Prediction of Bone Damage Formation in Resurfacing Hip Arthroplasty

Nor Aiman Nor Izmin, Mitsugu Todo, Abdul Halim Abdullah

Abstract**:** ***Resurfacing Hip Arthroplasty (RHA) is a hip replacement method that is widely known nowadays. However, the complication on femoral bone fracture often happens in this hip replacement method which associated with the implant positioning. The objective of this study is to predict the damage formation on the bone which resulting from the RHA pin malposition. Finite element analysis was conducted in order to predict the damage formation on the bone model based on the computed tomography (CT) image of a patient. A 3D inhomogeneous bone model was developed from a 47 year old patient with an osteoarthritis disease located on the left femur. The material used for the RHA implant model is cobalt chromium and the implant is then being inserted into the femoral bone. Straight implant position with angle 130° was selected as a reference in the analysis while another three position of varus (> 130°) and valgus (<130°) were selected and known as the pin malposition. The simulation was conducted on each of the selected angles in order to predict the damage formation towards the bone model. The damage formation obtained was from the results of elements failure which occurred after applying the load. Physiological loading of a human which focusing on the normal walking condition was selected as the loading and boundary condition in this study. The femoral bone model experienced the highest damage formation when the implant located at the varus position while reduced significantly when the implant placed at the valgus position.***

Index Terms**:** ***Hip Osteoarthritis, Resurfacing Hip Arthroplasty, Implant Positioning, Bone Fracture, Damage Formation***

I. INTRODUCTION

Resurfacing Hip Arthroplasty (RHA) is one of the hip replacement methods in solving the problem related to the human hip. Since the past decade, orthopaedic surgeons are showing their interest in using this method as an alternative besides the other method which is Total Hip Arthroplasty (THA). End stage of osteoarthritis patient can use this method and it is recommended for the young man with active lifestyles [1]. Since there are more than one methods in hip replacement, therefore, both of the methods had their own specialties and risks. In general, the surgical procedure of Resurfacing Hip Arthroplasty (RHA) method is simpler than the conventional method, Total Hip Arthroplasty (THA). The affected area of the femoral head of the femur caused by the hip disease will be removed and being replaced by the RHA implant. Despite the surgical process is simpler however, there are many cases reported on the failure of RHA [2]. Complication on the femoral bone fracture often happened to the patients that having a Resurfacing Hip Arthroplasty (RHA) especially on the femur neck area [2], [3].

There are plenty of tendencies of femoral bone fracture by having the RHA method. One of the potential tendency towards the fracture and being discussed among the cohorts is the poor surgical technique. The poor surgical technique here is been interpreted when there is a mal-positioning or misalignment of the RHA implant. Based on the study made by Freeman et al., 81.4 percent (%) of all failures aside from the patient selection and design error was being caused by the technical errors [3]. In human anatomy, the femoral bone has its own dimensions. Naturally, the normal angle of the human femoral neck is 130° to the femur shaft [4]. Therefore, if the implant is more or less than this natural angle which also known as varus and valgus position, it can be categorized as implant mal-position [5], [6].

Higher implant stiffness could reduce the load transfer from the implant to the proximal femur thus the stress shielding will be increased [7]. Stress shielding that occurred as an effect from the insertion of the implant could reduce the bone strength since the bone needs encouragement to keep remodeling to maintain its mass. Since the load that usually taken by the bone has reduced and the load exerted more towards the implant, thus the bone becomes weaker [8]. The implant itself has a huge impact in terms of bone strength, therefore, malposition of the implant might also contributing to the incompatibility of stress and increasing damage at the femur bone. Thus the aim of this study is to predict the damage formation against the bone with RHA implant malposition and as a consequence, it maybe hastens the ability of femoral bone fracture.

II. MATERIALS & METHOD

CT Based Image was used in this study. The purpose of using CT image is to develop the 3D bone model aside from it can produce more accurate quantitative data on bone geometry by differentiating the contrast between human bone tissue and soft tissue [9], [10]. The CT image which is in a standard DICOM format. As recommendation stated on patient suitability to perform RHA [11], CT image of a patient by age 47 years old with a hip osteoarthritis disease on his left femur was selected.

Revised Manuscript Received on 20 October, 2019.

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The CT image has been imported into Mechanical Finder v10, a commercial biomedical software in order to develop the 3D model by FE analysis. Tetrahedron elements were applied for the bone model. In this study, the inhomogeneous bone model has been developed. The inhomogeneous bone model was generated as the 'apparent density' and gray data values in Hounsfield units (HU) for each element were assumed to be in a linear relationship [12]. As for the material properties on the bone elements, the study by Keyak et al. [13], [14] was applied and Fig. 1 shows the bone mineral density and young's modulus on the pre-operative femoral bone model of the patient. Cortical and cancellous bones can be referred to the higher and lower values of the Young modulus respectively.

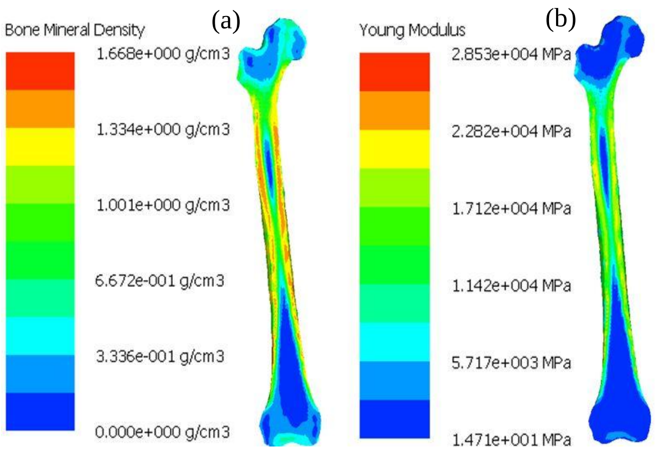

Fig 1: (a) Bone mineral density distribution and (b) young modulus of inhomogeneous femur model

A. Resurfacing Hip Arthroplasty Model

Resurfacing Hip Arthroplasty implant was inserted into the bone in the Mechanical Finder v10 software as a replacement for the affected femoral head. The pin was aligned properly in order to archive the straight implant position. The insertion of the straight implant was determined by referring to the midline of the anatomic axis of the femoral neck with the implant pin. The angle of 130° was measured by referring to the shaft midline as in Fig. 2. The material used on the RHA implant is Cobalt Chromium Alloy (CoCr) with its mechanical properties are the same as the study made by A. H. Abdullah et al. [15] where the Elastic modulus (GPa), Poisson ratio, Critical stress (GPa), Yield stress (GPa) and Density (g/cm^3) are 230, 0.30, 0.94, 2.70 and 8.28 respectively. The connections between bone and RHA implant were assumed to be rigidly bonded.

B. Malposition of Resurfacing Hip Implant

In the interest to identify the effects of pin malposition towards the bone, three (3) different angle of malposition varus and valgus has been selected. In order to simulate the effects from all these angles, a straight implant was inserted into the femur bone model before the implant angle being alternated to the desired varus and valgus position. The minimum angle for the malposition starts with the addition of 8° from the straight implant followed by 2° of increment consequently. The varus and valgus zone are as shown in Fig 3. The preferred angles of varus and valgus positions that have been used for simulation in this study were indicated in Table I. As for the elements, the total number of both bone and the straight implant is 39182. The total elements (including bone) for varus position 138°, 140°, and 142° are 166914, 166004 and 166251 in each instance. For the valgus position, the total elements are 166794, 167091 and 167316 for the angle of 122°, 120° and 118° respectively.

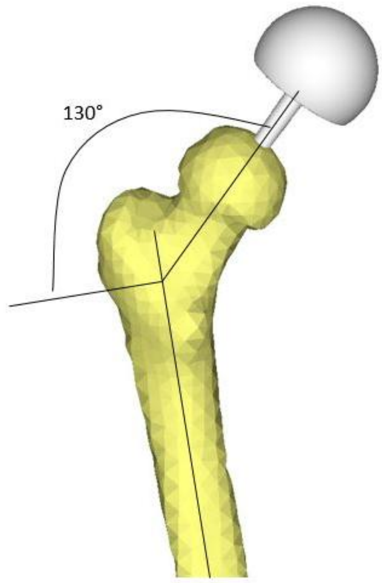

Fig 2: Insertion of straight RHA implant

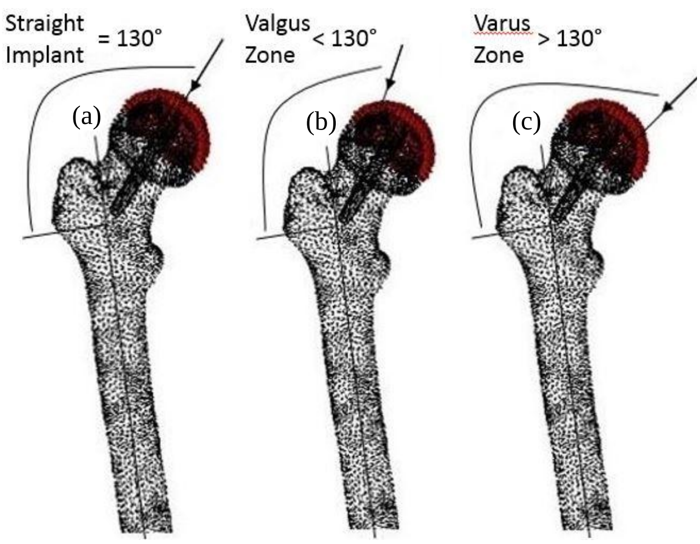

Fig 3: (a) Straight RHA pin = 130° (b) Valgus position RHA pin < 130° (c) Varus position RHA pin > 130°

Table I: Selected angle of pin malposition in this study.

Valgus position (<130°)	122°
	120°
	118°
Varus position (>130°)	138°
	140°
	142°

C. Loading and Boundary Condition

The simulation performed is this study focused on the physiological loading of a human. In human daily activities, the force acting on a body is a part of physiological loading. In this paper, the normal walking condition was selected as the loading condition. As the comparison made from the humans' daily activity such as standing (up and down), normal walking movement and stair climbing; normal walking is the second condition that having the highest loaded hip contact force aside from stair climbing. According to the study made by Bergman et al. [16], the human hip was loaded with 238% of the person bodyweight (BW) during normal walking. As for the stair climbing, the joint contact force acting on the human hip was slightly more which is 251% of BW when going upstairs and 260% BW for downstairs. Patients are advised to avoid extreme activities after performing the resurfacing hip arthroplasty therefore, the normal walking condition is enough to be applied as loading condition in order to identify the effects of pin malposition towards the bone since it is a common activity for every human.

The force was applied to the femoral head and greater trochanter on the femur in which these areas exposed the most within the region of interest [17]. Heller et al. [18] suggested that 104% BW known as abductor force took place on the greater trochanter during normal walking, hence both forces were used to simulate the peak loads during normal walking. A 2045.267 N of force exerted on the femoral head while 893.73 N applied on the greater trochanter by referring to the patient body weight. The direction of forces applied (Fig. 4) is the same as the published study on the human hip forces during walking [18,19,20].

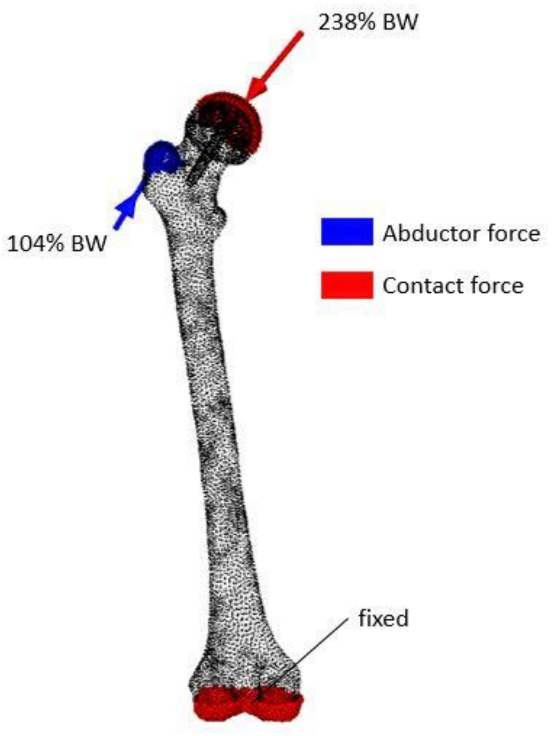

Fig. 4: Contact force and abductor force direction.

D. Failure of Elements

Failure of the element can be predicted in the Mechanical Finder v10 software. There were numbers of cracked solids, plastic solids, and crushed solids which representing the tensile and compression towards the element when the load applied. Based on the failure element structure at the bone model, damage formation could be seen and it could lead to the prediction of the bone fracture. The failure of element criterion on the inhomogeneous bone model was determined as a result of the Drucker-Prager equivalent stress as summarized in Table II.

Table II: Failure of element criterion [15].

Failure direction		
tensile	Initiation to failure	$\sigma_p > 0.8\,\sigma_r$
Compressive	Transition to yielded state	$\sigma_D > \sigma_r$
	Initiation of failure	$\varepsilon_p < -3000$ (in yield state)

σ_p = maximum principal stress
σ_D = Drucker-Prager equivalent stress
σ_r = yield stress
ε_p = minimum principal strain

The potential of bone fracture is higher when there is an increment of failure elements. As a comparison on the real event, the bone tends to fracture if there is a damage on the cortical bone [20] and for the case of cancellous bone, small damage from it may not be effect critically to cause a fracture. In that case, failure elements showed in this study were on the cortical bone. Overall, the structure of damage formation towards the bone can be determined based on the failure elements on the bone model.

III. RESULTS & DISCUSSION

The results obtained from the subprogram installed in the Mechanical Finder v10. Based on the CT image of the patient, inhomogeneous femoral bone has been developed. As the load applied, this study was able to determine the minimum and maximum stress exerted on the bone and also predicting the damage formation based on different RHA pin malposition.

A. Stress Analysis on the Bone Model

In this computational study, reading of maximum and minimum principal stress for each implant positions have been taken. Every angle of the selected pin position is giving a different stress value towards the bone model. The angle of the straight implant which is 130° is selected as a reference to compare with the other angles. Fig. 5 shows that the value of the minimum and maximum principal stress for each angle.

Results in Fig. 5 show the values on maximum and minimum principal stress between all angles of implant position. The maximum principal stress of the femur model had increased as the implant moves towards the varus position. By referring to the

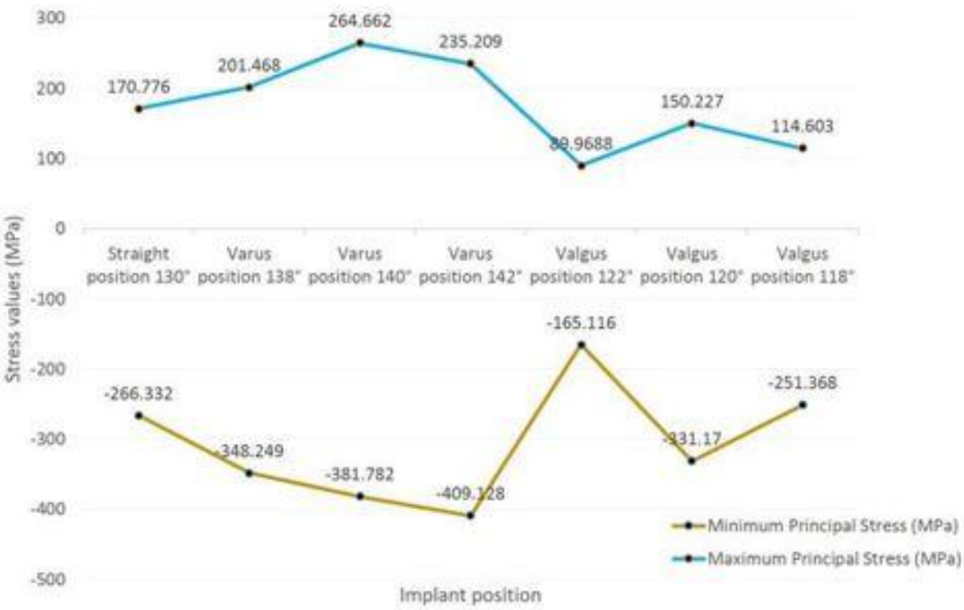

Fig. 5: Result of maximum and minimum principal stress between all angles

straight implant, the stress is rising from 170.776 MPa until reaching its highest value among all positions which acting on the varus position 140° with a stress value about 264.662 MPa. The maximum stress, however, decreased when the implant positioning moves towards the valgus position. The lowest maximum principal stress value acting on the femur model is on the valgus position 122° by only 89.97 MPa which even lower than the straight implant position. The results also show that, the other two angles on the valgus position which are 120° and 118° also having a lower stress value as compare to the straight implant. Maximum principal stress acting on the bone mainly shows that the area is experiencing a tensile condition. The comparison of contour display on maximum principal stress between (a) straight implant, (b) varus position 140° and (c) valgus position 120° are as shown in Fig. 6.

As for the minimum principal stress, the pattern is much likely with the maximum principal stress that acting on the varus position. The stress values had increased from -266.32 MPa from straight implant positioning to the highest value which taking action on the varus 142° position with -409.13 MPa. The values significantly drop when it comes to valgus positioning. Valgus 122° position once again is having the lowest minimum principal stress value that is less than the straight inserted implant with only -165.17 MPa. However, in this minimum principal stress result, the other two angles on the valgus position which are 120° and 118° are slightly more than the straight implant. The minimum principal stress showing that the affected area is facing a compression condition when the load applied onto the femur bone.

Comparison of contour display for minimum principal stress occurred between these angles are as shown in Fig. 7. The figure represented by the highest value between varus position and valgus position by comparison with a straight implant.

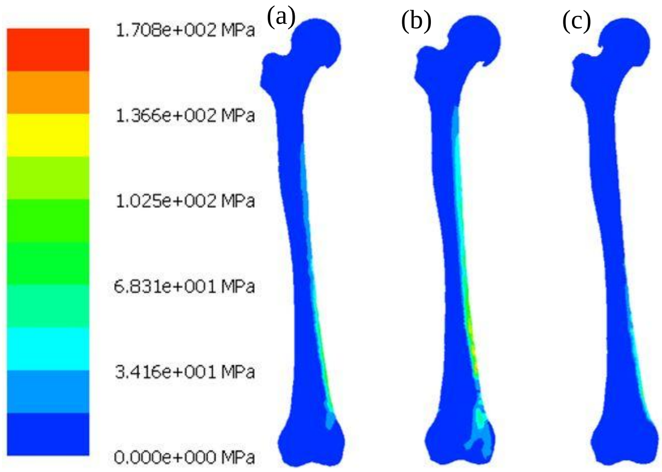

Fig. 6: Contour display of maximum principal stress between (a) straight implant, (b) varus position 140° and (c) valgus position 120°

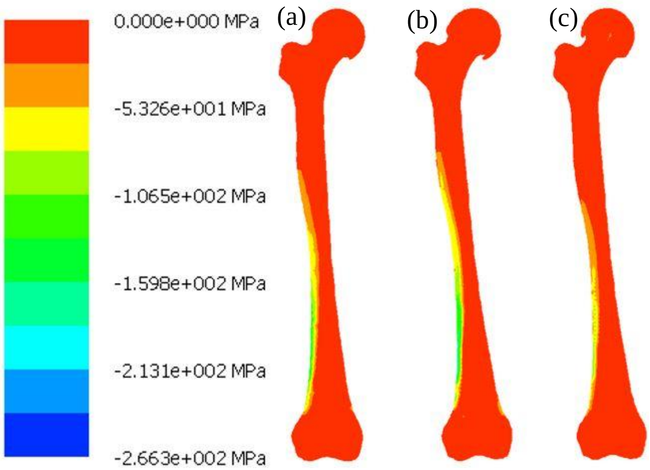

Fig. 7: Contour display of minimum principal stress between (a) straight implant (b) varus position 142° and (c) valgus position 122°

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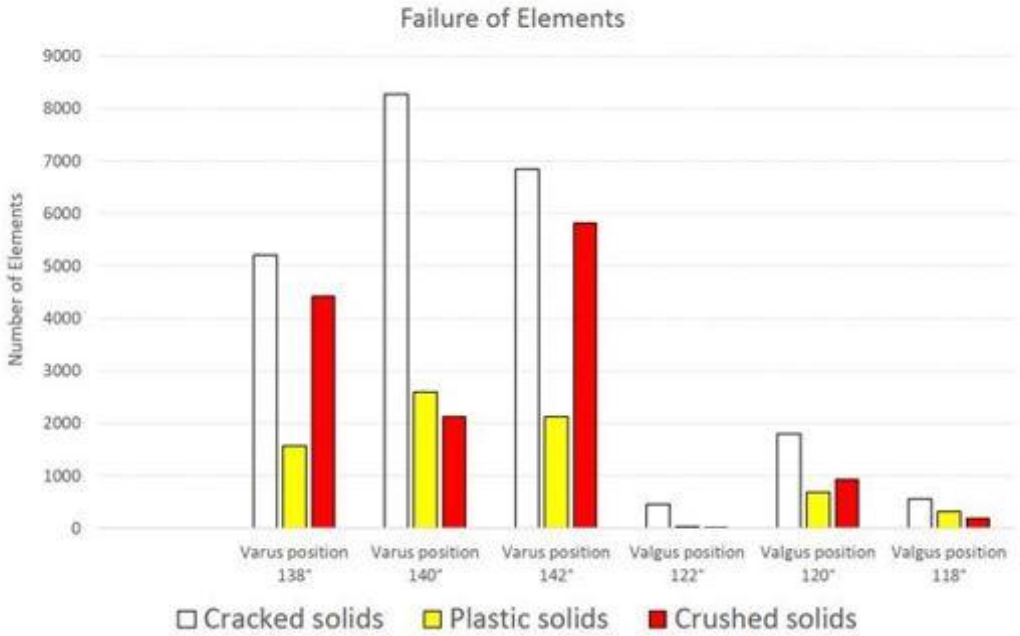

Fig. 8: Failure of elements information between implants angle.

The results shown are based on the normal walking condition with the loading direction. The load is based on the peak cycle during walking. Therefore, the prediction on the maximum principal stress is dominant on the inner side of the cortical bone which acting on this left femur since the area is having the highest tensile stress condition while taking a step upon waking. The fixed end representing the condition during taking a step. Concerning the compressive stress, it happened the most towards the other side of the cortical bone during this peak load of walking condition. The stresses variation on the bone explained that the bone adaptation occurred for every different angle of implant position [21].

B. Prediction of Damage Formation on the Bone Model

The aim of this study is to predict the effects of damage formation on the femur bone model based on the RHA pin malposition. In that case, the element failure will be taken into consideration as to predict the damage formation which leads to the potential of bone fracture. The elements failure has appeared in three (3) conditions which are cracked solids, plastic solids, and crushed solids. The displays that indicate on all these three conditions are white, yellow and red respectively. Fig. 8 shows the data information of failure elements while Fig. 9 and Fig. 10 show the display of damage formations of all the pin malposition implants.

Cracked solids has corresponded to the tensile failure while plastic solids and crushed solids were represented the compression failure. The cracked solids occurred when the principal stress of the element exceeds the critical stress. Regarding the plastic solids, the failure of the element becomes plastic when the equivalent stress exceeds yield stress and for the crushed solids, it happened when the minimum principal strain of the plastic element exceeds crush strain.

The major failure of elements was expected to occur on the varus position 140° since this position also has the highest value of maximum principal stress. There were 8270 elements turns cracked, 2601 becomes plastic and 6782 elements crushed out of 166004 from its total elements when the load applied. Fig. 9 (b) shows that the crushed solids elements are dominant on the left side of the femur while plastic solids element occurs in the middle part of the femur. On the right side, the majority of the elements experience a crack solid. Significant damage formation emerges clearly at the distal end of the femur while there is no sign of damage at the femur neck area upon this loading magnitude. As for the varus position 138° and 142°, the numbers of failure elements were also huge as comparison towards the valgus position.

Meanwhile, the valgus position presents a significant difference in damage formation. There were only small elements that failed when the implants were shifted into the valgus positions. Minor failure of elements happened on the valgus position 122°. There were only 486 of cracked elements, 37 elements become plastic and 12 elements turned crushed out of 166794 from its total elements. Most of the failure elements happened in the middle of the femur which located around the distal end as in Fig. 10 (a). In regard to the other two valgus positions, 120° and 118°, the damage formation were also better than the varus position. There was also no sign of damage element occurred on the femur neck area based on the loading magnitude applied in this study.

The results in this study were highlighted on the RHA implant positioning towards the femoral bone. Potential of bone fracture is higher when the pin malposition happened in the varus position while the results in valgus position showed were vice versa. Based from the damage formation results, we agreed that placement of the RHA implant towards the valgus position below 10° may reduce the potential of bone fracture and increase when the implant

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located on varus position. This result is similar to the conclusion on findings made by Angelin et al. [22] and Radcliffe et al. [23] while improving the findings by predicting the damage location that may lead to the initiation of bone fracture.

In addition, the damage formation which affected from the pin malposition in RHA is predicted to increase significantly especially on varus position with the increment of loading magnitude as proven in the study made Abdullah et al [24].

Fig. 9: Damage formation of (a) varus position 138° (b) varus position 140° (c) varus position 142°

Fig. 10: Damage formation of (a) valgus position 122° (b) valgus position 120° and (c) valgus position 118°

IV. CONCLUSION

The pin malposition had influenced the stress distribution and damage formation towards the bone. Our findings suggested that the RHA implant towards the valgus position below 10° may reduce the potential of bone fracture and increase when the implant located on varus position. Further research continuation can be made on this study by applying a different loading and boundary conditions which focusing on the other types of physiological loading that acting on a human. In addition, to clearly see the fracture results, it is also can be obtained by increasing the loading magnitude by the percentage of the patient body weight (%BW).

ACKNOWLEDGMENT

This research was supported by Universiti Teknologi MARA, UiTM under Grant No. 600-IRMI/PERDANA 5/3 BESTARI (103/2018). We thank and acknowledge Ministry of Education, Malaysia and to our colleagues from Faculty of Medicine, UiTM who provided insight and expertise that greatly assisted the research.

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