Study of Primary Stability of Hip Implant for Semi Hip Replacement by Using Finite Element Analysis

Haslina Abdullah, Mohamad Shukri Zakaria, and Norfazillah Talib

Abstract One factor contributing to the failure of hip arthroplasty or hip surgery is the loosening of the hip implant. Loosening of the hip implant is assessed by primary stability that is associated with the relative displacement occurring at the interface between the bone and the implant. The geometrical of hip implant significance influences the primary stability. Hence, this paper investigated the effect of the geometry of the implant to the primary stability. A three-dimensional of femur was constructed based on the computed tomography dataset acquired from a Malaysian patient. In contrast, the type of hip implant was produced based on the dimension of the bone. The finite element method was implemented to simulate the primary stability based on normal walking conditions. Then, the primary stability is defined based on the differences of displacement at the interface of the bone and implant interface. From the analysis, it was found that rectangular hip implants led to the better stability at the proximal area and the tips distal end of the implant. It can be concluded that the finite element method predicted the implant's primary stability and enhanced the surgery's performance.

Keywords Hip implant · Stability · Finite element analysis

1 Introduction

Hip surgery is a practice to substitute the injured bone in the hip joint with an implant known as hip stem. Through this surgery, it is expected to reduce the pain in a patient. To ensure the success and longevity of hip surgery, several factors need to

H. Abdullah (✉) · N. Talib
Faculty of Mechanical Engineering and Manufacturing, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia
e-mail: haslinaa@uthm.edu.my

M. S. Zakaria
Fakulti Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, Durian Tunggal, Melaka, Malaysia

M. H. A. Hassan et al. (eds.), *Proceedings of the 2nd Human Engineering Symposium*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-99-6890-9_11

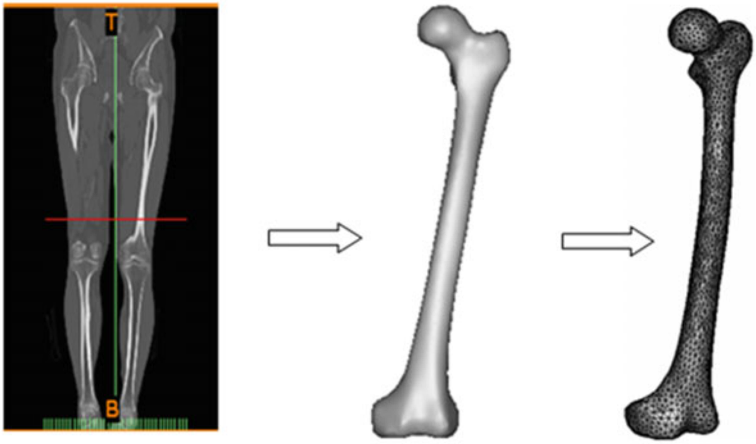
be considered, for example, distribution of the femur bone and the primary stability of the hip implant. Therefore, studying stress distribution and stability of the hip implant is essential. The finite element technique has been utilised to simulate the distribution of stress induced by hip implants. By using this simulation, it will help to design a better hip implant. There were many studies that have been conducted to perform the simulation of stress distribution in a hip implant. For example, Sahai et al. [1] developed a hollow lightweight hip implant model with biocompatibility material, Ti-6Al-4V material. In this study, there were three models of hip implants: design without hole, design with 3-mm hole and design with 4.5-mm hole. The feature of a hole is expected to produce lightweight of hip implant design. It was found that a design with 3-mm hole produced better stress distribution than the design with 4.5-mm hole, while Chethan et al. [2] performed simulation to analyse the consequences of implant geometry on the stress distribution. Several types of geometry have been developed: oval, circular, trapezoidal-ellipse and shaped stem designs. Based on the simulation, it was found that all the design had produced less stress than its yielded strength.

The implant material plays an essential role in ensuring the longevity of the implant. In the previous study by Bhawe et al. [3], two various of materials were studied. For the first set of designs, UHMWPE for the acetabular cup, Ti-6Al-4V was nominated as the backing cup material, CoCr has been chosen for the femoral head and Ti-6Al-4V was used for hip implant. For the second type, CoCr has been used for the backing cup, CoCr for the femoral head, UHMWPE used for the acetabular cup and CoCr material was used for the stem of the implant. A simulation has been executed to define the stress distribution, and it was found that the best arrangement of material was Ti-6Al-4V for stem and a backing cup of CoCr and an acetabular cup of UHMWPE that produced a lower von Mises stress. Meanwhile, Faris et al. [4] studied the effect of titanium-niobium-hydroxyapatite (Ti-Nb-HA) material weightage difference on stress distribution. However, the design of hip implant was fixed. There were five set of materials, such as Ti-6Al-4V, CoCr, Ti0%NbHA, Ti10%NbHA, Ti20%NbHA, Ti30%NbHA and Ti40%NbHA. It was found that the highest equivalent von Mises stress and maximum contact pressure are produced by the implant with Ti30%NbHA material.

Besides the geometry and materials, other types of activity also influenced the performance of the implant. Therefore, various researches have been performed to determine the effect of activity. A study by using finite element analysis (FEA) was conducted by Rosli et al. [5] to evaluate the different types of cycle on deformation of the implant based on different activities, such as slow walking, tripping, climbing and climbing down. Based on the simulation, it showed that tripping affects to produce larger stress and strain distribution in the hip joint, with the biggest total deformation occurring on the acetabular cup. At the same time, slow walking had the lowest parameters, while a study conducted by Putra et al. [6] made a comparison between three types of activities, such as normal walking, walking down of stairs and jumping. The study showed that the activity walking down the stairs produced higher principal stress. Similar results were also obtained based on the study by Annanto et al. [7], whereby jumping activity produced higher stress in the artificial hip implant. It can be concluded that activities with more movement influenced the stress and strain in hip implant.

Besides the stress and strain distribution, many authors have agreed that primary stability is one of the circumstances that played a role to the continuing longevity [8, 9]. Camine et al. [10] constructed a collarless implant and collared type to study the effect on primary stability based on loading conditions, with good press-fit. It was observed that the effect of collar gave no significant difference in primary stability of the implants. Both designs produced good stability, with lower micromotion below the decided threshold, whereas the collar did not influence subsidence or micromotion. On the other hand, the alteration of the Zweymüller stem with smaller proximal design did not significantly affect the axial stability but affecting the rotational stability [11]. To achieve a better stability, the condition of the surface between bone and the implant is also considered as a factor that influenced the stability. In a research performed by Ismail et al. [12], the impact of the value of interference fit (δ) on the stability has been performed by defined coefficient of friction, such as 0.15, 0.40 and 1.00. It was discovered that the 0.50-mm interference fit produced a better primary fixation. In a research by Kanaizumi et al. [13], the stability was determined based on the value of micromotion. The implant design with a short stem, rectangular cross-section and with fins. The investigation showed that the rectangular stem and finned stem did not affect the primary stability. However, the highest micromotion had occurred at the proximal and tip of hip stem. Besides, Hosny et al. [14] and Lomami et al. [15] measured the stability of hip implants by using a different method known as EBRA-femoral component analysis (FCA) software, as a gauge of accomplishment of initial stability.

Primary stability indicated the total of micromotion occurring at the interface between bone and the implant stimulated by the physical loading instead of the biological development. Though, secondary stability is the micromotion at the bone-implant surface as soon as the biological process is completed [16]. Many aspects affect the initial stability, for instance, geometrical aspects and properties of implant material, quality of the bone, and the types of patient's activity. Several methodologies have been applied in assessing the stability of either by using a simulation or experimental work. These methods were essential to increase the fixation of hip implant and the effectiveness of the hip surgery. Therefore, this study's motivation is to evaluate and verify the displacement at the interface of bone and implant for the cementless type of implant by considering the effect of the geometry of the implant by focusing on the impact of shoulder at the proximal region of the hip implant. Then, the difference in micromotion between cylindrical and tapered rectangular designs was studied. In this paper, an investigation on the effect of cylindrical, trapezoid and rectangular hip implant by using finite element analysis was performed. The main purpose is to estimate the displacement between the surface of bone and implant based on normal walking situations. A three-dimensional femur bone created from the CT dataset was acquired from a Malaysian patient. Then, the implant was produced to fit the size of the femur bone.



(a) (b) (c)

Fig. 1 Process of development of bone: **a** CT dataset, **b** 3D model of bone and **c** mesh bone

2 Methodology

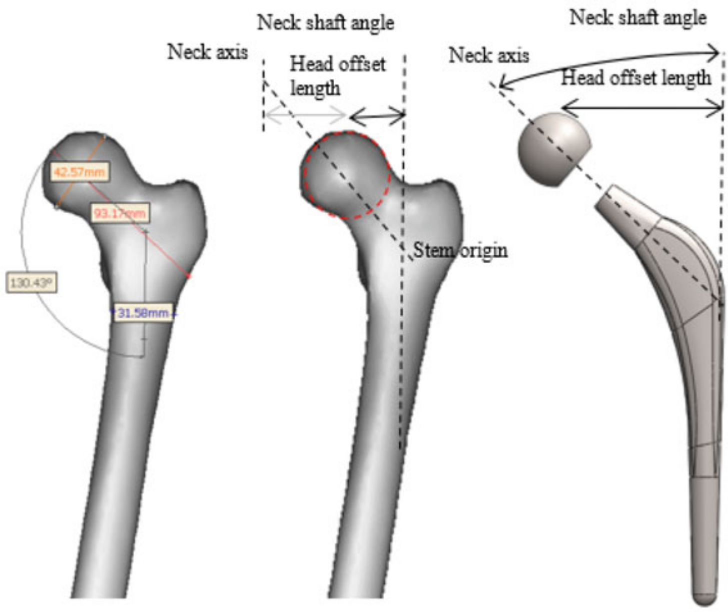
2.1 Development of a Three-Dimensional of Femur Bone

In this study, the three-dimensional femur bone was created established from a computer tomography (CT) dataset acquired from a Malaysian patient. This is because the design of the implant should follow the size of the Malaysian patient. To construct the bone, the slice of the two-dimensional dataset was collected repeatedly to create the triangular surface of the femur bone by using AMIRA software. Figure 1 shows the finalised of the completed femur bone with a triangle meshing.

2.2 Development of a Three-Dimensional Hip Implant

To ensure the design of the hip implant is fixed with the bone when inserted into the cortical area, the implant was constructed based on the dimension of the femur bone extracted from morphological data. The size and the dimension of the hip implant must be related to the geometric of the bone as demonstrated in Fig. 2a, b. Several geometric constraints must be measured to construct a good hip implant, such as femoral head diameter, angle of femoral neck shaft, length of femoral head offset and size of the isthmus.

In this study, there were three types of the hip implant constructed, as shown in Fig. 3a–c. For the first design, the characteristics were cylindrical, straight, double tapered and collarless. Then, for the second design, the implant was designed with



(a) (b)

Fig. 2 Relationship between the size: **a** femoral bone, **b** implant

a larger cross section at the proximal section as illustrated in Fig. 3b, while for the third design, the cross section of the implant was altered to rectangular cross section with a larger area at the proximal area. The purpose of constructing these design was to examine the influence of cylindrical and trapezoid section on the primary stability.

Both the 3D femur and the hip implant were saved as STL files to be imported into the finite element software for the simulation procedure. However, only a half-model femur bone was considered for the part of the bone. With half femur, it would reduce the time of the simulation. For the simulation contact analyses, inserting the implant into the canal space was assumed to be seamlessly fit. Table 1 illustrates the mechanical properties that implemented in the finite element simulation, which is adopted from Singh and Harsha [17]. In this analysis, the materials were presumed elastic, homogenous and isotropic.

The initial or primary stability of the hip implant is evaluated by defining the differences value of displacement between the node of the bone and the implant. Therefore, contact analyses were implemented in the simulation. The interface between the bone and implant was assumed the frictional contact. In the contact analysis, the master surface needs to be defined for the implant and slave surface of the bone. Static loading was applied on the node on the femoral bone based on normal walking conditions and load value, as depicted in Table 2. The magnitude and position of force gained from [18] are shown in Fig. 4.

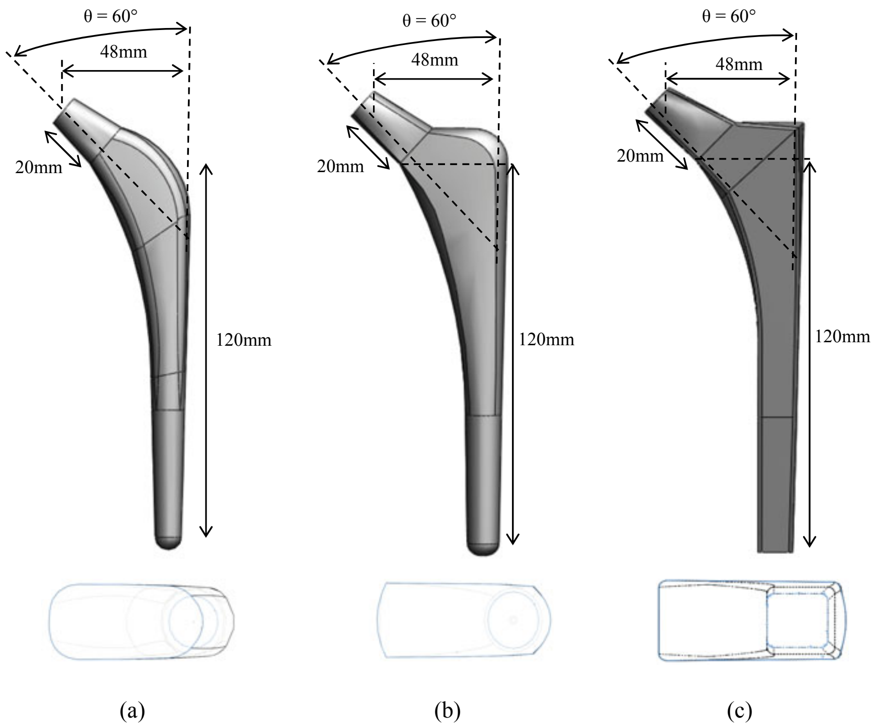


Fig. 3 Construction of 3D model of hip implant: **a** cylindrical, **b** cylindrical with larger proximal and **c** rectangular tapered with larger proximal

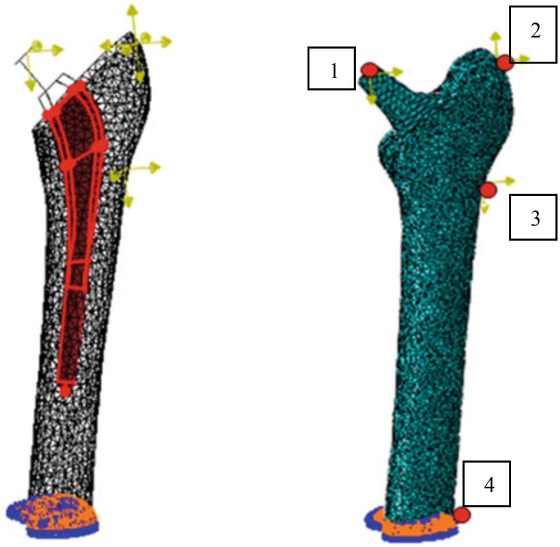
Table 1 Properties of material

Materials	Elastic modulus (GPa)	Yield strength (MPa)	Poisson ratio (ν)
Cortical bone	17.26	115	0.29
Titanium alloy	110	485	0.3

Table 2 Loading condition of normal walking

Force (N)	X	Y	Z	Point ()
Joint contact force	433.8	263.8	−1841.3	1
Abductor force	−465.9	−34.5	695	2
Tensor fascia lata, distal part	−4	−5.6	−152.6	2
Tensor fascia lata, proximal part	57.8	93.2	106	2
Vastus lateralis	7.2	−148.6	−746.3	3
Fixed	0	0	0	4

Fig. 4 Position of forces



3 Results and Discussion

The amount of relative displacement at the interface of bone and implant has been assessed in evaluating the primary stability on the effect geometrical of hip implant design. The displacement denotes to the primary stability of the implant attained by investigating the movement of nodes at the contact surface of implant and in x, y and z directions. Better stability is represented by a lesser relative displacement. The acceptable threshold value of relative displacement must be within 40–150 µm. In addition, the value of less than 40 µm will encourage osteointegration and enhance the bone growth rate to the implant surface. In contrast, the magnitude of relative displacement more than 150 µm indicated that the development of membrane tissue at the interface of bone and implant interface and led to the loosening of the implant. Figure 5 illustrates the graph of relative displacement for the first design occurring at the lateral and medial areas.

The graph shows that the relative displacement on the lateral side was between 2 and 33 µm. Since the displacement was lower than 40 µm, there was no significant difference and will not cause any failure of the implant. On the other hand, the magnitude of relative displacement along the medial side was between 2 and 146 µm. As this magnitude was within the threshold value, it would not contribute to any failure. It can been seen that normal walking activity produced the highest relative displacement at the proximal area along medial and lateral areas. This result findings agreed with the previous research conducted by Kanizumi et al. [13] and Chanda et al. [19].

To examine the effect of proximal shoulder and rectangular tapered design on the stability of implant, contact node has been defined along the lateral side as shown

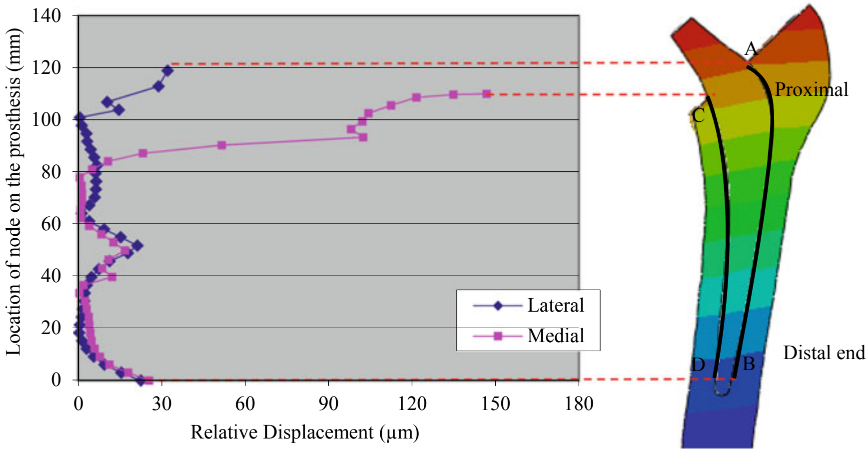


Fig. 5 Relative displacement for initial design along lateral and medial sides of initial design

in Fig. 6 and a graph of relative displacement was plotted as depicted in Fig. 7. It can be seen that the relative displacement for the initial design along the lateral side was lower than 40 µm. This magnitude was expected to enhance the bone growth. However, for the second and third designs, the values of relative displacement were higher than 40 µm. However, the value was within the area of critical threshold value. Although the magnitude did not exceed the maximum limit value, it was estimated to decrease the amount of bone growth to the implant surface. Similar to the initial design, the magnitudes of relative displacement for the second and third designs were larger on the proximal region due to bending loading.

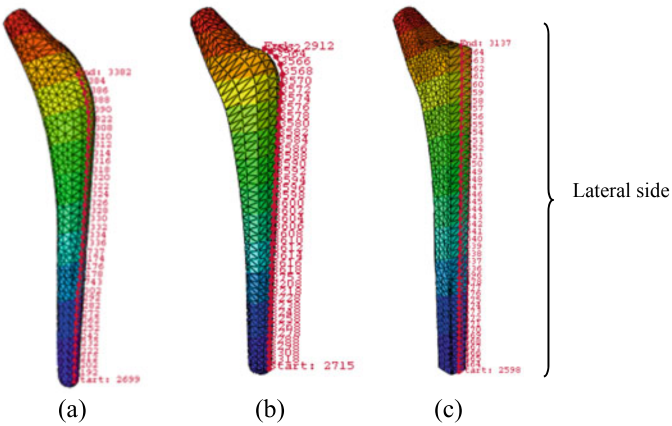


Fig. 6 Selection of node on the lateral side: **a** cylindrical design (initial design), **b** cylindrical with larger shoulder (second design) and **c** rectangular tapered (third design)

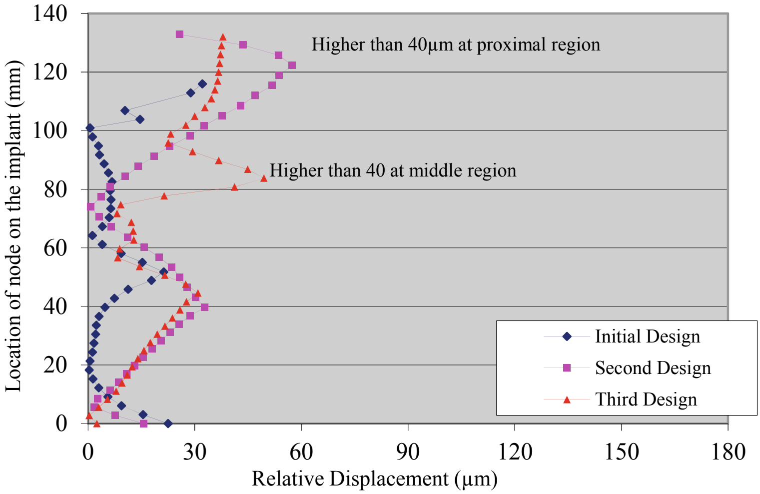


Fig. 7 Comparison of relative displacement for initial design along lateral sides

Generally, the value displacement for the second design along the lateral side was between 2 and 62 µm. This magnitude did not lead to loosening of prosthesis. Due to the larger proximal area at the shoulder, it decreased the relative displacement from 33 to 24 µm. This indicated that the larger surface area of prosthesis on the proximal region produced proximal fixation of prosthesis and increased the primary stability of prosthesis. For the third design, the magnitude of relative displacement along the lateral side was between 1 and 49 µm. Similar to the relative displacement of the second design, this magnitude did not lead to loosening of prosthesis. Overall, the values of relative displacement for all designs were sufficient to induce the bone growth to prosthesis surface.

Figure 8 shows the selection of node on the medial side. A graph has been plotted in Fig. 9 along the medial side to investigate the stability on the medial side; it can be observed that the highest relative displacements for all designs of prosthesis along medial side also occurred at the proximal region. For the second design, the maximum value of relative displacement was 149 µm, and for the third design, the highest value of relative displacement was 102 µm. Table 3 presents the summary of relative displacement for initial, second and third designs on the lateral and medial sides.

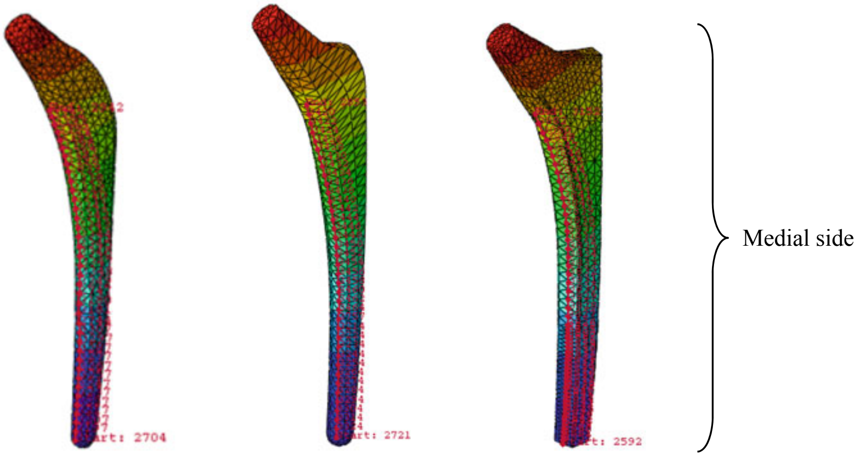


Fig. 8 Selection of node on the lateral side: **a** cylindrical design (initial design), **b** cylindirical with larger shoulder (second design) and **c** rectangular tapered (third design)

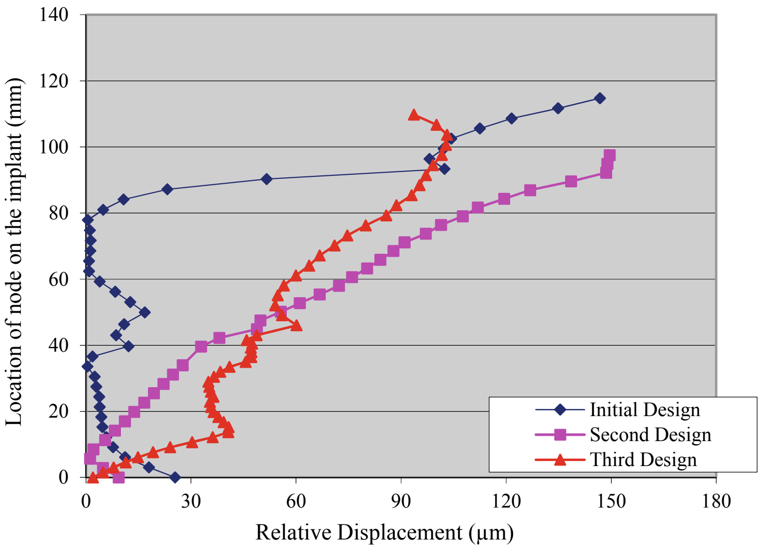


Fig. 9 Comparison of relative displacement for initial design along medial sides

Table 3 Summary of relative displacement on lateral and medial side

Prosthesis	Lateral		Medial	
	Highest value (μm)	Lowest value (μm)	Highest value (μm)	Lowest value (μm)
Initial design	40	2	146	2
Second design	**62**	**2**	**149**	**3**
Third design	59	1	102	2

4 Conclusion

To achieve the hip implant's a better stability, the dimensions of the implant are referring to size of the bone from a patient. This study focused on the implant design based on the collarless and cementless types. The stability of the hip implant for hip surgery was evaluated by determining the relative displacement of node on the surface of the implant between the node on the bone surface by using the finite element analysis. The relative displacement was measured along the medial and lateral sides. Then, the value was compared with the threshold value, which is 40–150 μm. For the first design, it was found that the relative displacement on the lateral side was between 5 and 3 μm. These amounts were within the threshold limit of between 40 and 150 μm. However, along the medial side, the relative displacement was between 5 and 146 μm. The maximum relative displacement was close to the maximum threshold value and was expected that it could lead to the loosening of the implant if a higher loading was applied. Therefore, several other geometries need to be created in order to produce a hip implant with a better stability.

Acknowledgements This research was supported by University Tun Hussein Onn Malaysia (UTHM) through Tier 1 (vot Q384). The authors also would convey their appreciation to the University Teknologi Malaysia.

References

1. Sahai N, Saxena KK, Gupta N, Garg S, Bora U, Baishya UJ, Borah V (2021) Designing and simulation of a lightweight hip implant stem: an FEM based approach. Adv Mater Process Technol 00(00):1–9
2. Chethan KN, Shyamasunder Bhat N, Zuber M, Satish Shenoy B (2019) Finite element analysis of different hip implant designs along with femur under static loading conditions. J Biomed Phys Eng 9(5):507–516
3. Bhawe AK, Shah KM, Somani S, Shenoy BS, Bhat NS, Zuber M, Chethan KN (2022) Static structural analysis of the effect of change in femoral head sizes used in total hip arthroplasty using finite element method. Cogent Eng 9(1)
4. Faris M, Manap A, Shuib S, Ismail H, Zainudin M, Shaari NS (2022) Comparative analysis of TiNbHA with existing materials for hip implant using finite element method. In: Proceedings of mechanical engineering research day, pp 109–110

5. Rosli INAM, Shuib S, Shokri AA, Ghani ARA, Hamizan NS, Arrif IM (2021) Development of hip implant: gait study and finite element analysis. In: 1st national biomedical engineering conference, NBEC 2021, pp 30–35
6. Putra AD, Andoko, Wulandari R, Kurniawan GA (2020) Simulation of hip joint implants using finite element method with time and load variations. Key Eng Mater 851:111–121
7. Annanto GP, Saputra E, Jamari J, Bayuseno AP, Ismail R, Tauviqirrahman M, Anwar IB (2018) Numerical analysis of stress distribution on artificial hip joint due to jump activity. E3S Web Conf 73:1–5
8. Panwar K, Cutter B, Holmboe M, Card R, Pistel W, Law JI (2016) Instability in total hip arthroplasty. INTECH 11:13
9. Fontalis A, Epinette JA, Thaler M, Zagra L, Khanduja V, Haddad FS (2021) Advances and innovations in total hip arthroplasty. Sicot-J 7
10. Malfroy Camine V, Rüdiger HA, Pioletti DP, Terrier A (2018) Effect of a collar on subsidence and local micromotion of cementless femoral stems: in vitro comparative study based on micro-computerised tomography. Int Orthop 42(1):49–57
11. Bieger R, Freitag T, Ignatius A, Reichel H, Dürselen L (2016) Primary stability of a shoulderless Zweymüller hip stem: a comparative in vitro micromotion study. J Orthop Surg Res 11(1):10–15
12. Ismail NF, Shuib S, Yahaya MA, Romli AZ, Shokri AA (2018) Finite element analysis of uncemented total hip replacement: the effect of bone-implant interface. Int J Eng Technol (UAE) 7(4):230–234
13. Kanaizumi A, Suzuki D, Nagoya S, Teramoto A, Yamashita T (2022) Patient-specific three-dimensional evaluation of interface micromotion in two different short stem designs in cementless total hip arthroplasty: a finite element analysis. J Orthop Surg Res 17(1):1–9
14. Hosny HAH, Srinivasan SCM, Hall MJ, Keenan J, Fekry H (2017) Achievement of primary stability using 3D-CT guided custom design femoral stems in patients with proximal femoral deformity: EBRA-FCA analysis. Acta Orthop Belg 83(4):617–623
15. Albini Lomami H, Damour C, Rosi G, Poudrel AS, Dubory A, Flouzat-Lachaniette CH, Haiat G (2020) Ex vivo estimation of cementless femoral stem stability using an instrumented hammer. Clin Biomech 76(April):105006
16. Vollmer A, Saravi B, Lang G, Adolphs N, Hazard D, Giers V, Stoll P (2020) Factors influencing primary and secondary implant stability—a retrospective cohort study with 582 implants in 272 patients. Appl Sci (Switzerland) 10(22):1–14
17. Singh S, Harsha AP (2016) Analysis of femoral components of cemented total hip arthroplasty. J Inst Eng (India) Ser D 97(2):113–120
18. Rafiq M, Kadir A, Hansen UN (2007) The effect of physiological load configuration on interface micromotion in cementless femoral stems. Jurnal Mekanikal 23:50–61
19. Chanda S, Mukherjee K, Gupta S, Pratihar DK (2020) A comparative assessment of two designs of hip stem using rule-based simulation of combined osseointegration and remodelling. Proc Inst Mech Eng, Part H J Eng Med 234(1):118–128