Anatomical modelling and simplified modelling in total hip replacement: difference in contact mechanics perspective

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Abstract. Total hip replacements (THR) is a surgical operation to replace defect bone at the hip joints. The rate of success of THR post-operative still debatable as complication and failure rate of the prosthesis still exists. Edge-loading, dislocation, fracture and longevity are among the concerned issues with many studies were conducted via software analysis. This study aims to simulate the difference of anatomical and simplified modelling in finite element analysis (FEA) and investigate edge-loading effect at different inclination angle in both modelling conditions. A CT scan hemi-pelvic model was reshaped and converted into 3D model in SolidWorks and the next step, FEA was conducted in ANSYS Workbench V16 at different inclination angle. Anatomical and simplified model were run in ANSYS Workbench and the results were recorded. The anatomical modelling produced less contact pressure range 26% to 51% compared with simplified modelling at four inclination angle conditions. Von Mises stress and total deformation in anatomical also produced reduction of more than 65%. Both modelling conditions shows agreement that elevated inclination angle had induced higher contact pressure at superior region of acetabular cup. The inclusion of hemi-pelvic model gives lower value recorded in FEA as contact stress dispersed into the bone that already integrated with the implant given statistically significant (p<0.05). Noteworthy to include bone integration into implant during FEA study to produce unambiguous contact mechanics studies.

1. Introduction

A hip joint replacement known as THR was considered a successful intervention in orthopaedic field for hip joint related disease. Despite the successful outcomes, the clinical complications and unexpected failure of the prostheses remains concerned. Issues such as aseptic loosening, bone-implant interface, dislocations, edge-loading effect and superior region defect of the acetabular cup are among the top complication related to THR that required revision [1–4]. The contact of the femoral head on the edge of superior region acetabular cup was observed as the edge loading effect. In numerical aspect, the articulate contact patch between femoral head towards to the extended rim of the acetabular cup was known as true edge loading effect [5, 6]. The complications upon THR are interrelated among them as dislocation was induced by the edge-loading effect and excessive contact pressure inside the acetabular cup upon doing daily living activities (ADL). Studies shows that edge loading may reduce the efficiency of the tribological performance of the articulate contact [7–10].
The occurrence of edge loading was being discussed with numerous previous studies [11, 12]. Influence of femoral head size [13], acetabular cup design[14], safe zone orientation[15, 16] and impingement[17] are among the issues that will leave adverse effect post-operational THR. There are three types of acetabular components; Metal-on-Metal (MoM), Ceramic-on-Ceramic (CoC) and Metal-on-Polymer (MoP). Studies shows that edge loading in MoM and CoC could produce faster articulate wear, malpositioning and fracture of the materials [18]. Meanwhile, studies conducted on MoP indicated that edge loading does not particularly induced rapid wear, but stress and plastic strain substantial increasing will lead to fatigue and fracture [19].

The aims of the present study were, firstly to determine the difference of anatomical modelling and simplified modelling of THR contact analysis, and secondly, to inquire the edge loading effect of inclination angle in FE model analysis during normal walking (NW) gait cycle at both conditions.

2. Material and Methods
This study was conducted at hard on soft bearing combination of THR. A typical modular MoP total hip replacement system, consisting of metal shell, polyethylene liner and metallic femoral head, was analysed. The nominal diameter of femoral head and polyethylene liner were 28mm and 28.6mm respectively, giving a radial clearance of 0.3mm. The outer diameter of the acetabular component was at 50mm. A hemi-pelvic bone CT-scan format was obtained from one of the patients from USM Kubang Kerian with consent. The irregularity of the hemi-pelvic bone was removed by using Mimics software.

The hemi-pelvic bone model consists of cancellous bone surrounded by cortical shell. The Hounsfield Unit used for the segmentation process was chosen to be 1035 to eliminate unnecessary element such as tissue or blood vessel. The thickness of the cortical shell was at 1.5mm. The acetabular subchondral bone was assumed to have been reamed completely prior to implantation.

All the materials in the FE model were modelled as homogenous, isotropic and linear elastic except the polyethylene liner which was modelled as non-linear elastic-plastic with the plastic stress-stain constitutive relationship [20]. The mechanical properties of the materials are shown in Table 1. The femoral head was considered as rigid material to reduce computational time. A mesh sensitivity studies were carried out at the contact condition of femoral head and acetabular cup in order to optimize the computational efficiency. The anatomical finite model was comprised of approximately 26133 nodes and 14436 elements with solid tetrahedral dominant element as it produces faster convergence.

| Component         | Materials   | Young’s modulus (GPa) | Poisson’s ratio |
|-------------------|-------------|-----------------------|-----------------|
| UHMWPE cup        | UHMWPE      | 0.95                  | 0.3             |
| Acetabular shell  | Titanium    | 117                   | 0.25            |
| Cortical shell    | Cortical bone | 17                 | 0.3             |
| Cancellous bone   | Cancellous bone | 0.8            | 0.2             |

The contact interference of the anatomical model of hemi-pelvic and Titanium shell was assumed as fully bonded, while the contact of femoral head and UHMWPE liner was assumed frictionless. Full constrained at sacroiliac joint and pubic symphysis for the anatomical model where on contrary, the Titanium shell was assumed as fully constrained for the simplified model. The femoral head was constrained at rotational movement and only allowed at translational movement freedom for both models. The loading exerted was at 2450N in vertical component direction via gait studies conducted by [23] where the loading assumed at normal walking (NW) condition. The coordinate system of anatomical model was assumed to be aligned with in vivo study of pelvis coordinate system.
Figure 1. The FE modelling and the boundary condition. a) Anatomical model b) Simplified model

The FE simplified model was validated by Korduba et al.[21] and Hertzian Contact Theory at static dry contact. 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. 2. Meanwhile, simpler configuration will yields 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. Elastic deflection of the surface under applied pressure is given by the following relation where is the elastic deflection.

\[
u_z(x, y) = \frac{2\pi}{E'} \iint \frac{p(x', y')}{\sqrt{(x - x')^2 + (y - y')^2}} dx' dy'
\]  

\[
1 = \frac{1}{R_1} - \frac{1}{R_2} = \frac{R_1(R_1 + c)}{c} 
\]  

\[
E' = \left( \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \right) 
\]  

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.

\[
F = \frac{4}{3} E'R^{1/2}d^{3/2}
\]  

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

\[
a = \frac{3}{2} \frac{3FR'}{E'}
\]
Figure 2. Ball-in-socket configuration a) ball-on-plane geometry b) setup for hip implants, where y is the vertical direction [24]

3. Results and Discussion
The contact pressure of Korduba Model and Simplified Model shows good agreement with less than 12% error which indicate the method was run as perfectly in well-mannered. From the analysis, anatomical model shows reduction of contact pressure at almost 30% for 40° and 50° inclination angle compared to simplified model as shown in Figure 3. On the other hand, the contact pressure reduction of more than 50% was recorded at 70° inclination angle for the anatomical model. Based on Hertzian Contact Theory, model also shows good agreement of less than 10% error. The values of simplified model at 0°, 40°, 50° and 70° inclination angle were 5.98MPa, 8.72MPa, 11.03MPa and 18.89MPa, respectively. Meanwhile, the values of anatomical model at 0°, 40°, 50° and 70° inclination angle were 3.41MPa, 6.43MPa, 7.82MPa and 5.90MPa, respectively.

Figure 3. The contact pressure of acetabular components in three different model at different inclination angle

In term of Von Mises stress analysis, elevating the inclination angle of acetabular components showed Von Mises stress increased in both anatomical and simplified model. In spite, the reduction of Von Mises stress was higher in anatomical model compared to simplified model which recorded a reduction of 72.6%, 86.8%, 87.4% and 65.9% at 0°, 40°, 50°, and 70° inclination angle, respectively. The results show that including hemi-pelvis model apart from the analysis will reduce the stress data as the stress are not concentrated at the back side of acetabular shell only. FEA concluded that the stress was distributed towards the hemi-pelvis model as the shell and acetabulum was fully bonded. The stress was at maximum on the sacroiliac joint area in all inclination angle as shown in Figure 4.

Based on FEA analysis, it was indicated that the total deformation was almost insignificant difference recorded when inclination angle elevated in anatomical model. The results were recorded as contrary
with simplified model, where a steep deformation was recorded from 50° to 70° inclination angle. In the Figure 5 shows that anatomical model gives reduction of total deformation at 85.2%, 91.2%, 94.2% and 97.0% for 0°, 40°, 50°, and 70° inclination angle, respectively. From these results, an assumption could be made; the small margin deformation analysis data recorded at the anatomical model proved the rational of human body could withstands almost 8 times of their own BW doing daily living activities. Although simplified model still applicable, it is suggested to include vital component of human body part to produce better accuracy in term of FE analysis. A small margin deformation produced from the FEA also suggested that the THR can be fit at the acetabulum without greater motion that will increase the THR stability.

An indication could be presumed that deformation of THR from FEA was considered as sub micrometre data which agreed with previous research that shown no significant difference in deformation but the value still affecting the implant lifespan [25]. The deformation occurring during intraoperative impaction and press-fit was not included in this study, thus the results valid at postoperative phase when the implant is fully integrated in the bone.

![Figure 4](image)

**Figure 4.** The equivalent Von Mises stress of anatomical model in three inclination angles. The red marked rectangular shape shows that the stress pattern at the superior region of the acetabular cup.

Note: The 0° inclination was not shown

![Figure 5](image)

**Figure 5.** The difference of simplified model and anatomical model in term of a) Equivalent Von Mises Stress and b) Total deformation
4. Conclusions
There are hugely different data recorded in simplified model and anatomical model in term of contact pressure, equivalent Von Mises stress and Total deformation. Although the trend looks similar in both models which the value increasing with elevated inclination angle, the anatomical model produced lower results in all analysis that was conducted in this study. It is believed that the hemi-pelvic model affecting the FE analysis where the bone integration in FEA will disperse the pressure evenly compared to centralize concentrated at acetabular shell. Thus, analysis of THR using FEA should including anatomy model as the data will produce more accurate data. This study purposely for preliminary studies on improving the THR optimization in order to increase the lifespan from FEA aspect. Hence, further studies will be manifest in term of safe zone orientation, designs and material selection towards the longevity of the THR operation. Individual hemi-pelvic model results are varied and depending on many factors, yet the inclusion of the model in any analysis to improve the THR operations are vital.

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