Dynamic analysis and life estimation of the Artificial hip joint prosthesis

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Abstract. While discussing the hip joint failure, material selection and apposite dimension of the femoral head are a great concern for the artificial hip replacement. In this context, an attempt was made to optimize both ball head and socket material from different combinations like femoral head (metal) – acetabular liner (Polyethylene) and femoral head (ceramic) – acetabular liner (ceramic) in consideration of a different set of femoral ball head size of 28mm, 30mm and 32mm. The material and femoral head size were optimized in the perspective of minimum stress that eventually enhances the prosthesis life and minimizes the wear of counter bodies. The hip joint prosthesis was designed in CATIA followed by Finite element analysis (FEA) was performed in ANSYS 17.2. Dynamic FEA was performed when the 100kg human in jogging. A theoretical optimization established the combination of ceramic-ceramic articulating body consist of 30.02mm ID acetabular liner – 30mm OD femoral head made of zirconia toughened alumina (ZTA) experience less stress and deformation that eventually exhibit very low wear rate per cycle of jogging. This design exhibits 0.629mm wear depth after 10years of activity; however, similar theoretical analysis can be done under different degree of dynamic motions. The proposed material and design combination has excellent potential for the artificial hip joint.

Keywords: Total hip replacement(THR), Prosthesis, Dynamic analysis, ZTA, wear.

1 Introduction

The hip joint is ball and socket joint, where femoral head is a ball, and the socket is the acetabulum. Its primary function is to support the weight of the human body both in static (Standing) and dynamic (Walking and Running) positions and found as the most significant and most reliable joint in the body. Total hip replacement (THR) is a joint replacement surgery used to replace damaged, arthritic hip joint with an orthopaedic prosthesis. Instability and dislocation are the main problems for the failure of THR. Dislocation rates are 0.5% to 10% for primary THR [1] and 10% to 25% for revision THR [2]. Dislocation mainly two types, early and late dislocation. The early dislocation occurs due to the impingement of the femoral neck from the acetabular liner cup lip, and the late dislocation is due to wear rate. The paper is focused to generate the stresses in the hip joint and analyse the wear of the hip joint. To estimate the stresses a Finite element analysis was performed. In the present hip joint prosthesis is made of components femoral stem, femoral head, acetabular liner and acetabular socket. The femoral stem fixed in femoral bone F, and the acetabular socket fixed in acetabular bone A. The dynamic analysis was performed used a slow jogging load.

2 Finite element modelling of hip joint

The Fig.1. Represents Hip joint model developed using CATIA modelling software. The femoral stem, femoral head, an acetabular liner, acetabular socket, femur bone (bone F) and Acetabular bone (bone A) separately built and assembled using CATIA assembly options. Three different hip joint models developed in CATIA. The three models are 28mm head THR model, 30mm head THR model and 32mm head THR model.

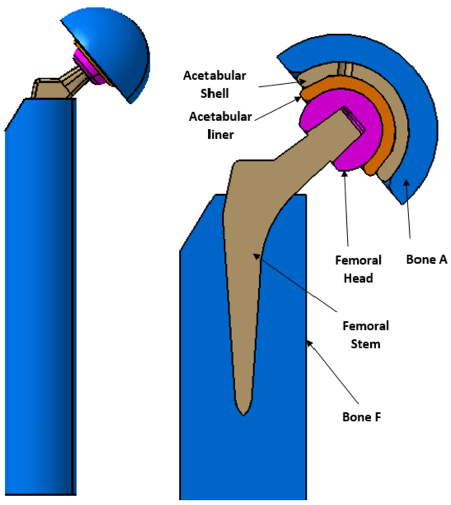


Fig. 1. Schematic representation of THR model system.

Three femoral head of size 28mm, 30mm, and 32mm designed for analysis. To accommodate femoral head in three acetabular liners were designed to match the femoral head with a radial clearance of 100µm. The acetabular liner inner and outer diameter are 28.02/38mm, 30.02/40mm, and 32.02/42mm, respectively. The inset distance of 28mm, 30mm and 32mm head are 2.93mm, 3.11mm and 3.28mm respectively.30mm femoral head and acetabular liner with dimensions shown in fig.2.

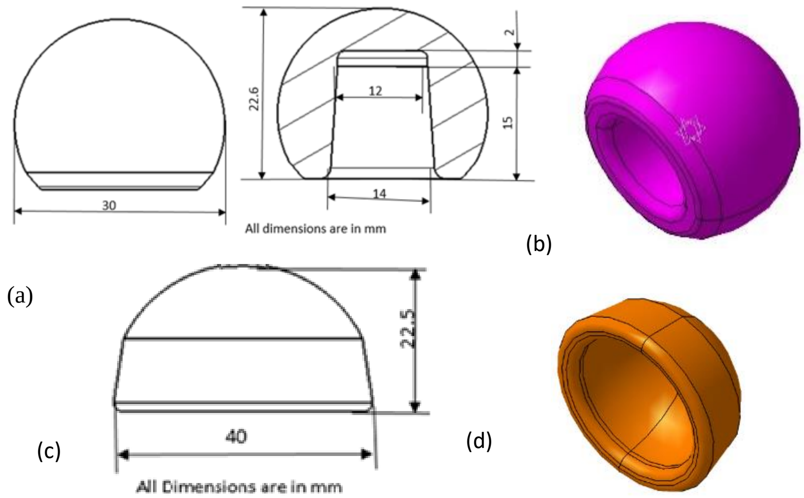


Fig. 2. (a) Femoral head dimension (b) Femoral head CAD model
(c) Acetabular liner dimension (d) Acetabular liner CAD model.

The femoral stem designed with stem length 81.73mm, vertical height 24.65mm, medial offset 38.58mm, neck length 30.03mm, taper angle 12/14 and neck shaft angle 130^{o}. The acetabular socket inner and outer diameter are 38.02/48mm, 40.02/50mm, and 42.02/52mm for 28mm, 30mm and 32mm femoral head respectively was maintained. All the three models exported into ANSYS 17.2. THR models finely mesh through ANSYS with element size as 2.5mm with tetrahedral elements. The meshed 28mm, 30mm and 32mm THR models has nodes 4,21,960 & elements 2,90,078, nodes 4,30,105 & elements 2,95,434 and nodes 4,39,268 & elements 3,01,434 respectively.

3 Material properties of THR model

Two bearings considered for analysis of each model, i.e., ceramic head/ceramic liner, metal head/Polyethylene liner. The material used for ceramic head & ceramic liner bearing is ZTA composite (95wt% Al_2O_3,5wt% 3YSZ) and the materials used for metal head & Polyethylene liner are Ti6Al4V & UHMWPE. All materials are assumed to be homogeneous, isotropic and linear elastic. By using the rule of the mixture the ZTA composite young's modulus 375GPa and poison's ratio, 0.3 calculated. The essential material properties required for the FEM analysis tabulated in Table.1.

Table 1. Properties of materials for FEM analysis [3].

Sl.No.	Material	Young's Modulus (GPa)	Poisson's Ratio	Mass Density (g/cm^3)	Yield Strength (MPa)
1.	Alumina (Al_2O_3)	380	0.3	3.95	665
2.	Zirconia (ZrO_2)	210	0.3	6.05	711
3.	Ti-6Al-4V	110	0.3	4.5	800
4.	UHMWPE	1	0.4	0.93	23.56
5.	Simulative Bone	20	0.3	1.932	-

4 Loading and boundary conditions

An average human load 100kg considered for analysis. The boundary conditions for the dynamic load applied in this work are normal to hip joint. The loads were determined from experimental observations of G-Bergmann et. al [4]. The high contact forces and also with the friction moments in the joints has the danger of fixation of the acetabular socket, the failure of various implants is due to cup loosening [5-7]. It is important to use moments to identify the effect of cup fixation. In addition to the contact forces & moments, the coefficient of friction between the components affect the loads in the THR assembly. Among the daily activities, the jogging considered for dynamic analysis. The contact forces are maximum during slow jogging at 7km/hr. The 4839N force act on the femoral head was 68% higher than during walking and nearly five times the BW(100kg). The jogging load illustrated in fig.3 (a). Which represents the loading pattern, the maximum load applied at 2sec of load cycle of 4839N and 0.8Nm.

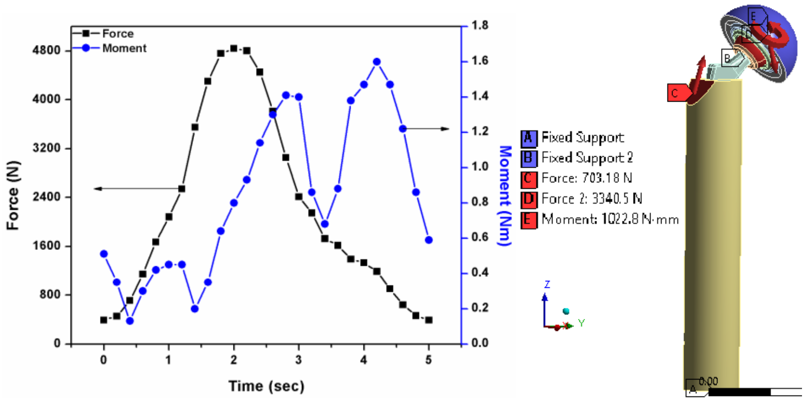


Fig. 3. (a)The variation of force and moment applied on the prosthesis during jogging. (b) Loads and boundary conditions on THR model system.

Another force abductor muscle force determined from Tsouknidas et al [8]. The abductor muscle force of 703N is applied to the bone F to counter the femoral head force. The base of bone F and the top surface of Bone A fixed in all directions. The fig.3(b). Represents the dynamic loading and boundary conditions of THR model.

The frictional coefficient of bearing interface varies with bearing materials. According to Bergmann et al. [9], the coefficient of friction between metal on metal bearing was between 0.1 and 0.2. Fialho et al. [10] used the coefficient of friction 0.05 for ceramic on the ceramic bearing to calculate frictional heating. Jun Qu et al. [11] claimed that the coefficient of friction between Ti6Al4V and Alumina as 0.44. According to Rancourt et al. [12] the coefficient of friction between the interface between porous-surfaced metals and tibial cancellous bone was in between 0.3 and 1.3. The coefficient of friction between alumina on alumina bearing was 0.05-0.1. [13] The coefficient of friction was 0.55 between Ti6Al4V and UHMWPE under bovine serum [14].

In the present study, therefore the coefficient of friction between simulative bone and metal was considered as 0.2. The coefficient of friction between metal on metal bearing as 0.2, the coefficient of friction between ceramic on the ceramic bearing as 0.2, the coefficient of friction between metal and Polyethylene bearing as 0.15 respectively. The coefficient of friction between metal and ceramic took as 0.2 for analysis.

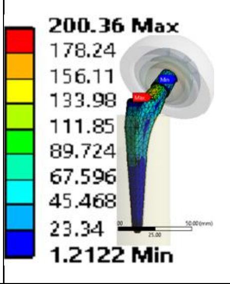
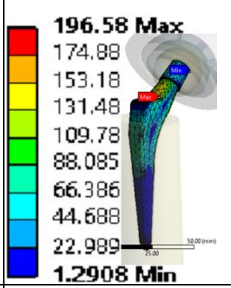
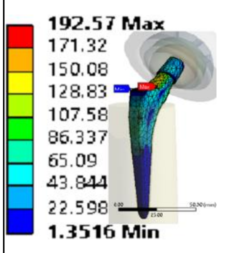
5 Results for dynamic analysis

The idea of analysis of two bearings and three head sizes is to analyze the stress and deformation on the dynamic load during jogging. The analysis of two bearings with three heads are tabulated in Table.2. The von mises stress obtained from the dynamic analysis in ceramic/ceramic bearings are 182.33, 180.88 and 179.5MPa for 28,30and 32mm head, as the head size increased the stress values decreased. The same was observed in metal/polyethylene bearing.

All the von mises stress developed in both bearings are lower than the yield stress of prosthesis material. The results of dynamic analysis show maximum stress concentrated on the upper neck portion of the femoral stem hip joint compared to femoral head and acetabular liner. For all THR model Ti6Al4V material is used for the femoral stem, hence maximum stresses generated in the stem. The von mises stress decreased with the increase of the head size due to increase in the area of the bearing load. The stress generated in the bone for the two bearings are in the range of 7-20MPa which is less than the yield strength of bone (104-121MPa).

The Z- component load of jogging has a significant effect on the deformation of the femur bone. In case of metal on Polyethylene bearing the maximum deformation was observed in femoral head as the acetabular liner material was polyethylene and in case of ceramic and ceramic bearing the deformation observed in the metal acetabular socket as both femoral head and acetabular socket ceramic material used.

Table 2. Dynamic analysis: The von mises stress and total deformationof three 28, 30 and 32 THR models with two bearings.

<table>
<tr><th></th><th></th><th>28mm</th><th>30mm</th><th>32mm</th></tr>
<tr><td rowspan="2">Metal/Polyethylene bearing</td><td>von mises stress (MPa)</td><td>
</td><td>
</td><td>
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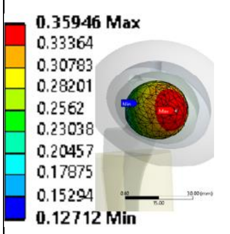
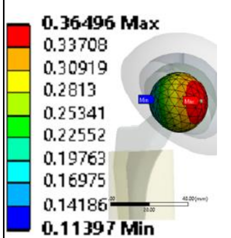
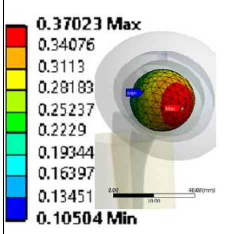
<tr><td>Total deformation (mm)</td><td>
</td><td>
</td><td>
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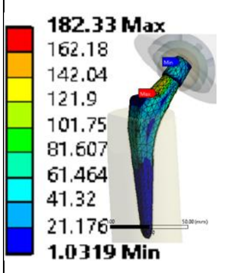
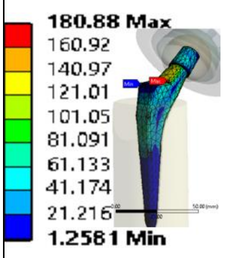
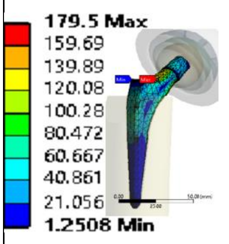
<tr><td rowspan="2">Ceramic/Ceramic bearing</td><td>von mises stress (MPa)</td><td>
</td><td>
</td><td>
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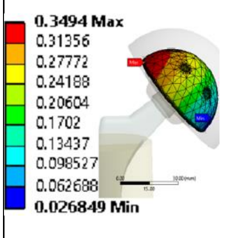
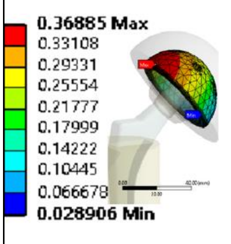
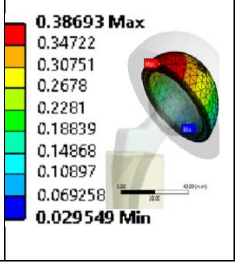
<tr><td>Total deformation (mm)</td><td>
</td><td>
</td><td>
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In a combination of different materials and head size, von misses stress, total deformation and equivalent elastic strain are calculated and found ceramic-ceramic bearing surface is the best choice compared to metal/polyethylene bearing, as it has less stress and deformation. Among the three heads 30mm ceramic is considered as optimum ceramic femoral head, as it has a high degree of freedom and lower size 28mm results dislocation under continuous activity, but higher size 32mm experience more deformation compare to other sizes.

6 Wear of 30mm ceramic/ceramic bearing total hip replacement

Wear is the gradual removal of material from the surface of the body. The wear of hip prosthesis is due to contact of components, sliding distance and tribological properties of materials used. Archad's law was used to estimate the wear [15].

V=Kw X S X Pn where V is the volume of wear debris produced, S is the sliding distance, Pn is the contact pressure.

dV=ΔAdh =Kw X σ X A X ds

dh =Kw X σ X ds.

Wear coefficient (Kw) is a function of material properties and counterface roughness and can be obtained experimentally. Wear coefficient is determined from the ball on disk experiment [16], and for Al_2O_3 and ZTA combination, it is 5.3E-8 mm3/Nm. The calculated maximum contact pressure (σ = 56.75 MPa) and assuming no change in socket geometry, wear depth (dh) can be estimated for known sliding distance (ds).

The sliding distance was considered from walking cycle, walking cycle has motions of hip flexion, extension, adduction, abduction and internal-external rotation. The flexion and extension have more contributions compared to other motions. In half walking cycle, the flexion angle is 23° and extension angle is 17°. In the complete walking cycle, hip joint rotates through 80°. In the present study, the radius of femoral head 15 mm is considered for analysis.

Total hip rotation in one cycle =80°= 1.396rad

Sliding distance (ds)= head radius X rotating angle

= 15 X1.396 = 20.94mm =20.94E-3m

Wear depth (dh) using Archad's law.

Wear depth (dh) =Kw X σ X ds.

= 5.3E-8 X 56.75 X 20.94E-3

= 6.298E-8 mm/cycle.

Average human takes one million steps in one year; the wear rate was estimated to be 0.062mm/year. After 15 years 0.93mm of wear depth takes place at a constant point.

7 Conclusion

A typical 28,30,32mm THR model designed with components femoral stem, femoral head, acetabular liner and acetabular socket and the appropriate material is used for dynamic analysis. The load considered as high as 100kg for dynamic analysis analogous to slow jogging. During dynamic analysis, the stress generated in the THR components is less than the yield stress of the prosthesis material used. Hence the design is safe in the human body. The high stresses are observed in the femoral stem neck region. The wear is estimated by using Archad's law, wear depth of 0.062mm/year has calculated for the 30mm femoral head of ZTA material. Based on the wear of femoral head it is assumed that the hip joint is safe for 15years.

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