Numerical Simulation of Artifical Hip Joint Movement for Western and Japanese-Style Activities

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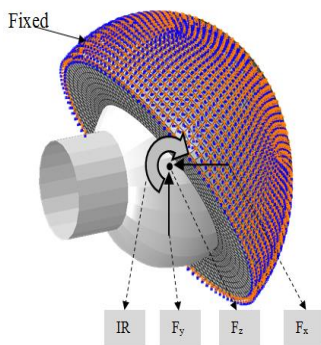*Corresponding author: ekosaputro984@gmail.com

Graphical abstract

Abstract

A numerical simulation model for observing the artificial hip joint movement with respect to the range of motion during human activities is presented in this paper. There were two human activities discussed, i.e. Western-style and Japanese-style. Previous investigation has reported the range of motion on the artificial hip joint for Western-style and Japanese-style, measured from the postoperative total hip arthroplasty patients. The aim of this investigation is to observe the probability of prosthetic impingement and to calculate the von Mises stress during these activities using finite element analysis (FEA). The Western-style activities consist of picking up, getting up and sitting, while the Japanese-style activities consist of sitting on legs with fully flexed at the knee (seiza), squatting and sitting on legs with fully flexed at the knee (zarei). The FEA uses a three-dimensional nonlinear model and considers the variation of the acetabular liner cup positions. Result shows that a prosthetic impingement is found in the Western's picking up activity. This activity induces a prosthetic impingement in a certain the acetabular liner cup position. In the Japanese-style activities there is no prosthetic impingement observed. However, a critical value in the range of motion was observed for the Japanese's Zarei activity for certain the acetabular liner cup position. The acetabular liner cup positions influences the probability of prosthetic impingement.

Keywords: Finite element analysis; artificial hip joint; range of motion; human activities; impingement

Abstrak

Model simulasi berangka untuk memerhatikan gerakan sendi pinggul tiruan terhadap gerakan manusia ditunjukkan dalam kajian ini. Terdapat dua jenis gaya pergerakan manusia dibincangkan, iaitu gaya-Barat dan gaya-Jepun. Kajian sebelum ini telah melaporkan pelbagai gerakan pada sendi pinggul tiruan untuk gaya-Barat dan gaya-Jepun telah diukur daripada jumlah pesakit postoperatif arthroplasti pinggul. Tujuan penyelidikan ini adalah untuk melihat kebarangkalian pelampiasan tiruan dan mengira kadar tekanan von Mises dengan menggunakan analisis unsur terhingga (FEA). Pergerakan gaya-Barat melibatkan pergerakan mengambil, bangun dan duduk, manakala pergerakan gaya-Jepun dari duduk dengan dua kaki di bawah (seiza), membongkok dan duduk berlutut kehadapan (Zarei). FEA secara model linear tiga dimensi dan mengambil kira pelbagai posisi acetabular telah digunakan. Dapatan kajian menunjukkan bahawa pelampiasan tiruan berlaku bagi pergerakan gaya-Barat. Namun tiada pelampiasan dalam pergerakan gaya-Jepun. Walau bagaimanapun, nilai kritikal dalam pergerakan diperhatikan pada acetabular untuk pergerakan Zarei. Kedudukan acetabular dilihat mempengaruhi pelampisan pada sendi pinggul tiruan.

Kata kunci: Analisis unsur terhingga; sendi pinggul tiruan; pelbagai gerakan; aktiviti manusia; pelampiasan

1.0 INTRODUCTION

Dislocation is one of the main problems for total hip arthroplasty (THA) patient during their daily activities [1]. There are two types of dislocation: early dislocation and late dislocation [2]. The early dislocation occurs due to the impingement of the femoral neck from the acetabular liner cup lip and the late dislocation is mostly related to wear [2-3]. The impingement in early dislocation is induced by the limitation of the range of motion (RoM) of the artificial hip joint for the THA patient. This limitation of the RoM can be influenced by the femoral head diameter, femoral neck diameter and acetabular liner cup position. Human activities have

different ranges of motion. The excessive or inordinate activities can induce a higher RoM and causes the impingement. THA patients will get typical procedures from their orthopedics specialist for doing activities in order to avoid the impingement.

Activities of the THA patients and its implication to RoM and impingement have been reported. Sugano *et al.* [4] presented the measurement of RoM for Western-style activities and Japanese-style activities. The measurement was conducted using the measurement results of 19 postoperative THA patients. It was reported that the RoM of the Western-style activities consist of picking up, getting up and sitting, while the RoM of the Japanese-style activities consist of seiza, squatting and zarei. Kluess *et al.* [5] developed a three-dimensional model for artificial hip joint movement by finite element analysis. Several position of the acetabular liner cup during the movement was simulated in order to observe the occurrence of impingement. This paper presents a 3D movement simulation to study the RoM of the Western-style and Japanese-style activities. The impingement is then predicted by a finite element analysis. The relation of the resisting moment, the internal rotation and the von Mises stress are reported in this paper.

■2.0 EXPERIMENTAL

2.1 Material Model

The finite element model of the contact system in the present study consists of femoral head, femoral neck and acetabular liner cup. The femoral head and the femoral neck component are assumed to be rigid. The acetabular liner cup component is modeled as an elastic-plastic material with isotropic hardening and assuming a visco-elastic-plastic material behavior of the ultra-high-molecular-weight polyethylene (UHMWPE). The modulus of elasticity, the Poisson's ratio and the yield strength of the UHMWPE are set to 945 MPa, 0.45 and 23.56 MPa, respectively [6]. The plastic strain is calculated based on the work of Fregly et al. [7], see the graph in Figure 1:

$$\varepsilon = \frac{1}{2}\varepsilon_0 \frac{\sigma}{\sigma_0} + \frac{1}{2}\varepsilon_0 \left(\frac{\sigma}{\sigma_0}\right)^n \tag{1}$$
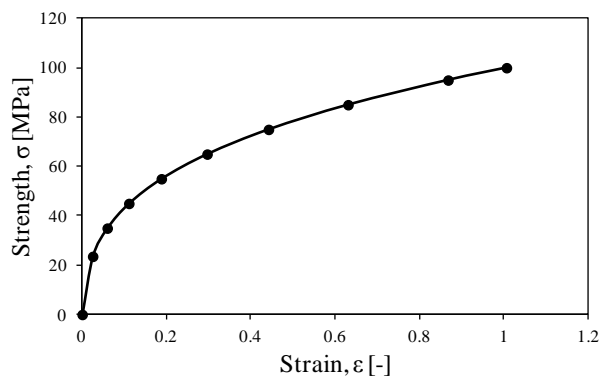
where the material parameter, *n*, is equal to 3.

Figure 1 The plastic strain curve

2.2 Finite Element Method

2.2.1 Geometry

The geometrical modeling of the unipolar artificial hip joint follows the model of Kluess *et al.* [5], as is depicted in Figure 2(a). Diameter of the femoral head and the femoral neck are 28 mm and 14 mm, respectively. The thickness of the acetabular liner cup is 7 mm. A gap between the femoral head and the acetabular liner cup is 24 μm and it is modeled as a lubrication space.

Figure 2(b) shows the finite element meshes for the acetabular liner cup. The commercial finite element software ABAQUS is employed. The element type of hexahedral 8 nodes linear brick (C3D8R) is employed, while the number of the element is approximately 9000.
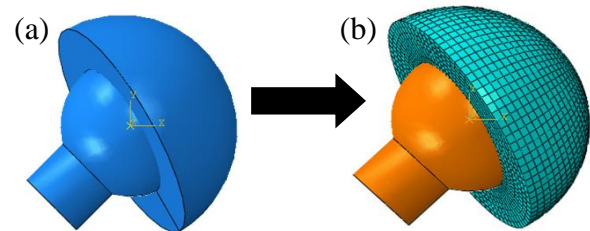

Figure 2 (a) Model of the femoral head and the acetabular liner cup and (b) the finite element meshes of the acetabular liner cup

2.2.2 Boundary Conditions

The value of the applied load of the present model is taken from the work of Kluess *et al.* [5], but the direction of the load follows the work of Bergmann *et al.* [8]. The loads in the x, y and z directions are $F_x = 15$ N, $F_y = 270$ N and $F_z = -427.5$ N, respectively, and are applied on a point at the center of the femoral head, see Figure 3. All the degree of freedom at the outer surface of the acetabular liner cup is constrained.

The simulation is conducted in two steps: firstly, the load is applied to the center of the femoral head with constraining the rotation of the femoral head is constrained and secondly, the load at the center of the femoral head is constrained with rotating the femoral head. The range of the internal rotation (IR) is according to the RoM of human activities.
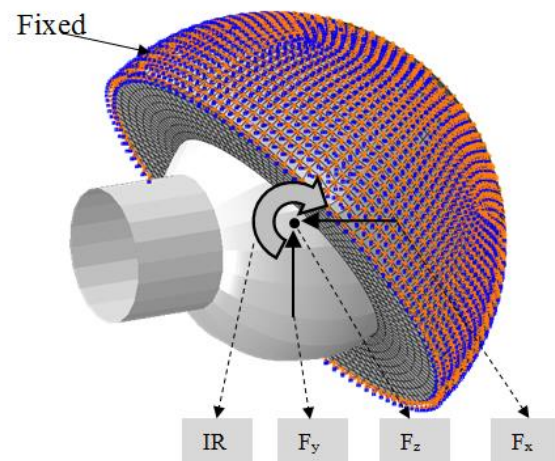

Figure 3 Boundary conditions on finite element model

2.2.3 Human Activities

The simulations are performed for the Western-style and the Japanese-style activities. Here, the value of the RoM is taken based on the work of Sugano *et al.* [4]. The Western-style activities consist of picking up an object while sitting on the chair, getting up from the chair, and sitting down on the chair. The Japanese-style activities consist of bowing while sitting on legs with fully flexed at the knee (zarei), squatting, and sitting on legs with fully flexed at the knee (seiza).

Figures for expressing all these activities can be seen in Figure 4 [4]. Those activities give a certain value of the RoM in degree. Maximum flexion, adduction and internal rotation are the component items for the RoM value. Table 1 shows the value of RoM for the human general activities.
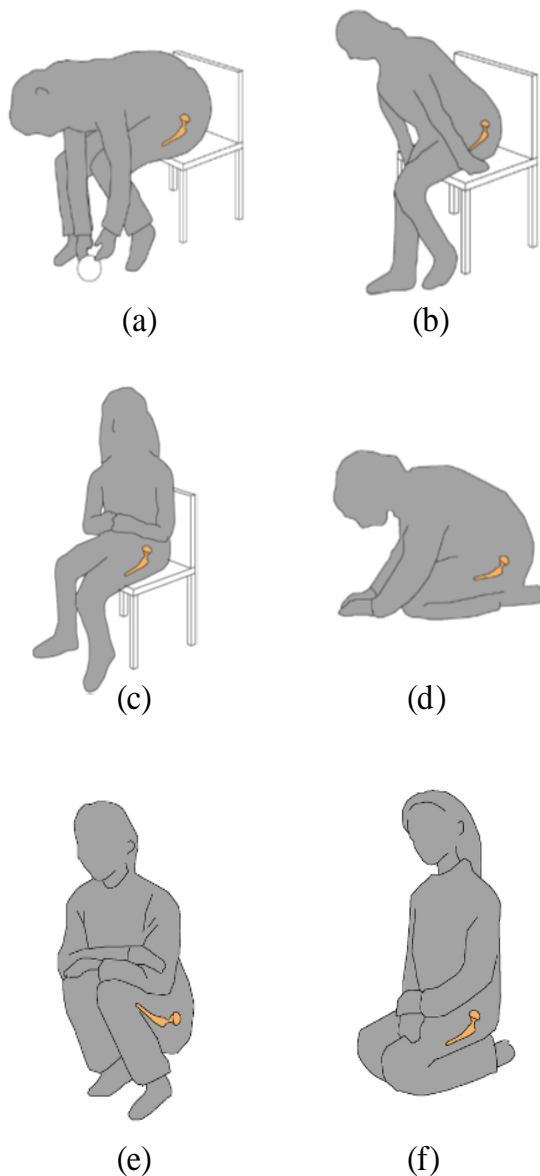
Table 1 Hip joint angle [°] during human activities [4]

Motion, Degree	Average ± Standard deviation		
	Max Flexion	Adduction	Internal Rotation
Western-style activities on the chair			
Picking up an object while sitting on the chair	86 ± 13	−6.1 ± 7.3	−12 ± 11
Getting up from the chair	76 ± 12	−2.5 ± 5.2	−11 ± 10
Sitting down on the chair	62 ± 10	−0.92 ± 5.5	−7.0 ± 11
Japanese-style activities on the floor			
Bowing while sitting on legs fully flexed at the knee (zarei)	84 ± 13	−2.1 ± 4.9	−12 ± 11
Squatting	80 ± 16	−8.6 ± 9.5	−9.2 ± 11
Sitting on legs fully flexed at the knee (seiza)	61 ± 12	−1.2 ± 4.4	−15 ± 11

2.2.4 Variation

The variation of the angle between inclination and anteversion of the acetabular liner cup is simulated in order to study the possibility of the impingement to occur between the femoral neck and the acetabular liner cup lip. The variations of inclination of the acetabular liner cup are 45º and 60º and the variation of anteversion of the acetabular liner cup are 15º and 30º. The angle of the femoral neck axis line and the femoral stem axis line is 135º. The simulation uses a femoral head diameter of 28 mm. The variations in the present study follow the work of Kluess *et al.* [5].

■3.0 RESULTS AND DISCUSSION

3.1 Validation

In order to check the developed model simulation, a validation was conducted by comparing the results to the work of Kluess *et al.* [5]. The inclination and anteversion of the acetabular liner cup were fixed for 60º and 30º, respectively. Result of the validation is shown in Figure 5. The average deviation between the present model and the Kluess *et al.* model is about 1.32 %. The developed model is in good agreement with literature with respect to the predicted resisting moment.
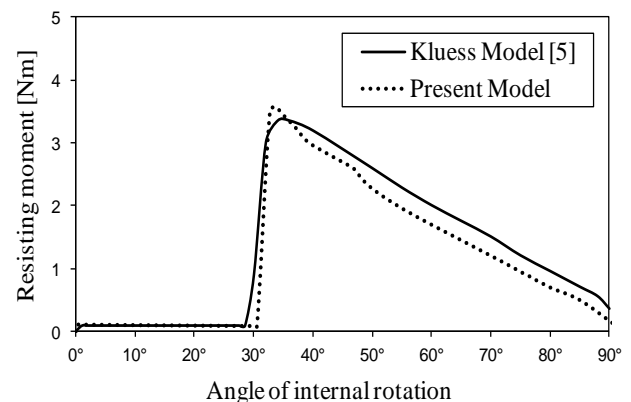

Figure 4 (a) Picking up an object while sitting on the chair, (b) Getting up from the chair, (c) sitting down on the chair, (d) Bowing while sitting on legs fully flexed at the knee (zarei), (e) squatting, and (f) sitting on legs fully flexed at the knee

Figure 5 Comparison between the present model and the Kluess model [5] in predicting the resisting moment as a function of the angle of internal rotation

3.2 Western-style Activities

Figure 6(a) and 6(b) show the degree of impingement for the Western-style activities. In Figure 6(a) the internal rotation for the picking-up, getting-up and sitting down activities is reported with considering four different position of the acetabular liner cup. The minimum requirements of the internal rotation for picking-up, getting-up and sitting down activities are 12°, 11° and 7°, respectively. The highest resisting moments for picking-up, getting-up and sitting down activities are 4.41 Nm, 3.88 Nm and 3.21 Nm as is depicted in Figure 6(b).

The unipolar artificial hip joint does not induce an impingement for most of the Western-style activities. Yet, the picking up activity, for the acetabular liner cup inclination of 45° and anteversion of 15°, could be critical as the impingement is predicted to occur at 8° of the internal rotation. Therefore, the THA patients are suspected not to be able to finish the picking up activity due to the fact that it needs at least 12° of internal rotation.
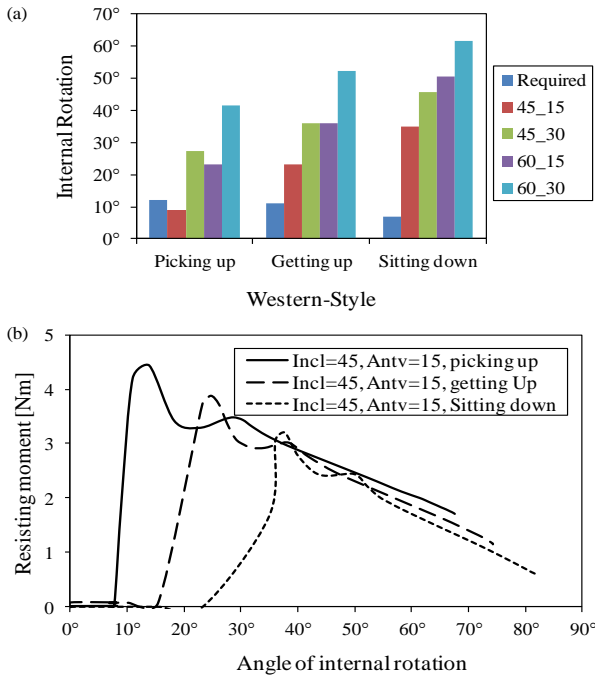

Figure 6 (a) Comparison of the calculated value of internal rotation obtained from variations of the acetabular liner cup position in the Western-style activities and (b) plot of its resisting moment as a function of its internal rotation angle

Figure 7 shows the von Mises stress analysis. Figure 7(a,c) shows the stress analysis for getting up activity, Figure 7(b,d) shows the picking up activity, and Figure 7(e) shows the sitting down activity, where the combination degree of the acetabular liner cup inclination and the anteversion is 45°-15°. Two impingement positions can be found from the analysis based on this figure, namely impingement site and egress site.

Dislocation is predicted to occur for the patients who are trying to perform the picking up activity. The other combination positions of the acetabular liner cup for inclination and anteversion are also reported in a safe position, 45°-30°, 60°-15° and 60°-30°.
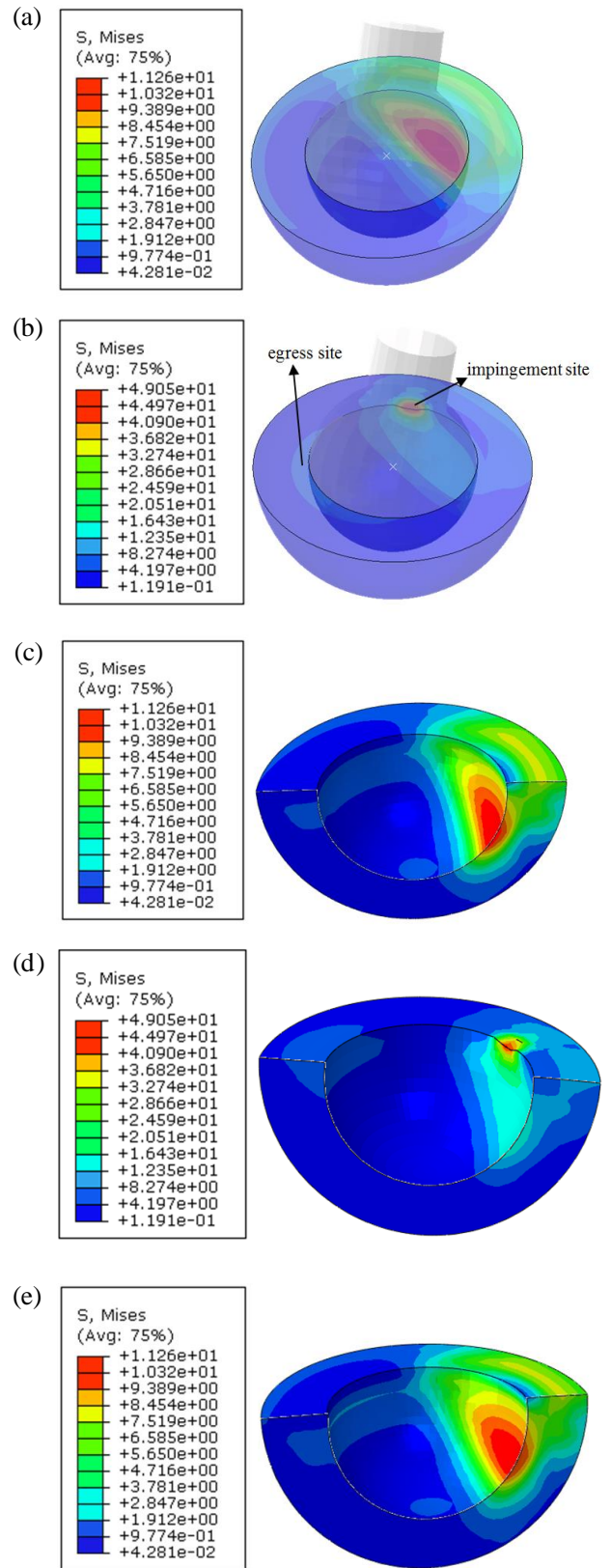

Figure 7 The von Mises stress for: a,c) the full and half of acetabular liner in getting up activity, b,d) full and half of acetabular liner in picking up activity, and e) half of acetabular liner in sitting down activity, where the acetabular liner cup position is 45° inclination and 15° anteversion of the Western activity

However, based on several testimonies of the orthopedic specialist, it is stated that the inclination and the anteversion of the acetabular liner cup combinations of 45°-15° are mostly used. It is suggested that the unipolar artificial hip joint, proposed by Kluess *et al.* [5], need to be redesigned to accommodate the picking up activity with respect to the inclination and the anteversion of the acetabular liner cup combination of 45°-15°.

3.3 Japanese-style Activities

The degree of impingement for the Japanese-style activities is shown in Figure 8. In Figure 8(a) the internal rotation for the three activities is reported with considering four positions of the acetabular liner cup. The minimum requirements of the internal rotation for zarei, squatting and seiza activities are 12°, 9.2° and 15°, respectively. Figure 8(b) shows that the highest resisting moment for zarei, squatting and seiza activities are 4.33 Nm, 4.10 Nm and 3.15 Nm, respectively.
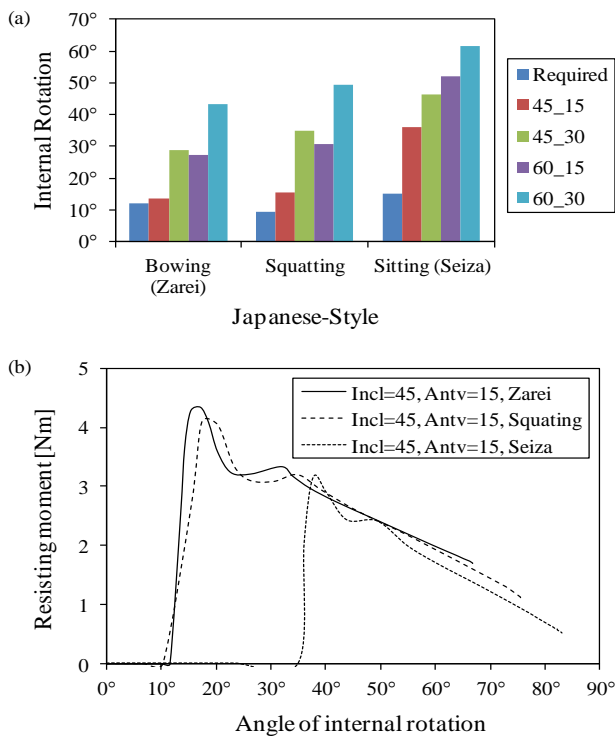

Figure 8 (a) Comparison of the calculated value of internal rotation obtained from variation of the acetabular liner cup position in the Japanese-style activities and (b) plot of its resisting moment as a function of its internal rotation angle

In general, the unipolar artificial hip joint models for the Japanese-style activities are predicted safe in term of the impingement. However, the zarei activity, for inclination of 45° dan anteversion of 15° of the acetabular liner cup, is still not suggested. This is because the impingement of the zarei activity is predicted to occur at 13.53° of internal rotation whiles the result shows that the required degree of the zarei activity is 12°. Moreover, the safe margin of the internal rotation is about 10° as was suggested by Sugano *et al.* [4]. Therefore, an evaluation is still needed for the unipolar artificial hip joint model proposed by Kluess *et al.* [5]. The model needs to be redesigned for accommodating the zarei activity in a more safe condition. The von Mises stress contours for the Japanese-style activities are

shown in Figure 9(a,c), 9(b,d) and 9(e) for squatting, zarei and seiza activities, respectively, with the combination of inclination and anteversion of the acetabular liner cup of 45°-15°.
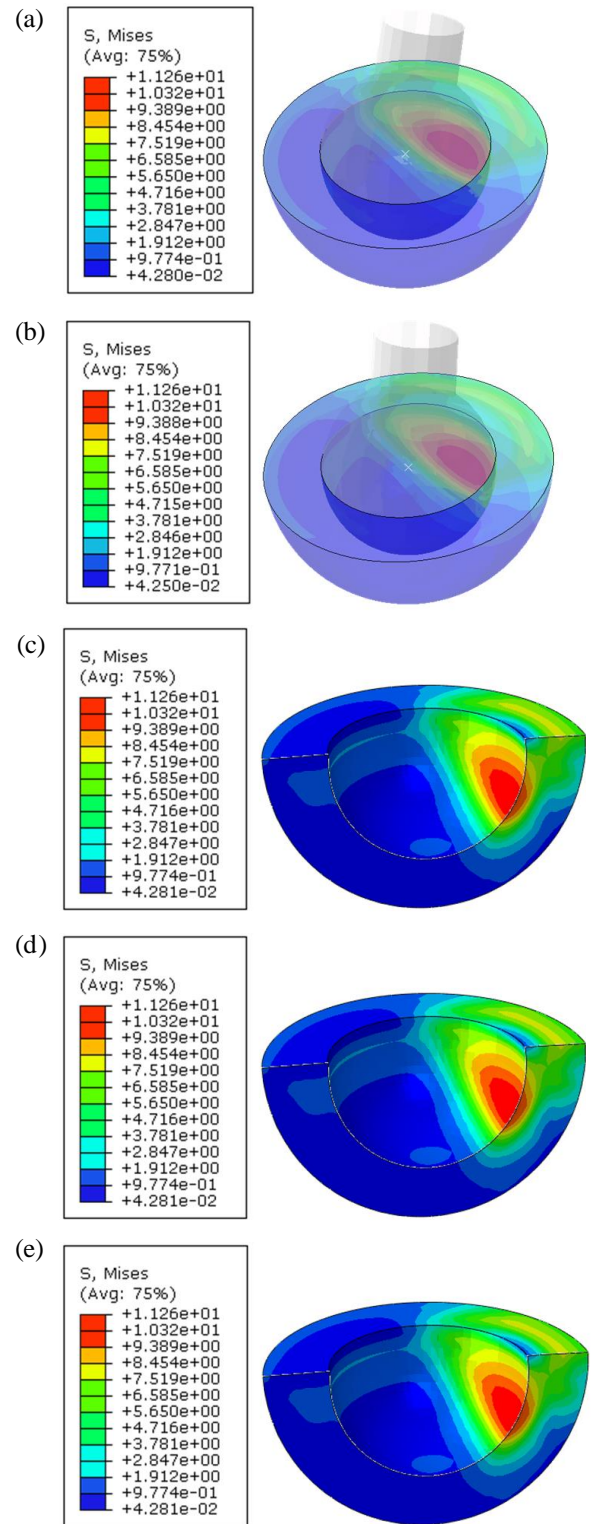

Figure 9 The von Mises stress for: (a,c) the full and half of acetabular liner in squatting activity, (b,d) the full and half of acetabular liner in zarei activity, and (e) half of acetabular liner in seiza activity, where the acetabular liner cup position is 45° inclination and 15° anteversion of the Japanese activity

■4.0 CONCLUSION

This paper investigated the range of motion of the human activities of the Western-style and the Japanese-style using finite element analysis for THA patient. The unipolar artificial hip joint model was used in the simulation. Based on the results it can be stated that for the THA patients the Western-style and Japanese-style most activities can be performed safely. The impingement and dislocation are predicted to be occur at picking up activity in the Western-style activity for the inclination and anteversion combination of the acetabular liner cup of 45°-15°. The seiza activity in the Japanese-style activitiy is not recommended to be performed for the THA patients because of the safety margin of the internal rotation is less than 10°. The impingement between the femoral neck and the acetabular liner cup lip during a contact situation can be predicted by the finite element simulation. It is demonstrated that the von Mises stress at the impingement position is higher than the yield strength of the material.

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