existing designs of artificial knee do not provide the comfort of squatting, which is a common activity in the eastern world. For this case the novel high flexion design [3,4] is taken into consideration for analysis.

**NOVEL DESIGN FOR HIGH FLEXION KNEE**

A Novel Design of an artificial knee was developed using computer 3D Modelling. The High flexion knee is obtained by using a multi-radii design pattern. The increase of final 20 degrees in flexion is obtained by increasing the condylar radii of curvature. [3,4]. Two models of the high flexion knee were developed and one of the models is subjected to finite element modelling. The two novel designs are shown in Fig. 2 [a & b]

The Model –II with the peg restrainer is used as it is a stable design which also save a maximum of the bone stock. [3,4].

**FINITE ELEMENT MODELLING OF THE ARTIFICIAL KNEE**

Finite Element Analysis [FEA] has become common place in recent years, and is now the basis of a multibillion dollar per year. Numerical solutions to even very complicated
stress problems can now be obtained routinely using FEA, and the method is so important that even introductory treatments of Mechanics of Materials – such as this modulus – should outline its principle features.

Perhaps the most important function of theoretical modelling is that of sharpening the designer’s intuition. Finite Element codes are less complicated than many of the word processing and spreadsheet packages found on modern microcomputers. Nevertheless, they are complex enough that most users do not find it effective to program their own code. A number of pre written commercial codes are available.

COSMOS software was used in this research to perform FEA.

**BIOMATERIAL SELECTION**

The compositions of components in the artificial knee are, Femoral Component and the tibial component are metal where as the patellar component and the meniscal insert are made using polyethylene. The metal component used for the analysis in this study is Ti₆Al₄V and the polyethylene used is UHMWPE.

The table 1. describes the mass volume property for the selected material (Ti alloy with UHMWPE).

**Figure 4**

Table 1: Artificial Knee Material Properties

<table>
<thead>
<tr>
<th>Body Name</th>
<th>Material</th>
<th>Mass</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meniscus</td>
<td>UHMWPE</td>
<td>0.0183701 kg</td>
<td>1.97518x10⁵ m³</td>
</tr>
<tr>
<td>Tibial Component</td>
<td>Ti₆Al₄V</td>
<td>0.0504655 kg</td>
<td>1.32012x10⁵ m³</td>
</tr>
<tr>
<td>Femoral Component</td>
<td>Ti₆Al₄V</td>
<td>0.153122 kg</td>
<td>3.49742x10⁵ m³</td>
</tr>
<tr>
<td>Total Artificial Knee Assembly</td>
<td></td>
<td>0.225858 kg</td>
<td>6.75x10⁵ m³</td>
</tr>
</tbody>
</table>

**LOADING CONDITIONS FOR THE ANALYSIS**

The Knee joint in normal conditions gets loaded up to 2 to 3 times the body weight. The maximum load that the knee joint gets is up to 8 times the body weight. We have taken the load 10 times the body weight. The weight over single knee in only half the maximum load as the load is shared between the two knee joints. But for the analysis, we have taken the full load of 10 times the body weight considering that the patient standing in one leg. So the following are the loading conditions, taking average body weight to be 70Kgs and taking extreme loading conditions of upto 10 times the body weight, i.e. 700Kgs on each of the leg we perform the FEA over the newly designed knee. The loading is done at an increment of 100 Kgs.

The table 2 describes the loading conditions and the meshing details for the analysis of the assembly.

**Figure 5**

Table 2: Artificial Knee Assembly Meshing Information

<table>
<thead>
<tr>
<th>Jacobian Check</th>
<th>Model 1</th>
<th>Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element Size</td>
<td>0.46735 cm</td>
<td>0.46735 cm</td>
</tr>
<tr>
<td>Tolerance</td>
<td>0.020367 cm</td>
<td>0.020367 cm</td>
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<tr>
<td>Quality</td>
<td>High</td>
<td>High</td>
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<tr>
<td>Number of elements</td>
<td>80909</td>
<td>80909</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>126898</td>
<td>126898</td>
</tr>
</tbody>
</table>

**RESULTS OF ANALYSIS**

**LOADING THE COMPONENT**

Total number of loading points : 28 Face(s) apply normal force 25 kgf using uniform distribution.

Total number of restraints : 6 faces fixed.

The loading is incremented in terms of 100 Kgs starting from 100 Kgs to 700 Kgs. That would be approximately 3.6 Kgf load on each loading point for every load of 50 Kgs. Shown in Fig.3,4,5,6.
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Figure 6
Figure 3: Static Nodal Stress – Artificial Knee Assembly

Figure 7
Figure 4: Static Displacement – Femoral Component

Figure 8
Figure 5: Static Strain – Femoral Component

Figure 9
Figure 6: Max. Von Mises Stress – Femoral component
The FEA results have shown that the design with the given material properties behaves very well within the linear mechanical limits. The high concentrations of the stresses on the models are seen in the cases of extreme loads such as 10 times the body weight. But considering the fact that most of the times the loading is within 3 to 4 times the body weight. So the accumulation of the static stress would not affect the designs. 

The linear behaviour of the models is observed in the Fig7 and Table 3. However, we see a slight elevation in the peak stresses with a load of 600 Kgs. Also we observe a decrease in peak stress at 700 Kgs load. To avoid cyclic loading pattern, we therefore conclude a load of maximum 600 Kgs is optimum for this model.

The other components also observed linear elastic behaviour for the applied loads. Based on these results it is determined that the load bearing capacity of these models are well within the failure levels of the materials used for the analysis. Based on the results above, it is evident that the design can be forwarded for the prototyping.

CONCLUSION
Thus the novel high flexion knee design was subjected on to extreme loads and analysed using FEM techniques and the results have been satisfactory. The maximum loading level for this artificial knee with Ti- UHMWPE combination is determined to be 600Kgs.

References
4. Šudes Sivarasu & Lazar Mathew; “Modelling an artificial knee for customized needs of Indian population”; INCOB-08, VITU, Feb 6-8, Pages 138-139
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