Finite-element-based design optimisation of a novel high flexion knee used in total knee arthroplasty

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The application of finite-element modelling in medical applications has been evolving as a field of high importance in recent times. Total knee arthroplasty (TKA) has been in existence for over 6 decades. The generic artificial knee implants used in the TKA have a restricted range of motion of around 90 degrees. A new design allowing a flexion extension range of over 120 degrees was designed and is used for analysis. Loading conditions of 10 times the body weight are considered. The finite-element analyses of the designs were carried out based on standard biomaterials used in orthopaedic implants. The results of the analyses were used in identifying areas of extreme stress within the design and the spots prone to higher deformation. On the basis of these results slight modification of the designs was carried out. The results are also verified whether the body is within the linear deformation levels. The results obtained were very satisfactory and based on these results the models have been recommended for prototyping.

Keywords: artificial knee; total knee arthroplasty; finite-element modelling; biomaterials; design optimisation

1. Background

The joint replacement surgeries are doubtlessly a gift of science and technology for human welfare. The history of joint replacement begins way back in the late fifties. Initially the hip, then the knee and now shoulders, ankles, elbows, and almost all the joints are replaced nowadays.

Knee replacement procedures have been followed for almost 50 years in the surgical procedure called the total knee replacement (TKR) or the total knee arthroplasty (TKA). Here the cartilage and the bones which have been degenerated by arthritis are removed and replaced with metal components either using cemented or cementless procedures (Raymond et al. 2005; Karsh and Ploeg 2005). The metal and the polyethylene components are together called the artificial knee (Vilegas et al. 2004).

A thin layer of bone is removed from the damaged surface of the femur (thigh bone) by using special instruments. The removed bone is then replaced by a thin layer of metal, approximately of the same thickness as the bone that 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 kneecap (patella) may also be resurfaced with a piece of plastic. This procedure is called total knee arthroplasty (TKA).

2. Components of an 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 of the components of the artificial knee is shown overleaf.

2.1. Artificial knee

In this procedure 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 Figure 1.

3. Novel high flexion knee design

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 final increase of 20 degrees in flexion is obtained by increasing the condylar radii of curvature. (Sivarasu and Mathew 2007). 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 Figures 2 and 3.

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Table 1. Materials in artificial knee components.

• Femoral component	• Metal
• Tibial component	• Metal
• Patellar component	• Polyethylene
• Meniscal insert	• Polyethylene

Table 2. Biomaterials selection for FE analysis.

• Femoral component	• Metal	• SS 316 alloy
• Tibial component	• Metal	• SS 316 alloy
• Patellar component	• Polyethylene	• UHMWPE
• Meniscal insert	• Polyethylene	• UHMWPE

Table 3. SS 316–material composition.

Components	C	Cr	Fe	Mn	Mo	Ni	P	S	Si
Wt. (%)	0.03	17	65	2	2.5	12	0.045	0.03	1

Table 4. Physical properties of SS 316 alloy.

Density	8 g/cc
Hardness rockwell	79
Tensile strength, ultimate	560 MPa
Tensile strength, yield	290 MPa
Modulus of elasticity	193 GPa
Elongation at break	50%
Specific heat capacity	0.5 J/g°C

Table 5. Loading conditions for FEA of artificial knee.

Maximum load	10 × Body weight
Average body weight	70 Kg (Sivarasu and Mathew, 2007)
Maximum load	70 × 10 = 700 Kg
Maximum load on single knee	700 Kg (considering the patient standing in single leg)

Table 6. Femoral component description.

No.	Body name	Material	Mass	Volume
1	Femoral component	SS 316 L	0.59454 lb	2.10985 in ³

Table 7. Femoral component meshing information.

Jacobian check:	4 Points
Element size:	3.2565 mm
Tolerance:	0.16283 mm
Quality:	High
Number of elements:	83,722
Number of nodes:	129,670

Figure 1. Knee implant components.

4. Biomaterial selection

The compositions of components in the artificial knee are shown in Table 1.

The metal considered for the analyses are shown in Table 2.

4.1. SS 316 alloy

The success of stainless steel is based on the fact that it has one unique advantage. The chromium in the stainless steel has a great affinity for oxygen, and forms a molecular level film of chromium oxide on the surface of the steel. The film itself is about 130 angstroms in thickness. Stainless steel has good strength and resists corrosion and oxidation well at elevated temperatures. The alloy

Figure 2. Model-I: regular conical insert.

Table 8. Static displacement results.

Name	Type	Min	Location	Max	Location
Displacement	Resultant displacement	0 m	(19.5784 mm, 35.3416 mm, -18.0131 mm)	1.37082e-006 m	(-10.3415 mm, 28.3411 mm, -9.02658 mm)
		Node: 16		Node: 65,906	

Table 9. Static strain results.

Name	Type	Min	Location	Max	Location
Strain	Equivalent strain	2.94086e-010	(25.9452 mm, 4.86378 mm, -26.2428 mm)	8.26513e-005	(-3.91515 mm, 32.005 mm, -25.4337 mm)
		Element: 69,363		Element: 20,012	

Table 10. Max. von Mises stress results.

Name	Type	Min	Location	Max	Location
Stress	VON: von Mises stress	45.1611 N/m ²	(24.75 mm, 5.38 mm, -26.8911 mm)	2.18686e+007 N/m ²	(-10.9919 mm, 27.323 mm, -9 mm)
		Node: 67192		Node: 8438

Chart 1. Displacement vs load applied.

Chart 2. Equivalent strain vs applied load.

Chart 3. Max. von Mises stress vs applied load.

Table 11. Tibial component description.

No.	Body name	Material	Mass	Volume
1	Tibial component	SS316L	0.226534 lbs	1.32013 e-005 m ³

Table 12. Tibial component meshing information.

Jacobian check:	4 Points
Element size:	2.3643 mm
Tolerance:	0.11822 mm
Quality:	High
Number of elements:	9178
Number of nodes:	15,112

of stainless steel used in medical applications is stainless steel 316 (SS 316), the material composition and physical properties of which are shown in Tables 3 and 4, respectively.

Figure 3. Model-II: peg restrainer for the PE insert.

Figure 4. Static nodal stress – femoral component.

Figure 5. Static displacement – femoral component.

Figure 6. Static strain – femoral component.

Figure 7. Max. von Mises stress – femoral component.

Figure 8. Static nodal stress – tibial component.

4.2. UHMWPE

UHMWPE is a linear polyolefin resin with a molecular weight approximately 10 times that of high molecular weight and high-density polyethylene (HMW – HDPE) resins. The extremely high molecular weight of

the resin (4 to 5 million) yields several unique properties including an excellent combination of superior abrasion resistance and impact strength. The low coefficient of friction results in self-lubricating, non-stick surfaces.

Figure 9. Static displacement – tibial component.

Table 13. Static displacement results.

Name	Type	Min	Location	Max	Location
Displacement	Resultant displacement	0 m	(10.0197 mm, 17 mm, 13.5625 mm)	1.39789 e-005 m	(33.1183 mm, 3 mm, -15.1537 mm)
		Node: 34		Node: 1265	

Table 14. Static strain results.

Name	Type	Min	Location	Max	Location
Strain	Equivalent strain	6.6565e-009	(52.9948 mm, 19.8844 mm, 8.0946 mm)	0.000799011	(14.1853 mm, 5.5258 mm, 11.231 mm)
		Element: 7640		Element: 2770	

Table 15. Max. von Mises stress results.

Name	Type	Min	Location	Max	Location
Stress	VON: von Mises stress	915.49 N/m ²	(52.3826 mm, 19.4178 mm, 8.32522 mm)	1.77698e+008 N/m ²	(14.6547 mm, 5.31745 mm, 12.2757 mm)
		Node: 14,226		Node: 14,577	

5. Finite-element modelling of the artificial knee

Finite element analysis (FEA) has become commonplace in recent years, and is now the basis of a multibillion dollar per year industry. Numerical solutions to even very complicated stress problems can now be routinely obtained 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

Figure 10. Static strain – tibial component.

Figure 11. Max. von Mises stress – tibial component.

Figure 12. Static nodal stress – PE insert.

Table 16. PE insert component description.

No.	Body name	Material	Mass	Volume
1	Meniscal insert	UHMWPE	0.0404991 lb	1.20533 in ³

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.

5.1. Loading conditions for the analysis

The knee joint in normal conditions gets loaded with 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. (Sivarasu and Mathew 2007). We have taken as the load 10 times the body weight. The weight over a single knee is 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 is standing on one leg.

Table 17. PE insert component meshing information.

Jacobian check:	4 Points
Element size:	2.7041 mm
Tolerance:	0.13521 mm
Quality:	High
Number of elements:	8990
Number of nodes:	14,416

The loading conditions are shown in Table 5.

5.2. FEA the femoral component

The femoral component has the most complex design in the artificial knee. The femoral component description and meshing information are shown in Tables 6 and 7. For our analysis we have chosen 28 loading points and 2 restraints.

5.2.1. Loading the component

The loading is incremented in terms of 50 kg starting from 50 kg to 700 kg. That would be approximately 1.8 kgf load on each loading point for every load of 50 kg as shown in Figures 4–7; Tables 8–10; Charts 1–3;

5.3. FEA of the tibial component

The tibial component acts in the momentum balance in the design of the artificial knee. For our analysis we have

Figure 13. Static displacement – PE insert.

Table 18. Static displacement results.

Name	Type	Min	Location	Max	Location
Displacement	Resultant displacement	0 m	(-1.72877 mm, 0 mm, 1 mm)	1.80263e-005 m	(-9.82897 mm, 12.8297 mm, -21.5 mm)
		Node: 51		Node: 202	

Table 19. Static strain results.

Name	Type	Min	Location	Max	Location
Strain	Equivalent strain	7.33804e-006	(30.1021 mm, 12.0926 mm, -7.75031 mm)	0.00118532	(10.2657 mm, 0.688369 mm, -17.6769 mm)
		Element: 3115		Element: 2227	

Table 20. Max. von Mises stress results.

Name	Type	Min	Location	Max	Location
Stress	VON: von Mises stress	38754.8 N/m ²	(29.7798 mm, 12.4148 mm, 7.71442 mm)	8.34861e+006 N/m ²	(-9.82897 mm, 0 mm, -21.5 mm)
		Node: 14,383		Node: 207

Figure 14. Static strain – PE insert.

Figure 15. Max. von Mises stress – PE insert.

chosen single loading point and 4 restraints as shown in Tables 11 and 12.

5.3.1. Loading the component

The loading is incremented in terms of 50 kg starting from 50 kg to 700 kgs as shown in Figures 8–11 and Tables 11–15.

5.4. FEA of the meniscal insert

The meniscal component provides the rolling and gliding interface for the metal components of the artificial knee. For our analysis we have chosen 2 loading areas, i.e., the condylar contact areas. The FEA details are shown in Tables 16 & 17.

5.4.1. Loading the component

Total number of loading points: 2

Total number of restraints: 1

The loading is incremented in terms of 50 kg starting from 50 kg to 700 kg. A maximum load of 350 kg is applied over each loading point as shown in Figures 12–15 and Tables 18–20.

6. Results and discussion

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 shown in the Charts 1–3. The results have been encouraging in making the author move the model for prototyping.

7. 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.

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