Finite Element Study of Acetabular Cup Contact Region for Total Hip Replacement (THR)

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ABSTRACT

Revisions of total hip replacement are caused by many factors. Dislocations, edge-loading and excessive contact pressure at the articulate surface of the acetabular component are among the factors of Total Hip Replacement (THR) failure which required revision. This study aims to simulate the acetabular components for THR with various parameters that may improve the implant lifespan in mechanical aspect. A 3D model of acetabular components is imported into ANSYS WORKBENCH V15 with a different acetabular cup orientation and different femoral head size. Meanwhile, other component parameters at acetabular region are maintained with respect to femoral head size for comparison failure analysis studies. The results showed an increasing of femoral head size diameter from 28mm to 36mm at all selected orientations; the Contact Pressure will reduce by 45% and will improve the Von Mises Stress of about 32%. The Total Deformation value has also improved by 48%. A new parametric study was done by considering an anteversion angle (β). This result indicates that bigger head and even anteversion angle (β) included may also improve the longevity of the prosthesis and boost the articulate motion between the head and acetabular cup. The pressure was distributed evenly at the inner side of the acetabular cup; thus, reduced the excessive contact pressure at the superior region.

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Introduction

Diseases such as osteoarthritis, rheumatoid arthritis, bone tumors or traumas are critical issues that require Total Hip Replacement(THR)[1]. However, the life expectancy of the hip prosthesis remains challenging as it possesses a limited lifespan of around 15 years only [2]. Researchers intended to increase the lifespan of the hip implant with the aim of studies to overcome the mode of failure that required THR to be revised.

Many factors contributed to the hip prosthesis failure that eventually required revision. Among the top issues raised are aseptic loosening, dislocations, edge-loading and excessive contact pressure at the superior region of the acetabular cup[3]–[6]. These factors are interrelated among them as dislocation is induced by the edge-loading effect and excessive contact pressure inside the acetabular cup upon doing daily living activities (ADL). Meanwhile, impingement is a term that introduced the meaning as the unnecessary contact between the femoral head and acetabular cup. It is believed that recurrent impingement induced dislocation will cause THR failure especially on the material used[8, 9]. Previous studies mentioned that multi-factorial could lead to the dislocation especially on the design of the acetabular components, femoral head size, head-neck diameter ratio, component orientation and femoral offset[3, 6, 10]. Edge-loading and excessive contact pressure is associated with improper orientation that will allow indentation deformation in the superior region of the acetabular cup and substantially increase equivalent plastic strain of the polyethylene liner[5].

To halt THR to be revised, the range of motion (ROM) must be complied; thus, the dislocation risk can be minimized. Based on previous studies, mathematical models are developed with their own parametric studies and results are promising on avoiding dislocation issue and excessive contact pressure inside the acetabular cup[9, 11]. The ROM is defined differently by every researcher based on their support finding and it is one of the main criteria to avoid dislocation and edge-loading effect.

Wang *et al.*[11] reported on hard on hard bearing combinations that maximum contact pressure decreased more than 79% even with a slight increase of 0.5mm major radius of the acetabular component. Acetabular component orientation, especially on the inclination angle, also affects the contact pressure since cups oriented more than 40° will induce failure[12]. However, there is still a conflict on defining proper safe zone orientation of acetabular cup, yet Lewinnek *et al.*[13] safe zone is widely referred at the range of 30°-50° inclination angle and 5°-25° anteversion angle. A study on cemented hard on soft bearing acetabular components showed that inclination angle of 65° and above had a significant increase in Contact Pressure and Von Mises Stress[14]. Meanwhile, a case study showed that too big femoral head diameter of more than 36mm was not appropriate for the hard on soft THR[15]. Based on contact mechanics, it reveals that finite element studies results suggested that steep cup inclination potentially facilitates the edge-loading effect on hard on soft bearing acetabular components[16]. Thus, this study will commence on the effect of femoral head size combined with various orientation parameters towards the contact region of acetabular component based on finite element modeler.

Material and Method

In this study, the focus will be on the hard on soft bearing combination with the femoral head and metal backing acetabular component assumed as stainless steel and represented by a sphere and cup respectively. The usage of metal backing cup procedure means that we intended on doing the simulation on the cementless acetabular component as the cementless acetabular component has better bone ingrowth on the younger patient[17]. As our studies are comparing the two types of acetabular components with different size of femoral head, we chose the typical size of 28mm diameter head size versus 36mm diameter head size. The 36mm diameter head size is considered as the maximum allowed size for the hard on soft bearing combination[15]. We have done the mathematical modelling previously to find the optimum safe zone orientation angle based on the Equation (1) that sums up all the MATLAB commands[18]. Figure 1(a) shows the schematic diagram of prosthetic cone where A is the maximum angle of the radius movement in the cup, n is the neck width at the impingement level and r is the radius of the head.

$$\theta = A - 2\sin^{-1}\frac{n/2}{r} = A - 2\sin^{-1}\frac{1}{head/neck} \tag{1}$$

For the simulation in Finite Element Analysis (FEA), we adopted the contact analysis formulations as shown in Figure 1(b) where the bearing surface articulations between femoral head and cup are highly conforming and usually modelled as a ball-in-socket geometry (Equation 2-5) based on Hertzian Contact Theory[1]. Eliminating the surface roughness, the notations of R_1 and R_2 are characterized by the head and cup radii, respectively, giving a radial clearance $c = R_2 - R_1$ as shown in Fig. 1. Meanwhile, simpler configuration will yield the effective radius R' and elastic modulus E^* where

E_1, v_1 and E_2, v_2 are the Young's Modulus and Poisson Ratio of the head and cup material, respectively

$$\frac{1}{R'} = \frac{1}{R_1} - \frac{1}{R_2} = \frac{c}{R_1(R_1 + c)} \tag{2}$$

$$\frac{1}{E^*} = \left(\frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \right) \tag{3}$$

From the theory, theoretical Total Elastic Displacement d can be calculated based on Equation (4) given the amount of force exerted, F on that configuration.

$$F = \frac{4}{3} E^* R'^{1/2} d^{3/2} \tag{4}$$

Applying the Hertzian Theory for a static dry contact will yield the radius of the contact area, a as shown in Equation 5.

$$a = \sqrt[3]{\frac{3FR'}{2E^*}} \tag{5}$$

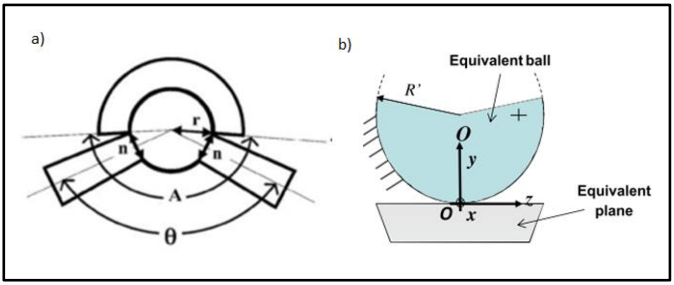

Figure 1: (a) Schematic diagram prosthetic range of motion cone, (b) configurations for hip implants contact theory where y is the vertical direction[1], [18]

Both combinations of acetabular components are positioned at 0°, 40°, 50° and 70° based on the fact that we want to analyze the failure of inclination angle upon different femoral head size and benchmarking it with Korduba et al.[12]. Addition to that orientation variation, we also take into account the previous studies which mentioned that range of safe zone orientations are assumed as the maximum of 42° inclination with 10° anteversion for 28mm femoral head and 48° inclination with 4° anteversion for 36mm femoral head size[18]. This means that we also considered the anteversion angle not just based on inclination angle only. The inclination and anteversion angles should be set first in SolidWorks drawing phase before converted into IGS format files. Proper orientation should be taken into account before the IGS files format is run into ANSYS WORKBENCH prior to Static Structural mode analysis.

Both combination components are drawn in SolidWorks with various orientation mentioned before and imported as IGS files to the ANSYS WORKBENCH v15. Fig. 2 shows an example in determining the orientation upon inclination and anteversion angle that is being performed in SolidWorks using TRIAD command. The inside diameter size of the acetabular cup and metal backing are with respect to the two mentioned before femoral head size which the thickness of metal acetabular component and acetabular cup (poly component) as 4mm and 7mm, respectively.

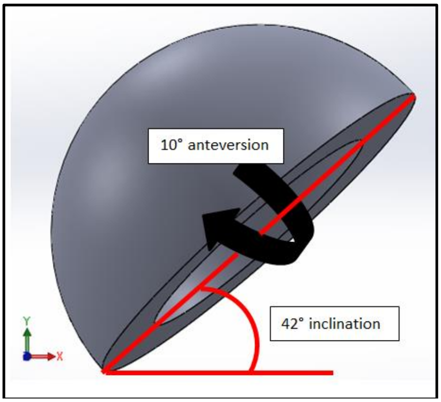

Figure 2: 42° inclination angle combined with 10° anteversion angle which represents as the maximum allowable orientation using 28mm femoral head size

Meanwhile, the acetabular cup was considered as ultra-high molecular weight polyethylene (UHMWPE) based on the recent material used for hard on soft bearing articulation. To simulate static linear elastic behavior with isotropic properties, we adapt from the research using Young's Modulus and Poisson's ratio of 945MPa and 0.45 respectively[7]. The femoral head and metal backing were modelled as a rigid body to reduce the computational time and also given the fact that the value of stainless steel Young's Modulus is too high. Thus, no deformation will be encountered on these two parts. The contact between the rigid femoral head and UHMWPE acetabular component were modelled as frictionless as the aim is to study the Contact Pressure between these articulate surfaces. The models were meshed with 10-noded solid tetrahedral elements and the size of the contact element between femoral head and acetabular cup was set at 1mm.

Remote displacement was applied to the femoral head in order to constrain its rotation. Besides, estimation load of 2450N vertically[12] in Y-axis direction is acted upon the center of femoral head. Fixed support is set on the acetabular cup outer surface when loading was applied. The loading conditions were assumed as the maximum applied load which is about two-three times of body weight even though there are variant forces upon different gaits which could reach up to five times body weight[15, 20].

Result and Discussion

The results of the FEA indicated that Contact Pressure (MPa) increased with higher cup inclination angle for both combinations. For the 28mm diameter femoral head, the highest Contact Pressure was found at 70° inclination angle (18.90MPa) and the lowest at 0° inclination angle (5.98MPa). On the other hand, 36mm diameter femoral head resulted the highest Contact Pressure which was found also at 70° inclination angle (9.83MPa) and the lowest at 0° inclination angle (3.64MPa). Table 1 indicates the maximum value of Contact Pressure based on the benchmarking inclination angles of 0°, 40°, 50° and 70° degrees.

Table 1: Comparison of The Results of Contact Pressure Analysis

Inclination Angle (α)	**Anteversion Angle (β)**	**28mm femoral head (MPa)**	**36mm femoral head (MPa)**
0°	0°	5.9825	3.6440
40°	0°	8.7251	4.4975
50°	0°	12.051	5.3197
70°	0°	18.889	9.8289

From Table 2, we could see that no data was included at 48° inclination angle combined with 4° anteversion angle as the study shows that this angle is not considered as the safe zone orientation for 28mm femoral head. The range of motion at postoperative surgery could not be achieved; thus, it easily fails. In other words, using 48° inclination angle with 4° anteversion angle for 28mm femoral head diameter will induce dislocation. These assumptions also applied for the 36mm femoral head diameter.

Table 2: Comparison of Contact Pressure and Anteversion Angle Analysis

Inclination Angle (α)	**Anteversion Angle (β)**	**28mm femoral head (MPa)**	**36mm femoral head (MPa)**
42°	10°	7.4271	N/A
48°	4°	N/A	5.1500

In terms of Von Mises Stress, the results shown in (Figure 3) histogram indicates that the maximum Von Mises Stress happened at 70° inclination angle for both types of acetabular components combination. For 28mm femoral head, the highest Von Mises Stress was recorded at 70° inclination angle 17.63MPa and the lowest at 0° inclination angle with a value of 3.66MPa. For 36mm femoral head, the highest Von Mises Stress was also recorded at 70° inclination angle at 12.42MPa and the lowest at 0° inclination angle at 1.88MPa.

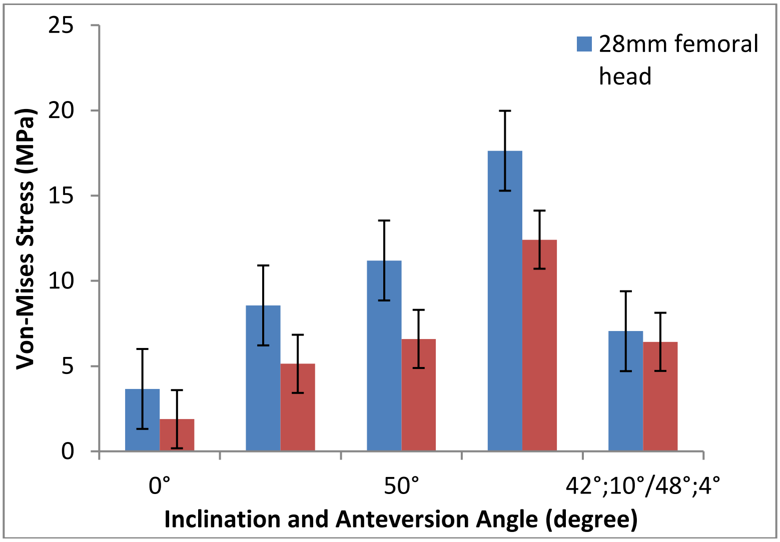

Figure 3: Comparison on Von-Mises Stress Distribution for 28mm and 36mm femoral head diameter

Total Deformation for the acetabular components also plays a vital role in discussing the failure of this implant. The graph of comparison for different orientation can be seen in Figure 4. The highest Total Deformation recorded for 28mm femoral head is at 70° inclination angle (0.13773mm) and the lowest at 0° inclination angle (0.0217mm). Total Deformation of 36mm femoral head also exhibits the trend that shows the highest Total Deformation occurred at 70° inclination angle (0.066767mm) and the lowest at 0° inclination angle (0.013318mm).

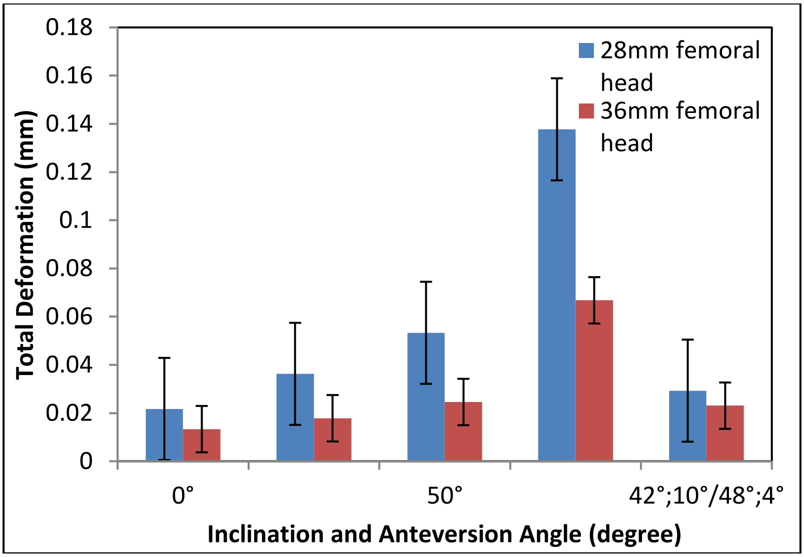

Figure 4: Comparison on Total Deformation for 28mm and 36mm femoral head diameter

Figure 5 shows the example contour results from the finite element analysis of the maximum and minimum of the Contact Pressure when dealing with 28mm and 36mm femoral head with respect of different inclination and anteversion angle. We could see that the contact region inclined towards the superior region of the acetabular cup when a higher inclination angle is chosen. However, an observation at the inclination angle at 40° between both sizes exhibits that the contact area patch is wider on the 36mm femoral head diameter compared to 28mm femoral head diameter. Additional to that, their highest Contact Pressure occurred at a region slightly lower from the superior region.

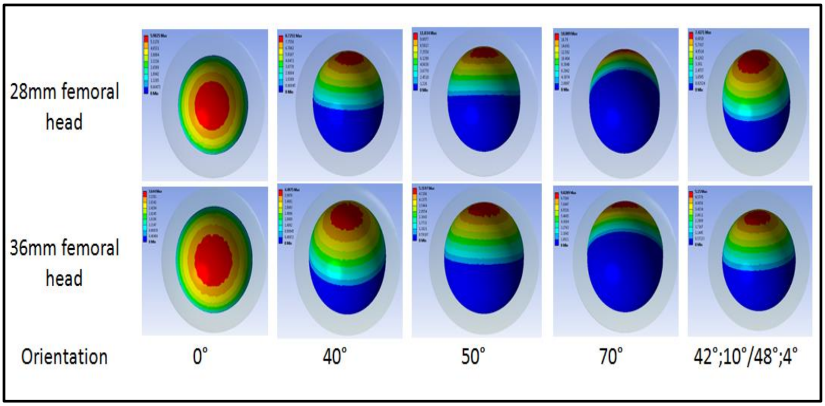

Figure 5: Contour analysis between two types of acetabular components with different orientation angle. Contour patch excessive at the rim superior region of acetabular cup for 50° and 70° inclination angle for both cases.

The results data of our finite element in terms of Contact Pressure using 28mm femoral head are consistent with the simulation work done by Korduba *et al*.[12] for four different inclination angles (α). We tried to replicate the methodology from them by using finite element methods and the errors shown were less than 12% which was in good agreement with our work. In addition to that, we also computed the mathematical formulation based on Hertzian Contact Theory in order to compare the Total Deformation at 0° for both numerical and simulations and the errors shown were about 11.3%.

We achieved our new findings upon acetabular components by adding new parametric studies which included the maximum safe zone orientation, anteversion angle (β) and bigger femoral head diameter. In addition to that, Von Mises Stress analysis and Total Deformation analysis were also taken into account as we intended to improve the information results being done by Korduba *et al*.[12]. Their work was mainly focused on the wear mechanism and wear generation on the inclination angle (α) only.

Moreover, we also analyzed a new set of acetabular component that is more stable upon dislocation and reduce excessive Contact Pressure at the superior region of the acetabular cup. Based on our results of previous studies, this work also takes into consideration the range of motion that is correlated with proper safe zone orientation with respect to the femoral head size[18] for the hard on soft bearing articulation. We added a new parameter aspect in which we included anteversion angle (β) into the finite element studies as this parameter was almost neglected when dealing with the orientation of acetabular cup in the case of using finite element method.

The results of Contact Pressure (MPa) and Von Mises Stress (MPa) are consistent with both types of acetabular components combinations in which the values of both analyses increased with a higher inclination angle (α). The contours of Contact Pressure are getting smaller and concentrated with a higher inclination angle (α). When the inclination angle (α) is at a maximum of 70º, the contact areas are concentrated in the superior region in only both types of acetabular components. However, a new set of using 36mm femoral head seems to get a lower value of Contact Pressure and lower Von Mises Stress. The data exhibited in the FEA are in agreement with previous studies that stated a larger femoral head will reduce the excessive Contact Pressure and provide more stability as the pressure is reduced when higher contact area is achieved[8, 21, 22].

In terms of Total Deformation, combinations that produce less deformation are better as it will allow smooth movement inside the articulating surfaces and delay the indentation deformation that may occur. From the results, we could see that 36mm femoral head size gives a minor and lesser deformation as compared to 28mm femoral head. However, in deliberation of using 28mm femoral head, it is highly recommended to include the anteversion angle (β) when considering the placement of acetabular cup. This is because the Total Deformation reduction is higher when considering placement at 40° inclination angle (α) but increasing the inclination angle (α) to 42° combined with 10° anteversion angle (β) will reduce the Total Deformation of about 19%.

Conclusion

Finite element methods are considered a powerful method in analyzing the effect of the contact region of acetabular cup with different orientation and different acetabular component sizes. Three main analyses results which are the Contact Pressure, Von-Mises Stress and Total Deformation prove that bigger femoral head with appropriate anteversion angle (β) of acetabular cup will reduce the excessive Contact Pressure at the superior region of the acetabular cup. Too steep inclination should also be avoided during the placement of acetabular components as edge-loading may occur during daily activities. This study is important not as a precaution of avoiding dislocation but also the deformation that may occur particularly in the superior region of the acetabular cup.

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