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# Stress and Damage Formation Analysis in Hip Arthroplasties using CT-Based Finite Element Method

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**Abstract:** Femoral neck fractures and prosthesis loosening are several biomechanical concerns in promoting the long term stability of hip arthroplasties. External high impact loading due to sideway falls may contribute to the risk of femoral fractures and joint failures. The purpose of this study is to investigate the biomechanical effects of hip resurfacing and total hip arthroplasty on the resulting stress and damage formation. Four loading conditions are considered in the analysis to represent sideway falls at different configurations. Finite element analysis is performed using CT-based femoral bone model to predict the stress and damage formation in both arthroplasties. Stress shielding effects and potential of femoral fractures are observed in the cortical bone adjacent to the prosthesis. The results show that stress adaptation is predicted at both hip arthroplasties cases which lead to stress shielding problems especially in total hip arthroplasty. The variation of damage formation at trochanteric region suggested for femoral neck fractures and potential of implant loosening in both cases.

**Key words:** Stress variation, damage formation, sideway falls, total hip arthroplasty, resurfacing hip arthroplasty

## INTRODUCTION

Total hip and resurfacing hip arthroplasties are two common surgical approaches for later stage of hip osteoarthritis patients. Long term performances of both methods are continuously discussed and explore. Post-clinical and patient-reported outcomes are important factors to be considered such as the ability to return function, pain relief and increase mobility. In biomechanical point of view, issue of stress shielding is an important factor to bone adaptation which further leads to bone resorption, altering the bone growth and hence lead to implant instability (Selamat *et al*., 2013). The presence of artificial implant at the hip joint has created a mismatch of elastic modulus between two materials inside the bone. Alteration of stress-strain stimuli in the bone will increase the resorption stage and initiate bone remodeling (Frost, 2001). The remodeling process will also contribute to gait adaptation to hip arthroplasty patients. They were always at risk of falls due to imbalance, medication side effects and difficulty of avoiding environmental hazards (Brunner *et al*., 2003). Sudden and complex impact loadings to the hip during sideway falls are very dangerous to elder patients especially to hip arthtoplasty patients. It may also lead to femoral bone fractures, joint failures and other successive injuries (Winter *et al*., 1995).

Understanding of biomechanical behavior of femoral bone will be benefit to predict long term performance of hip arthroplasty and gait stability. Thus, the purpose of this study are to develop inhomogeneous 3D model of intact femur and femur with arthroplasties (THA and RHA) from CT-based data and predict the damage formation in both hip arthroplasties at different configurations of sideway falls.

## MATERIALS AND METHODS

**Finite element model:** Computed Tomography (CT) based images of a 54 years old male were used in developing a 3D femoral model. The femur model is designed to be inhomogeneous material as defined by Hounsfield Unit of the CT images. CAD data of hip arthroplasties are imported and aligned to represent RHA and THA femur model. Figure 1 show young modulus distribution of the inhomogeneous femur model, RHA and THA femur.

**Material properties:** Prosthesis stem of THA is modeled as Titanium Alloy (Ti-Alloy) material while femoral ball as Alumina properties. Meanwhile, RHA implant is assigned as Cobalt Chromium (Co-Chromium) material. Details of

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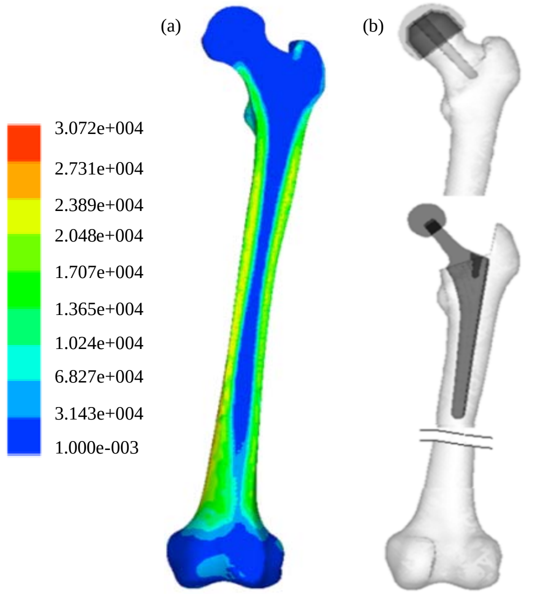


Fig. 1: a) Distribution of young modulus (MPa) in inhomogeneous intact femur model and b) 3D models of RHA (top) and THA (bottom)

Table 1: Materials property for hip arthroplasties

| Properties | Ti-alloy | Alumina | Co-chromium |
|---|---|---|---|
| Elastic modulus (GPa) | 114.00 | 370.00 | 230.00 |
| Poisson ratio | 0.34 | 0.22 | 0.30 |
| Critical stress (GPa) | 0.88 | 0.40 | 0.94 |
| Yield stress (GPa) | 0.97 | 3.00 | 2.70 |
| Density (g/cm$^3$) | 4.43 | 3.96 | 8.28 |

Table 2: Description of falling configurations at different angle α and β

| Configurations | α(°) | β (°) |
|---|---|---|
| FC1 | 120 | 0 |
| FC2 | 60 | 0 |
| FC3 | 60 | 15 |
| FC4 | 60 | 45 |

the material properties for each component are summarized in Table 1 (Keyak *et al*., 2001). Contact between both implants and bones are considered to be perfectly bonded at the interface.

**Loading and boundary conditions:** Variation of loading directions in each configuration is developed based on α angle (with reference to the long axis of femur in frontal plane) and β angle (with reference to femoral neck axis in horizontal plane) as suggested by Bessho *et al*. (2009). The description of loading directions is shown in Table 2. Meanwhile, loading and boundary conditions of the Falling Configurations (FC) namely FC1, FC2, FC3 and FC4 are illustrated in Fig. 2. The loading magnitude of 3.9 times of patient Body Weight (BW) is applied to represent hip impact during the sideway falls (Groen *et al*., 2007). Finite element analysis combined with a damage

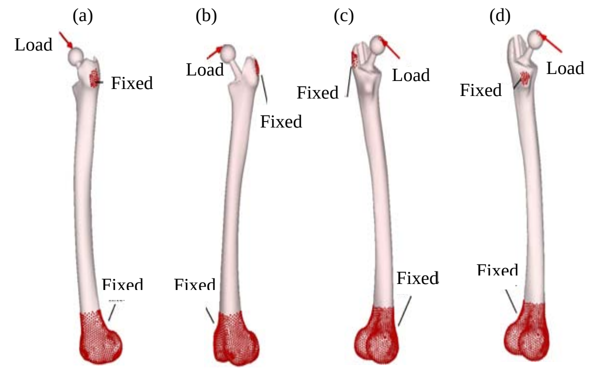


Fig. 2: Loading and boundary conditions for: a) FC1; b) FC2; c) FC3 and d) FC4

mechanics model was then performed to calculate the damage formation and further predict the bone fractures in both arthroplasty models.

## RESULTS AND DISCUSSION

Prediction of femoral fracture for RHA and THA femurs are discussed in corresponding to maximum principal stress and damage formation criterion. Fracture mechanism of femurs was referred to the prediction proposed by Keyak and Rossi (2000). The load bearing strain was set to 3000 micron, the physiological bone loading that leads to bone formation. The test strength was wet to 80% of the yield strength determined from the CT images (Kaneko *et al*., 2003; Taylor *et al*., 2003).

**Maximum principal stress:** Variation of maximum principal stress distribution for RHA and THA femurs are shown in Fig. 3. Higher magnitudes of stress are indicated at medial proximal region for all configurations. It was expected as the sideway fall gave a high impact at the trochanteric regions. In the intact and RHA femur, stress are concentrated at medial neck region suggested the bending effects at the femoral neck due to impact load during fall. However, the loading impact in THA femur is absorbed by the stiffer prosthesis stem. Different pattern of stress distribution between both arthroplasties in each configuration proved that the presence of implant in femoral shaft will contribute to stress shielding effects. Replacement of total femoral head with prosthesis stem has modified the environment of femoral shaft while resurfacing technique offers minimum changes as compared to intact femur.

Comparison of maximum principal stress magnitude experienced in each configuration is summarized in Fig. 4. Findings in FC1 suggested the configuration

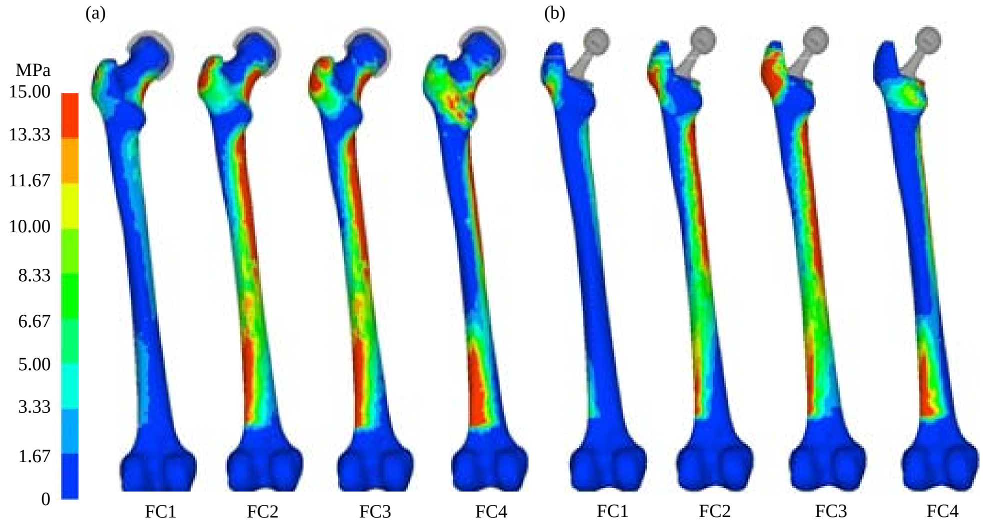


Fig. 3: Stress variations of: a) RHA and b) THA femur models at different sideway fall configurations

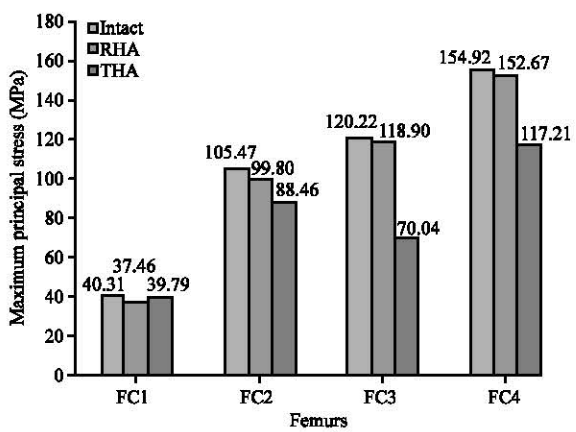


Fig. 4: Comparison of stress concentration for intact, RHA and THA femurs in FC1-FC4

provide minimum stress concentration while FC4 indicates highest stress concentration. The findings suggested the significant of loading directions at α and β angles to the impact of fall. The similar magnitude will give different effects and stress concentration depending on the loading direction itself. The presence of femoral component will also give difference influences. For instance, RHA and intact femurs experience higher stress concentration in FC3 as compared to FC2. However, the finding for THA femur is vice-versa in both loading configurations. This suggested the stress concentration will affected by the loading directions and the types of femoral component. The THA femur will produce minimum stress concentration as compared to RHA femur but it does not present the effectiveness of the implant.

Minimum changes of stress concentration in RHA femur to intact femur confirmed that the resurfacing technique will minimize the biomechanical effects to the femoral bone.

**Damage formation:** Results shown in Fig. 5 indicate the damage formation occurred in all falling configurations at different locations. Damage or failure element are indicated in red and yellow for tensile and compression directions, respectively. The findings of damage elements within the models suggested for bone fractures in real condition. Similar location of bone fractures are predicted for intact and RHA femurs in almost all configurations. For instance, the fractures are predicted to be dominant at the proximal femoral neck and greater trochanteric region at FC2-FC4 in both models. However, additional damage elements are predicted at the RHA rim which suggested for potential of implant loosening. Bending effects of the femoral component after loaded is expected to be the reason and lead to the consequences.

The prediction of damage location in the RHA femur is similar to Amstutz *et al*. (2004) whom reported the main causes of RHA failure were femoral neck fracture and implant loosening. Meanwhile, the patterns of damage formation in THA femurs show different trends. The failure elements are observed to concentrate at the inner or canal part of proximal bone. Damage elements are concentrated at the lateral region in FC1, FC2 and FC1-FC3 while at the medial region in FC4. The bending effects of prosthesis stem after loaded are believed to contribute to the findings. Consequently, prosthesis loosening at proximal region is also expected in THA femur.

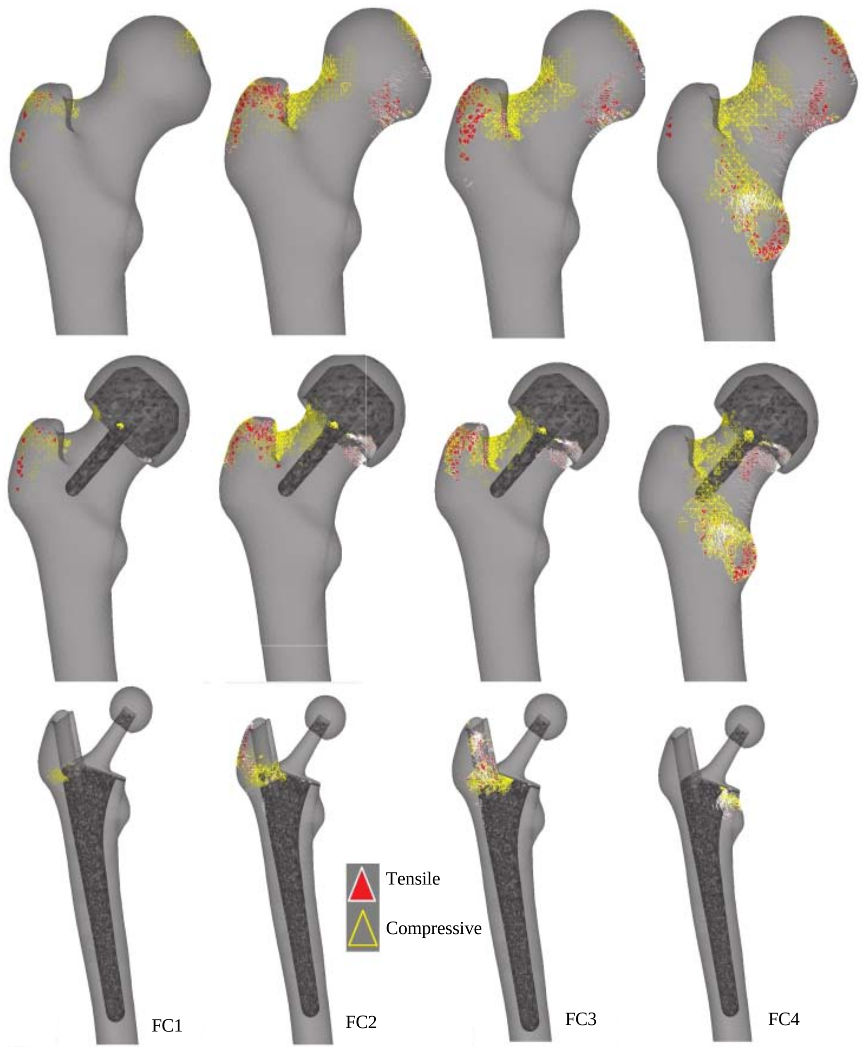


Fig. 5: Fracture locations of intact, RHA and THA femurs at different falling configurations

## CONCLUSION

The inhomogeneous CT-based finite element models of intact and arthroplasty femurs are successfully developed in this study to observe the bone behaviour. Resulting maximum principal stress and damage formation are measured to predict the stress variation and potential bone fractures in different arthroplasty models. The presence of stiffer femoral component in femoral bone has modified the environment and leads to stress shielding effects especially in THA femur. Prediction of damage formation in arthroplasty femur model at different configurations suggested for potential bone fractures at the trochanteric and proximal canal regions in RHA and THA femurs, respectively. Proximal implant loosening is also expected in both cases at most configurations.

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