ORIGINAL ARTICLE

Effects of Varus and Sagittal Implant Positioning to the Stress Adaptation in Cementless Hip Arthroplasty

Muhammad Syahmi Yusof[1], Nabila Aznan[1], Nor Fazli Adull Manan[1], Shahrul Hisyam Marwan[2], Muhammad Hazli Mazlan[3], Abdul Halim Abdullah[1]

[1] School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Selangor, MALAYSIA
[2] School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM), Terengganu Branch, 23200 Bukit Besi, Terengganu, MALAYSIA
[3] Microelectronics and Nanotechnology – Shamsuddin Research Center, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Batu Pahat, Johor, MALAYSIA

ABSTRACT

Introduction: Total Hip Arthroplasty (THA) is one of the most common procedures in orthopedic surgery to treat the later stage of osteoarthritis. Implant mal-positioning is one of the risks that may lead to implant instability after surgery. The objective of this study to predict the effects of varus and sagittal positioning implant in promoting implant stability in cementless hip arthroplasty. **Methods:** Femoral bone (E=17 GPa, v=0.33) and titanium alloy (E=110 GPa, v=0.3) implant was considered in the analysis to represent the total hip arthroplasty. Various implant positions in varus and sagittal plane from -3° to 3° were modeled and analyzed for stair climbing activity. **Results:** The findings are discussed on the resulting maximum principal stress at the femoral bone and the implant. The stress variation in varus and sagittal cases are increased in the proximal and distal region where the cortical bone is bonded with the implant. The varus orientations show the severe stress concentration than sagittal orientations where the percentage increased up to 75% compared to normal conditions. **Conclusion:** The variation of implant position in varus and sagittal plane had influenced the stress distribution and contribute to bone adaptation and stress shielding effects. The effects of varus positioning were more significant compared to sagittal position in predicting the stress adaptation.

Keywords: Finite element analysis, Hip arthroplasty, Implant stability, Sagittal positioning, Varus positioning

Corresponding Author:
Abdul Halim Abdullah, Dr.Eng.
Email: halim471@uitm.edu.my
Tel: +603-55436468

INTRODUCTION

Total Hip Arthroplasty (THA) is one of the most successful and common procedures in orthopaedic surgery to overcome the hip late stages of the hip problem (1). Previous studies by Kurtz et al reported the rate of THA increased 50% from 1990 to 2002 (1, 2). In the United States, the demand for THA is estimated to rise by 174% from 208,600 in 2005 to 572,000 in 2030. Even THA marked as a successful procedure in treating the hip problem, it may carry its own risk and complication towards implant stability in promoting the long-term performance and survivorship especially in developing a cementless technique which requires biological fixation between bone and prosthesis stem. Implant stability in THA refers to the implant positioning and orientation during primary fixation between the long axis of femur and prosthesis stem. The influence of implant stability may contribute to the risk of pre-dominant failure mode and aseptic loosening. In addition, the effect also leads to patient dissatisfaction and poor outcomes which causes the revision surgery after the pre-operative (3, 4). Furthermore, a major impact of implant positioning leads to the risk of femoral fracture after postoperative, thus it is a serious issue in implementing primary THA among the surgeon toward providing excellent long-term results.

Previous reports revealed that the revision surgery in the United States increased to 17% with the rate of THA increased 21% over five years period due to the dislocation or fracture (5). Another studied by Beer et al. found similar findings where implant orientation in a varus position had leading to the cause of surgical revision. A review of 215 primary THA, a 38% of them went to failure and subsequent revision within 4 years follow up after operation (6). A worst case of fracture after primary THA was reviewed based on 26 studies by Mount and Maar (7). A statistical analysis of the outcome revealed 487 patients with femoral fracture occurring about prosthesis stem. These reviews included general surveys, multi-center studies and case report which emphasize the fracture into several types. Exposure of femoral fracture is an uncommon but serious complication which needs various treatment methods in treating the fracture towards restoring patient anatomy. Thus, the continuous improvement in surgical procedure during pre-operative is important to avoid revision and failure of hip arthroplasty.

The finite element method becomes an essential part of engineering technology in medical field to optimizing the advanced surgical approaches towards the long-term performance and to enable successful in primary arthroplasty. Therefore, the aim of this study is to analyze the effects of implant positioning to the primary stability of cementless hip arthroplasty using finite element analysis.

MATERIALS AND METHODS

Finite element model

A Computer Tomography (CT) based images of a patient who suffers from osteoarthritis patient were converted into three-dimensional images using commercial biomedical software, Mimics. The CT images of the patient with osteoarthritis were obtained in DICOM (Digital Imaging and Communications in Medicine) format. The threshold profile of CT image was set to 662-1988 HU for compact bone and 148-661 HU for the spongy bone. These two ranges of threshold present the high material properties of bone compared to other material of small material properties which increase the processing time of analysis (8).

The Anatomic Modularly Locking (AML) implants were used in this study to represent the cementless hip arthroplasty. The AML stem is generally a cementless type model with cylindrical, and surface treated throughout the entire length. The CT scan images, and 3D model of the implant were provided by the Applied Biomechanics Lab, Kyushu University. Then, the THA model was reconstructed by replacing the femoral head and neck with prosthesis stem. The distal femoral bone was fixed on the femoral diaphysis. Various models of hip arthroplasty with respect to implant positioning in varus and sagittal plane were constructed, as shown in Figure 1A and 1B, respectively. Six different angles at varus and sagittal were assigned and range from -3°, -2°, -1°, 1°, 2° and 3°. A normal position of implant was also be considered for reference.

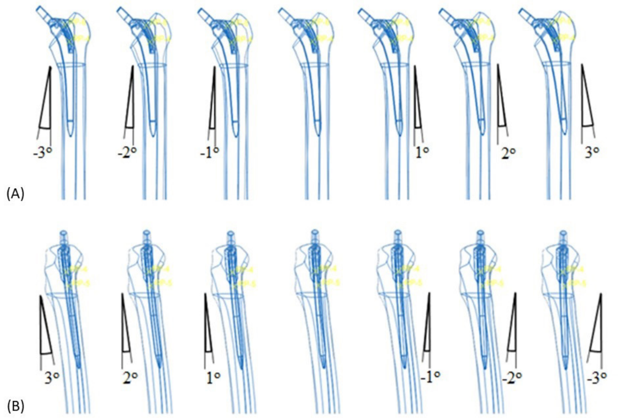


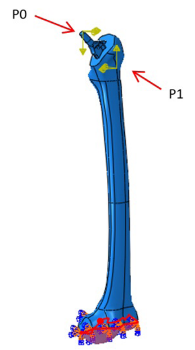
Figure 1 : Model of Total Hip Arthroplasty at different implant positioning. **(A)**. Implant tilting at varus plane and **(B)**. Implant tilting at sagittal plane with different angles (from left) -3o, -2o, -1 o, normal, 1o, 2 o and 3o.

Material properties

The femoral bone was designed as cortical bone as it is the main structure of the human skeleton mass. The cancellous bone was neglected for simplicity and improved solution time as the difference considering both cortical and cancellous bone were within 1% (9). The prosthesis stem was assigned to be Titanium alloy, the biocompatibility material. The stable alloy phase is found to be absolutely insert in the human body, immune to attack from bodily fluids, and biocompatible with bone growth (10). The material properties of the cortical bone (modulus of elasticity, E = 17 GPa, poisson ratio, v = 0.33, yield strength, σy = 115 MPa) and Titanium alloy implant (E = 110 GPa, v = 0.3, σy = 850 MPa) were assumed to be homogeneous, isotropic, and linear elastic (11). The contact between bone and implant was assigned to be perfectly bonded at the interface.

Loading and boundary condition

The load configuration was developed in the analysis to demonstrate the loading and boundary conditions. The loading conditions represent the highest peak load in gait pattern from the daily activities of a person (12). Stair climbing loading conditions were considered in this study in preference to walking and standing activities since the former involved higher workload than the two latter activities. The former is more representative than the latter in terms of simulation to the actual performance of THA as compared to other activities such as walking and standing. The successful prediction in this condition is believed to be presentable to other activities. The loading and boundary conditions applied to the THA model were acting on 2 points namely hip contact and abductor muscle. The distal end of the femur was totally fixed. The loading magnitude applied according to the previous studied by Heller et al. (13) and subjected to the patient's bodyweight (BW) loading of 836 N. Figure 2A shows the loading and boundary condition of the finite element model while Figure 2B describes the detail magnitude of hip contact and abductor loads for stair climbing activity.



(A)

Point	Hip Contact	Abductor Muscle
F_x (N)	495.7	-586.0
F_y (N)	506.6	-240.8
F_z (N)	-1975.5	709.8
Resultant (N)	2098.8	951.4

(B)

Figure 2 : Loading and boundary condition of the total hip arthroplasty (A). Location of hip contact (P0), abductor muscle (P1) and fixation at the distal end of femur **(B)**. Loading magnitudes for stair climbing activity.

Meshing

The cementless THA model consists of femur and prosthesis stem that were prepared for analysis by using commercial software. A finite element software namely, Abaqus was used to generate the mesh for the entire hip arthroplasty model to ensure that the algorithms produce robust and reliable numerical values. The mesh size for both femur and prosthesis stem was 2 mm and the body element used included ten nodes quadratic tetrahedron (14). The number of elements for femur and prosthesis stems were almost 501,365 and 24,447, respectively as shown in Figure 3. The material properties were assumed to be isotropic and linear elastic which indicate no plastic deformation in finite element analysis.

(A) (B) (C)

Figure 3 : Meshing elements of all models (A). Intact femur **(B).** Prosthesis stem. **(C).** Total hip arthroplasty**.**

RESULTS

Validation and convergence analysis of the mesh size

The femur model in this study was validated with the experimental study conducted by Simoes et al. (15). The validation of femoral model was defined by the strain distribution within the intact femur of femoral model. The similar loading configuration joint reaction plus the abductor muscle force were applied with a fixed boundary at the end of the femur as conducted by the experimental study (15). The result of strain distribution in medial and lateral as shown in Figure 4. The result indicated that the pattern of strain distribution demonstrated in our study was consistent to that reported by Simoes et al. However, the different magnitudes measured in this study were much lower than the experiment due to different bone models. Therefore, the general trends in strains in medial and lateral seems to correspond with the experimental data (15). Hence, the femur model is valid for further analysis.

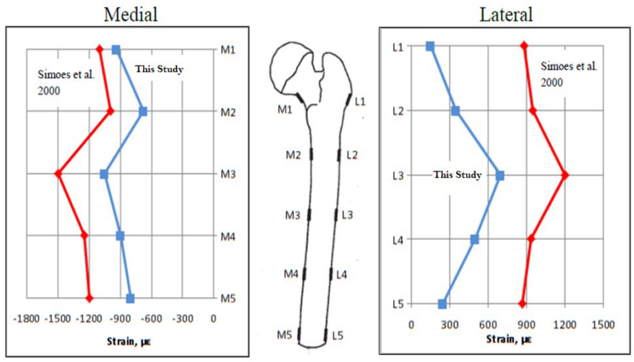


Figure 4 : Pattern of strain distributions at the medial and lateral plane of the femur.

A mesh convergence study was performed as shown in Figure 5. An analysis of bone displacement and maximum stress show a converged value using 5 different mesh size, 1 mm to 5 mm. Thus, 2 mm mesh size was selected to be used in this study. Based on the mechanical analysis, the smaller size of meshing is expected to give similar findings and only consume more computational time.

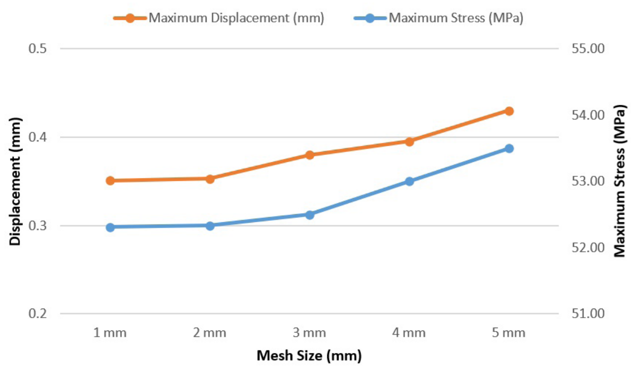


Figure 5 : Maximum stress and displacement of femoral bone model for convergence study.

Stress variation in the proximal femur

The analysis of stresses results was present in maximum principal stress as the properties of femur is a brittle material, which desired to analyze the femur being stress under loading (16). The presence of prosthesis stem contributes to stress adaptation along the THA femur. Most of the loads were dominated by stiffer implant due to the mismatch material with the cortical bone (8, 17). The proximal region of the THA femur indicates the changes. Figure 6A shows the variation of principal stress for varus and sagittal positioning. The highest stress was indicated at the implant position of varus 2° and sagittal 3° which were 102.2 MPa and 80.9 MPa, respectively. The stress was concentrated at the metaphyseal region of the proximal area which is essential for primary stability fixation of hip arthroplasty.

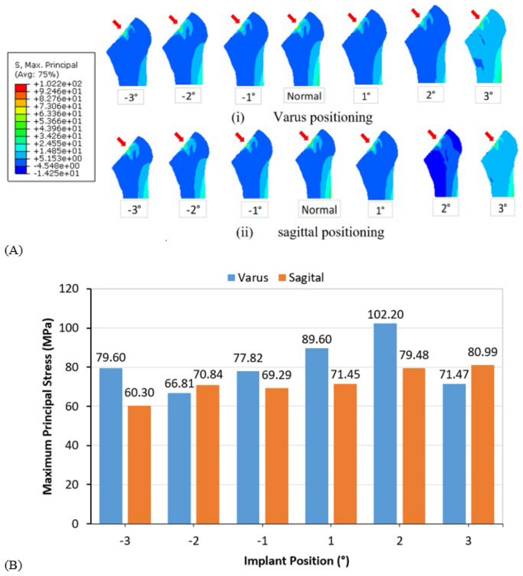


Figure 6 : Effects of maximum principal stress at different implant positioning (A). Variation of stress at proximal region of the THA femur **(B)**. Comparison of maximum principal stress in the femoral bone. The stress adaptation will contribute to stress shielding effects to the bone and may lead to implant instability.

The comparison of maximum principal stress in varus and sagittal positioning is shown in Figure 6B. Varus positioning indicates higher stress as compared to sagittal positioning. The highest stress was captured in varus positioning at +2°, followed by varus +1° with 102.2 MPa and 89.6 MPa, respectively. However, the magnitude of stress was low at varus with -2° and +3° of implant position. The highest maximum principal stress for sagittal positioning were between 60-81 MPa for all cases. The findings suggest the varus positioning and degree of implant tilting contribute to higher stress magnitude. While the changes in sagittal positioning do not really affect the higher stress magnitude at the proximal region.

Stress distribution & load transfer in femoral shaft

The highest stress of implant position in varus and sagittal located at 2° implant position which were 82.76 MPa and 65.35 MPa, respectively. The percentage of difference between both positions in varus and sagittal compared to the normal position are 75% and 38%, respectively. Thus, the effects of varus positioning were more significant than sagittal positioning. Most of the implant position in varus and sagittal exceed the average stress of femur in this study (70 – 78 MPa) which may lead to bone thickening. However, the maximum stress does not exceed the yield strength of the bone (115 MPa) and considered to be safe.

DISCUSSION

The reduced stress at the proximal cortical bone in all cases as compared to the intact femur suggested for the progression of stress shielding at the area. This situation is believed will lead to aseptic loosening and instability of the implant (17). The implant is expected to loosen in longer period and at risk for revision surgery. The revision surgery will be more complicated than the primary surgery. Issue of stress shielding in the femoral shaft is closely related to the load and stress distribution along the femoral bone. The stress is dominant within the prosthesis stem until the distal end of the prosthesis. Then, the stress is transferred to the femoral bone. Higher stress indicated at the bottom region of the femur had demonstrated the phenomenon. The higher stress at the respective region promotes to bone thickening activity. Issue of stress shielding in the femoral shaft is closely related to the load and stress distribution along the femoral bone. The stress concentration of the femur increases as the implant position is narrowing in both varus and sagittal positioning, as compared to normal position.

Low stress distribution at the medial plane was observed in all analysis of the present study. The variation of stress in THA femur can be categorized based on the Gruen zone. The critical stress of all cases occurred at lateral plane (zone 1 – 3) and minimum at medial plane (zone 5 – 7). Higher stress at zone 4 (lateral) may lead to bone thickening and may lead to the risk of femoral bone fracture (18). The clinical study by Sychterz and Engh (19) reported that the proximal region produced the highest percentage of bone loss which is 42.1%, followed by 23% at the midsection and 5.5% in the distal region. The proximal region is essential to promote primary stability fixation during primary total hip arthroplasty (8). The high stress on various implant positioning may contribute to stress shielding effects which could also lead to bone resorption and loosening to the prosthesis. The bone loss due to stress shielding indicated that extensive bone loss and identified as the major reason for implant loosening (8, 20, 21).

The computational conducted in this study was limited to a basic of biomechanical model and may not accurately represent the behaviors of the bone. The adoption of homogeneous model in this study was less accurate compared to inhomogeneous model. Thus, the identification of cancellous bone by bone density not directly measured. These findings of stress distribution involved only the primary cementless THA, not a general analysis of revision arthroplasty or failed management of hip athroplasty. The analysis with an increment of loading will help to predict the critical effect of implant malposition such as bone fracture and implant loosening. Future work is warranted to consider for better analysis and prediction.

CONCLUSION

The finite element analysis demonstrated the biomechanical analysis in predicting the stress adaptation in total hip arthroplasty with different implant positioning. The variation of implant position in varus and sagittal plane had influenced the stress distribution and contribute to bone adaptation and stress shielding effects. The effects of varus positioning were more significant compared to sagittal position in predicting the stress adaptation. The degree of tilting also contributed to the changes for both positioning. The effect of varus and sagittal position also influence the longevity of implant which lead to femoral fracture and require revision surgery. Thus, the result suggests that an optimum implant position during pre-operative of cementless THA will provide better stress adaptation and implant stability to promote long term performance of surgery.

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