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Different Material Properties of Cancellous Bone Influence Glenoid Component Loosening: A Finite Element Study.

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ABSTRACT

Glenoid component loosening is one of the common complications after total shoulder arthroplasty. In investigating the glenoid component loosening, the finite element study is one of the methods that have been utilised by experts. Therefore, assigning material properties for all finite element models become crucial to avoid any misinterpretation which, later, lead to the wrong prediction on the performance of the glenoid implant. This study was conducted to achieve two objectives; (1) to analyse the effect of different bone properties towards micromotion and stress at implant and cement, and (2) to clarify simplification of bone properties in evaluating glenoid component loosening. A load of 750N was simulated at three different glenoid locations (center - C, superior-anterior-SA, superior-posterior-SP) which imitate concentric and eccentric loadings for elderly people daily activities. Our result showed that large differences in micromotion and stress at implant between orthotropic model and another two model (isotropic and full cortical) do not allow simplification for assigning material properties for bone. Thus, assigning cancellous bone as the orthotropic material was a realistic material property to represent the real bone condition in evaluating glenoid implant loosening.

INTRODUCTION

Assigning material properties is a fundamental step in creating finite element (FE) models of bone. Therefore, it is important to assign properties which can mimic the real behaviour of bone. Scapula bone consists of the cancellous and cortical bone, where cancellous bone is an orthotropic material (Wirtz et al., 2003). However, in some previous studies simplified the cancellous bone by considering the whole scapula as a full solid cortical bone in their FE models (Yongpravat et al., 2013). Meanwhile, some studies dividing scapula into cortical and cancellous bone in two different cases. The first studies assumed the cancellous bone as isotropic material (Gupta, van der Helm, & van Keulen, 2004; Yongpravat et al., 2013) and another case assigned it as orthotropic material (Abdul Wahab, Abdul Kadir, Kamarul, Harun, & Syahrom, 2016; Couteau et al., 2001; Wahab, Kadir, Harun, Kamarul, & Syahrom, 2017). Based on the previous literature, there are no specific methods in assigning material of scapula which discussing the impact of different bone properties to assess glenoid implant loosening. Therefore, this study with an intention to investigate the aforementioned issue with two main objectives, (1) to analyse the effect of material properties of cancellous bone on performance of glenoid implant especially on micromotion at cement-bone interface, and stress at implant and cement (2) to clarify the simplification of bone properties for evaluating glenoid component loosening. In this study, three models had been analysed; the first model was assigned with full cortical where there is no cancellous bone, namely as Model 1). For another two models which consist of cortical and cancellous bone, but had different cancellous properties, which are Model 2 and Model 3.

MATERIALS AND METHOD

Component Design

Glenoid implant and cement was modeled using threedimensional computer-aided design (CAD) software (Dassault Systèmes SolidWorks Corp., USA). The material, shape, thickness and radius of curvature of the implant were set to all-polyethylene, pear-shaped, 4mm, and 29.5mm, respectively. The height, lower width, and upper width of the glenoid implant were measured from Malaysian glenoid bone CT dataset. For the lower width, upper width and height, of the implant, the measurement were 23.5mm, 16.7mm, and 32mm respectively. The length for peripheral and central peg were set to 10mm and 14mm, respectively and both had 3mm in diameter. The thickness of cement used was 0.5mm.

Finite Element Model

The scapula cortical and cancellous bone 3D model were reconstructed from intact CT image data using commercial software (Mimics 15, Materialise, Leuven, Belgium). The axial slice thickness of CT dataset was 0.537mm. Hounsfield Unit (HU) values have been used to differentiate between cortical and cancellous where HU>350 was set to cortical and as for cancellous bone was in between 120 – 350. A convergence study was confirmed that the optimum number of elements and nodes for cortical bone were varied between 161,021 to 239,401 and 42,857 to 52,523, respectively. While, for cancellous,

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the number of the element was 66,012 and number of nodes was 18,024. The number of elements for implant and cement was 50,361 and 69,465, respectively, and the number of nodes were 12,694 and 14,924, respectively. All parts of bone and implant have been assigned with 4-nodes tetrahedral elements. The prosthesis and cement meshed in Abaqus, Inc. software, and the implant was positioned into the bone via Mimics software. The prosthesis was fixed to the best-fit position, with minimally resect of glenoid subchondral bone and optimally support(Jones, 2013). The final model was saved in STL file and MSC Marc Mentat (MSC Software, Santa Ana, USA) software was used for further finite element analysis. As for contact at the interfaces, fully bonded for implantcement interfaces and not bonded for implant-bone and cement-bone interfaces were set accordingly. This can allow micromotion at the interfaces to be assessed. The friction coefficient (μ), for not bonded interfaces, were set to 0.6 (Terrier, Büchler, & Farron, 2005; Wahab et al., 2017). Mechanical parameters were considered that include stress at implant and micromotion at cement-bone and implant-bone interfaces. On top of that, the time for analysis to be done has been recorded in order to compare the models.

Material Properties

The material properties of cortical bone were assigned with isotropic material for all three models, while, material properties for cancellous bone had been set as, isotropic, and orthotropic material for model 2 and model 3 as stated in table 1. In model 1, the cancellous bone was not considered, therefore, it was set as cortical properties for the whole scapula bone. For glenoid implant, the properties were set with Young's modulus (E) of 965MPa and Poisson's ratio (v) of 0.34. While, for PMMA cement, Young's modulus (E) was set to 2000MPa, and Poisson's ratio (v) was set to 0.23.

Model	Material properties
Model 1 (Full Cortical)	E _{cort} = 16,000 MPa v _{cort} = 0.3
Model 2 (Isotropic)	$\frac{\text{Cortical}}{\text{E}_{\text{cort}}} = 16,000 \text{ MPa}; v_{\text{cort}} = 0.3;$
	<u>Cancellous</u> (Yongpravat et al., 2013) $E_{can} = 574 \text{ MPa}; v_{can} = 0.3$
Model 3 (Orthotropic)	$\frac{\text{Cortical}}{\text{E}_{\text{cort}}} = 16,000 \text{ MPa}; v_{\text{cort}} = 0.3;$
	$\begin{array}{l} \underline{Cancellous} \; (\underline{Couteau \; et \; al., \; 2001}) \\ E_{11} = 342.11 \; MPa, \; E_{22} = 212.77 \; MPa, \; E_{33} = 194.44 \\ MPa; \\ \nu_{12} = \nu_{13} = \nu_{23} = 0.26; \\ G_{12} = G_{13} = G_{23} = 100 \; MPa \end{array}$

Boundary Condition

Boundary condition was set as in Figure 1. The medial border of the scapula was fixed in all degree of freedom. As per axial load, 750N load was applied at three different location, which are center (C), superior-anterior (SA), and superior-posterior (SP) and this value represent the daily activities done by elderly people such as sitting down in a chair, lifting a 5kg suitcase, and walking with stick (Anglin, Wyss, Nyffeler, & Gerber, 2001).







Fig. 2 Contour plot showing stress distribution at implant.

RESULTS AND DISCUSSION

Cancellous bone properties were already known as an orthotropic material. *In silico* study, assigning material properties is a fundamental step in creating finite element models of bone. Therefore, it is important to assign material properties which can mimic the real behaviour of human bone. Scapula bone is made of cancellous and cortical bone, where, the cancellous bone was an orthotropic material (Wirtz et al., 2003). However, in some previous studies, the cancellous bone was neglected and considered scapula as a full solid cortical bone (Yongpravat et al., 2013). While, some studies dividing scapula bone into cortical and cancellous bone but some of the studies assumed the cancellous bone as isotropic material (Yongpravat et al., 2013), while, another assigned the cancellous as orthotropic material (Abdul Wahab et al., 2016; Couteau et al., 2001; Wahab et al., 2017).

OPEN O ACCESS Freely available online eISBN 978-967-0194-93-6 FBME Thus, in this study, three type of bone properties, which are full cortical (model 1), isotropic (model 2), and orthotropic (model 3), were compared to analyse the effect of different bone properties to micromotion at the interfaces and stress at the implant. Another objective of this study is to clarify either the simplification of bone properties could be made in order to analyse the micromotion at the interfaces and stress distribution at implant.

Stress at component

Model 1 experienced the lowest von Mises stress as compared with another two models with cancellous bone. The von Mises stress at implant for model 3 was 80% higher in C load, and 10% higher in SA load as compared to the implant for model 2. While, the percentage was even higher if model 3 was compared to model 1, where for C and SA load, the stress was high up to 126% and 32%, respectively. However, during SP load, model 2 had highest maximum stress (21 MPa) at implant if compared to model 1 and model 3, which have almost similar maximum stress at implant, 17 MPa. The maximum stress, as well as time for analysis for three different models in three different load location were shown in Table 2.

Figure 2 showed the stress distribution at implant for three different bone properties in three load cases. Based on the results, the maximum stresses at implant were associated with the load applied, where for centre load, the maximum stress located surround the central peg, whilst, for SA and SP load, the maximum stresses were located at the back side of the implant at superior-anterior and superior-posterior, respectively. The stress at implant was associated with glenoid component loosening especially during eccentric loading (SA and SP load). Results from this study in all models were in agreement with previous literature, where the eccentric load can increase the stress at the edge of the implant(P. Mansat, Briot, Mansat, & Swider, 2007; Zhang et al., 2013). However, large different percentage, which is up to 110%, give a sign where any simplification of bone properties could not be made, otherwise, it would lead to wrong results interpretation. For instance, lower stress produced in model 1 showing that there was no indication of implant loosening, however, in model 3, stress at the implant achieving the yield stress during SA and SP load. This can be confirmed that the implant might lead to implant loosening.

Load		С	SA	SP
Model 1 (full cortical)	σ _{max} (MPa)	4.27	18.23	17.63
(Time	2 h 42 m	1 h 51 m	2 h 7 m
Model 2 (Isotropic)	$\sigma_{max}(MPa)$	5.37	21.74	20.97
	Time	2 h 42 m	2 h 53 m	3 h 6 m
Model 3 (Orthotropic)	σ _{max} (MPa)	9.23	23.37	17.06
	Time	4 h 20 m	3 h 12 m	6 h 8 m

Table 2 Maximum stress and time for analysis for all cases.

Micromotion at interfaces

Other parameters which highly related to glenoid implant loosening are micromotion at the bone-cement interface (Terrier et al., 2005) and bone-implant interface (Sarah et al., 2010). From the results, micromotion at the cement-bone interface showed that model 1 had small micromotion values as compared to the other two heterogeneous models, model 2 and model 3 in all three load conditions. During the C load, micromotion at the cement-bone interface in model 3 (24.73 μ m) demonstrated five times higher compared to model 1 (3.83 μ m) and 72% different was found between model 2 and model 3. Similarly, during eccentric load, micromotion for model 3 was two folds higher during the SA load and three folds higher during the SP load compared with model 1 in both cases. While, different between model 2 and model 3 was 35% for SA load and 59% for SP load, Figure 3. Likewise, micromotion at the implantbone interfaces showed the same trend where model 1 had lowest values and model 3 had highest values for micromotion, while, micromotion for model 2 was in between model 1 and model 3. However, the different for micromotion at the implant-bone interfaces was smaller if compared to different at cement-bone interface. Model 3 had an average 40% higher compared to model 1, while different between model 3 and model 2 was less than 10%. Figure 4 showed micromotion at the implant-bone interface for three different bone models.



Fig. 3 Contour plot of micromotion at cement-bone interface



Fig.4 Contour plot of micromotion at implant-bone interface

Assuming glenoid bone model as a full cortical lead to inaccuracy of micromotion measurement as the result showed it had very low micromotion in model 1. On the other hand, the micromotion was higher in bone with cancellous compared to full cortical, model 1. It was due to a stiffer bone, which not mimicking real bone, surrounding the cement in model 1, prevent the cement motion. Additionally, the different in micromotion for model 2 and model 3 was due to different modulus definition for both models. For orthotropic properties, the modulus differed for each axis (x-axis \neq y-axis \neq z-axis) while,

OPEN O ACCESS Freely available online eISBN 978-967-0194-93-6 FBME isotropic only had one modulus which same for all axis (x-axis = yaxis = z-axis). Furthermore, the result from this study showed that peak micromotion at the bone-cement interface was differed between model 1 and another two, where in model 1, peak micromotion occurs at the tip of the cement for all three load conditions. While, for model 2 and model 3, peak micromotion occurs at the bottom side of the cement, where the cement touches the cancellous bone. It was in an agreement with the theory where the displacement was influenced by the modulus of the material as stated in equation 1.

2	PL	E-metion 1
0 =	AE	Equation 1

Where, δ was a displacement at one point relative to another point, P was pressure applied, L was distance between points, A represent cross sectional area, and E was modulus of elasticity for the material.

In terms of time consumption for analysing the models, model 1 was found to have less time for analysis (average time was two hours) than model 2 (three hours) and model 3 (four and half hours). Large different between three models, more than 10%, was not acceptable for finite element analysis if biological structure (Baca, Horak, Mikulenka, & Dzupa, 2008) and prevent from any simplification of the bone model could be made. As a result, orthotropic material properties was favourite to represent the cancellous bone at scapula. Even, the time taken for analysing was double compared to model 1 and model 2, however, it still within the acceptable time for analysis and the accuracy of the results would be prioritized in order to mimics the real case. Current study had several limitations to be noted, first, the current study was a fully simulation, nevertheless, this simulated analysis using orthotropic properties can be defined and represented as an actual bone behaviour, since these orthotropic properties was obtained from previous experimental study (Couteau et al., 2001; Pierre Mansat, Barea, Hobatho, Darmana, & Mansat, 1998) which used real scapula bone. Therefore, the results obtained from the analysis could avoid from underestimate or overestimate the data in order to predict the glenoid component loosening. Second, glenoid implant had been simulated without the humeral head, which can affect to load distribution. However, the load contact area for the eccentric load (SA and SP load) was located at 100 to the anterior and posterior of the glenoid surface and 20o to superior of the glenoid surface(Stone, Grabowski, Cofield, Morrey, & An, 1999). Thirdly, this study evaluates the bone as homogenous which in reality, the bone was inhomogenous. Thus, future studies should consider this aspect for simulating better clinical scenarios and result in more accurate results ...

CONCLUSION

This study successfully simulated three models of scapula fixated with a glenoid implant via finite element method. It can be concluded that different materials of cancellous bone affected the micromotion at the interfaces and stress distribution at implant. This study also found that the orthotropic behaviour is more favourable option to mimic real condition of the bone and allowed more reliable prediction on glenoid component loosening.

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