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Original Article

Biomechanical evaluation of lag screw fixation in oblique humeral shaft fracture: A finite element study♣

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Abstract

A common treatment for long bone fractures, namely lag screw and plate fixation, still has relatively high failure rates, especially in case of oblique fracture. The best practice for lag screw fixation condition, i.e. angle, is controversial. Therefore, the aim of this study was to biomechanically evaluate the effect of screw angle conditions on the stability of fixation to determine the optimal condition using finite element (FE) analysis. The FE models of simplified long bone fracture fixation with various screw angle conditions between 0° to 60° were created for analyzing and comparing their fixation performance. The analyses were performed under lag screw fixation condition and various load conditions (compression, torsion, and bending loads). The screw which installed perpendicularly to the longitudinal axis of bone provided the best performance in terms of generating the highest interfragmentary compression and performed the best stability while loads applied.

Keywords: long oblique fracture, lag screw and plate fixation, biomechanics, finite element analysis, interfragmentary compression

1. Introduction

Approximately 0.01% of the UK's population is affected by open long bone fractures each year (Court-Brown, Prakash, & Queen 1998). In the United States, there are around 7.9 million people who face the problem of bone fracture annually, and close to 10% of the patients suffer from either a lack of efficiency of bone healing or a failure of bone healing which could potentially be the cause of delayed union or nonunion of bone (Li *et al.* 2017). Around 1-3% of all fractures occur at the shaft of humerus which is a long bone in the body (van de Wall *et al.* 2019). One of the most common long bone fracture types is an oblique fracture which occurs in 30-40% of all fractures located at the shaft of the bone (Miramini *et al.* 2016).

The oblique bone fractures are complete fractures occurring in a plane which is oblique to the long axis of the bone. Due to the characteristic of the fracture, the severity and instability of the bone fracture relate directly to the degree of oblique angle. Moreover, the sharp end of the bone fragments may injure the surrounding soft tissue leading to the compound fracture, which increases risk of complications of the fracture healing process and consequently delayed healing or nonunion of bone (Owens 1898). There are various techniques which can be used to treat the oblique bone fracture, ranging from cast immobilization to open reduction and internal fixation. In order to choose an appropriate option for the treatment, severity of the fracture is an important factor that needs to be carefully considered as a criterion. A general technique widely used for oblique fracture treatment is traditional plate and lag screw fixation. Using of the lag screw fixation is performed with the aim of reducing fracture and

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generating interfragmentary compression at the fracture site of the bone to provide stability and encourage bone healing. In addition to the lag screw reduction, the neutralization plate is also used in order to resist the shear and rotational force and reduce movement of fractured bone for increasing stability of fixation during the bone healing process. (Court-Brown *et al.* 2015; Rüedi & Murphy 2000). However, the lag screw fixation plays an important role in the reduction of fracture gap to initiate an efficient direct fracture healing mechanism prior to stabilizing provided by plate fixation (Marsell & A. Einhorn 2011). Therefore, some studies focused only on the effect of lag screw fixation (Nquyen, Le, & Vo 2015).

According to the Arbeitsgemeinschaft für Osteosynthesefragen (AO) principles of fracture management, the lag screw should be inserted perpendicularly through the fracture plane in order to provide the optimal efficiency and stability of the bone fracture fixation (Rüedi & Murphy 2000). However, in some cases, the lag screw cannot be placed perpendicular through the fracture plane leading to doubt over decreasing of efficiency of the lag screw fixation at other angles. Moreover, failure rates of the oblique bone fracture fixation are relatively high due to several factors such as breakage of implant and loosening of lag screw (Owens, 1898).

In order to reduce the risk of failure, several studies evaluated mechanical behavior of bone and investigated various factors which might potentially be a cause of the fixation failure such as the screw position, material of screw, and screw thread geometry. However, these studies were not likely to be performed directly in the human body. Therefore, several studies investigated experimentally using various cadaveric biomechanical tests to quantify the fixation stability of each condition. However, performing the experiment may face some limitations including the high cost of instrument, the limitation of the device set-up, and the complication of preparation and testing process (Eraslan & Inan 2010; Goffin, Pankaj, & Simpson 2013; Kuzma *et al.* 2019; Nurmi *et al.* 2017).

To overcome these limitations, finite element analysis (FEA) may be a powerful tool for investigating the mechanical behavior of bone and determining the effect of various parameters on bone fracture treatment (Roberts & Pallister 2012). This technique has been widely used in orthopaedic biomechanics due to the advantages of being noninvasive, having low cost and providing adequate accuracy and validity with less time consumed (Kluess 2010; Taylor & Prendergast 2015).

In several previous studies, various factors in bone fracture treatment were investigated and optimized by means of performing either biomechanical test or computational simulation (Liew *et al.* 2000; Tsuang *et al.* 2016). However, the effect of lag screw angle on fracture fixation stability and bone healing efficiency when treated by neutralization plate and lag screw fixation seem to be in doubt and controversial. Therefore, the objective of this study was to evaluate the effect of lag screw fixation at various angles on oblique fracture treatment of long bone with the aid of finite element analysis.

2. Materials and Methods

2.1 Simplified 3D model of oblique fracture fixation of long bone construction

The simplified 3D model of oblique fracture fixation of long bone was created in Siemens NX Version 12 (Siemens PLM Software, Plano, Texas, U.S.) which included a fractured long bone and a lag screw model. The long bone model was assumed to be a cylindrical shape, 20 mm in diameter, 4 mm in cortical bone thickness, and 80 mm in length mimicking the geometry of humerus (Murdoch, Mathias, & Smith 2002). To mimic the oblique fracture on the humeral shaft, a plane located at angle of 20° to the longitudinal axis of the bone was used to cut through the centroid of the long bone model dividing the model into two separated parts (Figure 1a). The lag screw model was also assumed to be a simple cylinder without the geometry of the screw thread, and the diameter of which was 4.5 mm. There were two different lengths of the lag screw, which were 36 mm and 50 mm, corresponding to the various angle fixations. The screw was placed at four different angles, which included 0° (perpendicular to the longitudinal axis of the bone), 20° (perpendicular to the oblique fracture plane), 40° and 60° passing through the centroid of the bone. Fixing hole was also created on the long bone model corresponding to the various locations of the screw. The lag screw with the length of 50 mm was only used for the 60° screw angle model, while 36 mm was used for the rest of the models. In addition to the unthreaded screw model, another model of half-threaded (3.0 mm in core diameter and 1.75 mm pitch) screw with the length of 36 mm located at an angle of 20° was created for further sensitivity study to determine effect of thread geometry on the FEA result.

2.2 Finite element (FE) model preparation

The 3D CAD model was imported into Abaqus Version 2020 (Dassault Systèmes, Vélizy-Villacoublay, France). to generate a FE model. There were three parts in total, which were two components of the humeral bone and

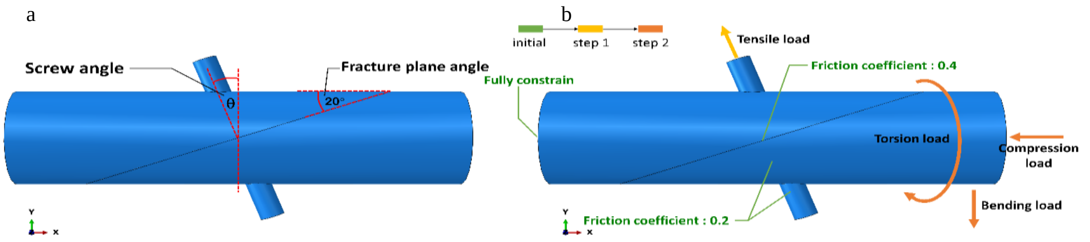


Figure 1. (a) Construction of 3D geometry of bone fracture model and (b) the illustration of boundary and loadings conditions applied to the FE model

one component of the screw, combining together into a construct of oblique fracture fixation of long bone. Material properties assigned to both humerus and lag screw components were assumed to be linear elastic, homogeneous and isotropic, and which are illustrated in Table 1 (Antoniac *et al.* 2019).

Boundary conditions and loads which are illustrated in Figure 1b were assigned to mimic conventional practice of the lag screw fixation and various physical loads that the construct might experience. Superior surface surrounding the fixing hole was fully constrained. Interaction between bone and screw at the hole which was located at the proximal end of the lag screw was assumed to be frictionless, while at the hole which was located at the distal end of the lag screw was assumed to be fully constrained to represent the mechanism of the screw thread. This condition was applied similarly on both half-threaded and unthreaded screw models. The friction coefficients of 0.4 and 0.2 were assigned to the bone-bone interface and the rest of the screw-bone interface respectively. There were two types of loads which were from lag screw tightening and physical loading applying through two different steps. Firstly, 500 N tensile load was applied to the screw head in the same direction as the longitudinal axis of the screw to represent the load which was the effect of tightening torque of the lag screw fixation technique. Finally, the physical loads, which included 1,300 N axial compressive load, 5 N·m torsion, and 200 N bending load, were then applied corresponding to the study case to investigate the stability of the construct when experiencing various loads in real situations such as the external loads and muscular forces from movement of the upper limb (Antoniac *et al.* 2019).

2.3 Mesh generation

Ten-node quadratic tetrahedron (C3D10) elements were chosen to mesh both the simplified humeral bone and lag screw components. A mesh convergence study was performed on the 20° screw angle model. Five mesh schemes were used with the element number approximately doubled each time from 15,000 up to 250,000 elements to ensure that the FEA result would not be affected by mesh density. The mesh convergence was achieved when the results differed by less than five percent compared to the FE model with double mesh density.

2.4 Output parameters collection

Output parameters were collected in order to evaluate the effect of lag screw fixation at various angles on oblique fracture treatment of long bone. The effect of the fixation was considered in terms of both the fracture fixation stability and bone healing efficiency. Therefore, the output parameters, which included von Mises stress, displacement, minimum principal strain, and clearance between surfaces, were necessary to be collected. The von Mises stress value was used to investigate the ability of the construct to withstand applied load, while the relative displacement between both ends of bone at the fracture site was used to determine the stiffness of fracture fixation. The two outcomes could be used together in order to evaluate the stability of fracture fixation. In order to investigate the efficiency of bone healing, the minimum principal strain and the clearance between surfaces, which were used as criteria to determine the mechanism of bone healing, were necessarily required.

Table 1. Material properties of the model components

Homogeneous and linear elastic material			
Components	Material	Young's modulus (MPa)	Passions ratio
Cortical bone	Humeral cortical bone	15,300	0.31
Lag screw	Titanium alloy	105,000	0.37

3. Results and Discussion

3.1 Mesh convergence study

After performing the mesh convergence study, the difference of relative displacement at the same location obtained between the two finest mesh schemes was 1.33% (9.54 μm and 9.41 μm for the finest mesh scheme and the optimal mesh scheme respectively). The plot of mesh convergence study and the model meshing are demonstrated in Figure 2. Based on the mesh convergence study, the optimal numbers of nodes and elements are shown in Table2.

Table 2. Nodes and elements of model

		Nodes	Elements
Model 0°	Bone	36,020	22,029
	Screw	19,939	12,909
Model 20°	Bone	36,241	22,127
	Screw	19,861	12,858
Model 40°	Bone	36,125	22,054
	Screw	19,762	12,784
Model 60°	Bone	38,360	23,492
	Screw	27,974	18,194

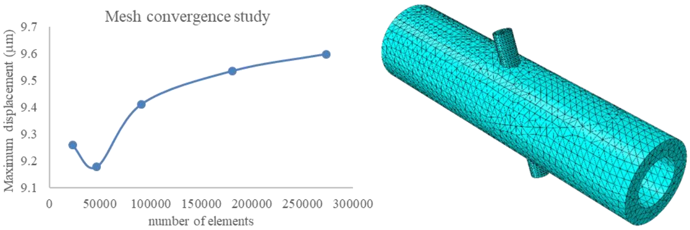


Figure 2. (a) Convergence of relative displacement using global mesh refinement and (b) model meshed with the optimal element size

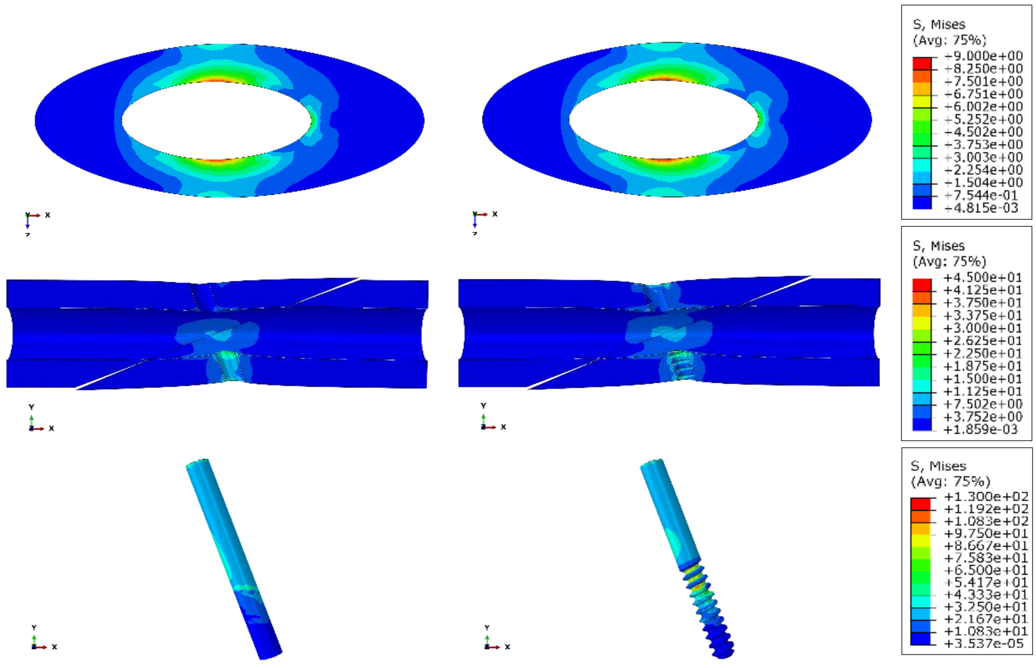
3.2 Sensitivity study of thread geometry on the lag screw model

In the sensitivity study, the results obtained from the analyses of the 20° screw angle FE models with and without thread geometry were compared in order to evaluate the effect of thread geometry on the lag screw. In this case, an output parameter chosen to compare was the von Mises stress, and the distribution of von Mises stress on each model is illustrated in Figure 3. The difference in magnitudes of von Mises stress obtained from the region of interest (at the fracture site) between both models was less than 5% (8.393 MPa and 8.028 MPa for threaded and unthreaded screw respectively), and almost of all stress distribution throughout both models seemed to be similar. This result was similar to the previous studies which focused on the effect of screw thread. Le and colleagues studied the effect of threaded and unthreaded scores on the stiffness of fixation. The results showed that differencing load applied to provide 5 mm displacement was approximately 4.5% (51.8624 N for smooth screw and 54.2199 N for fully-threaded screw) (Le *et al.* 2019). Similarly, Inzana and colleagues modeled the proximal humerus fixation by using threaded and unthreaded screw. This study observed no significant differences in displacement or peak strain for the on-axis applied loading, but the differences were observed when the load was applied off-axis (Inzana, Varga, and Windolf 2016).

At the development stage of the FE model of oblique fracture fixation of long bone, it was found that the meshing for the thread of the lag screw required an excessively large number of elements. Removal of the thread geometry could reduce the element number by 57% (81,979 elements and 34,985 elements for threaded and unthreaded screw respectively), and the running time of analysis was also reduced by 18% (4,230 seconds for threaded screw and 3,465 seconds for unthreaded screw). This is an indication that removal of thread detail can substantially decrease the computational cost. Moreover, the simplification makes the meshing procedure easier and also reduces error in meshing. Since the thread geometry only had a negligible effect on the output at the region of interest, the FE model of the unthreaded lag screw will be further used in the following analyses.

3.3 Biomechanical evaluation of lag screw fixation

The magnitudes of minimum principal strains (mostly compressive strain) at the fracture site, which were used as criteria to determine the mechanism of bone healing, obtained from all FE models seemed to be similar which were approximately 0.1% (less than 2%). This means that the bone healing mechanism at the fracture site of all models can be classified as the primary bone healing, which is the ultimate goal of fracture fixation (Marsell & Einhorn 2011). In order to ensure that the healing mechanism is the primary fracture healing, another criterion, the clearance between surfaces in the region of fracture, needs to be considered together. The contour plots of clearance between surfaces in the region of fracture obtained from all fracture fixation models are shown in Figure 4. In this case, the clearances between surfaces in the entire fracture area obtained from the 0°, 20°, and 40° angle FE models were lower than 0.01 mm, while the corresponding values obtained from the 60° angle FE model were higher than 0.01 mm in some areas (as shown in gray region in Figure 4d). The widest clearance obtained from the 60° angle FE model of nearly 0.026 mm on one side (right side) of the fracture region illustrates that the lag screw placed at extreme acute angle to the fracture plane could not provide



left right

Figure 3. The comparative of von Mises stress distribution in bone and screw between unthreaded (left) and threaded (right) models

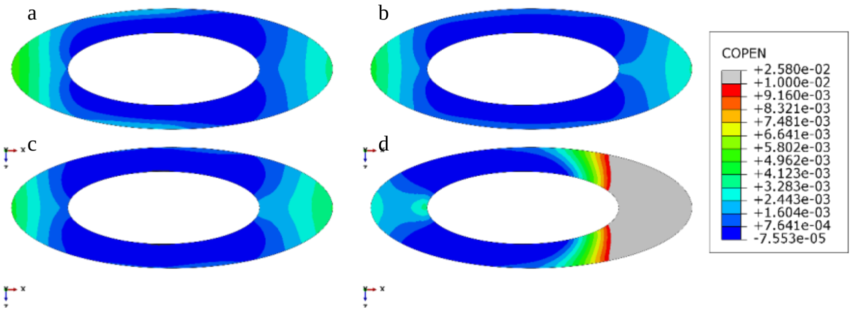


Figure 4. The gap distance between the fracture surface after performing the lag screw fixation of model 0°(a), model 20°(b), model 40°(c) and model 60°(d) (mm)

symmetric distribution of compression throughout the contact surface when tightening. In contrast, the distribution of compression provided by the lag screw which was installed perpendicular to the fracture plane in the 20° angle FE model seemed to be more symmetrical (Figure 4b). From the study of Marsell and Einhorn, the direct fracture healing could be classified into contact healing and gap healing using the criteria of gap distance (Marsell & Einhorn 2011). The contact healing would occur over the fracture gap below 0.01 mm and provide more mechanical strength. Otherwise, the gap healing would occur (Marsell & A. Einhorn 2011). Therefore, the fracture healing mechanism in the 60° angle FE model is likely to be a combination of contact healing and gap healing process. The direct fracture healing through gap healing mechanism will occur on the gray region, while the contact healing mechanism will occur on the rest of region (Figure 4d).

Both the von Mises stress and the relative displacement that occurred at the fracture site were used to determine the stiffness of fracture fixation. The distributions of the von Mises stress throughout the fracture surface which was affected by the lag screw tightening are illustrated in Figure 5, and the maximum magnitudes of von Mises stress occurred at the similar regions, and the relative displacements between fracture surfaces are shown in Figure 6. In all fracture fixation FE models, the locations of maximum magnitude of von Mises stress occurred on the fracture region were similar, which were at the edge of the inner surface on the level of the minor axis of an ellipse. The tightening of the lag screw in the 0° angle FE model provided the highest magnitude of von Mises stress (18.6 MPa), which is determined to be the stiffest fracture fixation by means of von Mises stress considering. In terms of relative displacement, the tightening of the lag screw in both the 20° and 40° angle FE models provided the lowest value of approximately 0.17 micrometers, which is also thought to be the stiffest fracture fixation. The lag screw inserted in the 60° angle FE model generated extremely greater movement than other models, which was 286.64 micrometers. This may be because the force exerted by the lag screw tightening in the 60° angle FE model seems to be a shear force instead of compressive force leading to the excessive slip of the bone fragments.

The von Mises stress was also used as a criterion to determine the risk of failure in fixation. On the lag screw when tightening in all FE models, the maximum magnitudes of von Mises stress occurred at the distal end, which was close to the fixing hole edge on the inner surface (Figure 7a). The maximum magnitude of von Mises stress on the humeral bone in all FE models when the lag screw tightened was located around the edge of the fixing hole on the inner surface, which was in the similar region to the stress on the screw (Figure 7b). The highest magnitudes of von Mises stress on both the lag screw and humeral bone were found in the 60° angle FE model. For the rest of the FE models, the similar values arranged in range order from the highest to the lowest were found in the 0°, 20° and 40° angle models respectively. In the 60° angle FE model, the maximum magnitude of von Mises stress of 422.6 MPa was found on the lag screw and 160.1 MPa found on the humeral bone, which was higher than the yield stress values of both objects. From previous studies, the yield stress of titanium alloy was 970 MPa (Boyer *et al.*, 2007) and cortical bone was 111 MPa (Dong *et al.* 2012). This means that the cortical bone of humerus at the region of the distal fixing hole edge is likely to be damaged, but may not consequently lead to failure of the fixation due to the small area of high stress. For the rest of the FE models, the maximum magnitudes of von Mises stress on the lag screw and the humeral bone were in a range of 55-80 MPa and 20-40 MPa respectively.

3.4 Biomechanical evaluation of lag screw fixation under physical loading

The analysis results obtained from all FE models are illustrated in Table 3. The 0° angle FE model provided the best performance among other models in withstanding compressive load in terms of the lowest relative displacement at fracture site and the lowest maximum magnitudes of von Mises stress on both the lag screw and humeral bone, which were 2.21 micrometers, 120.80 MPa, and 44.38 MPa respectively. In the aspect of relative displacement, the stiffer the fixation, the more difficult, it is for the fractured bone to move. Likewise, in the aspect of von Mises stress, the better the fixation to distribute the stress, the lower is the risk of failure. On the other hand, both the lag screw and humeral bone in the 60° angle FE model are likely to be damaged under the compressive load of 1,300 N because the magnitudes of the maximum von Mises stress generated were higher than the yield values. Similarly, in the 20° and 40° angle models, the bones are also likely to be damaged for a similar reason. These results correspond to the study of Arzimanoglou and Skiadaressis, who investigated the effect of screw angle on oblique bone fracture fixation, and reported that the most efficient screw angle was perpendicular to the

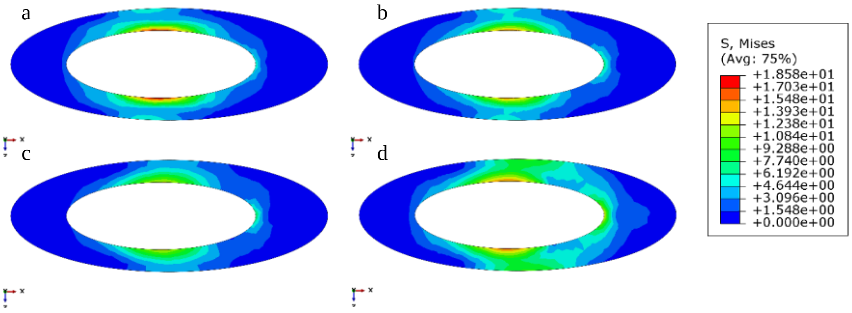


Figure 5. The von Mises stress distribution on the fracture surface after performing the lag screw fixation of model 0°(a), model 20°(b), model 40°(c) and model 60°(d)

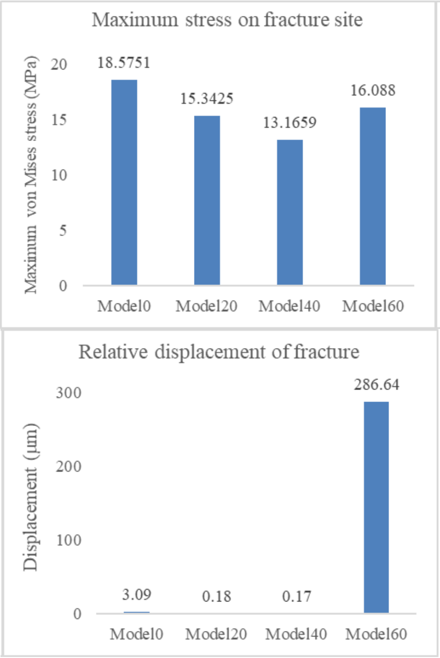


Figure 6. The comparative of maximum von Mises stress on the fracture site and relative movement of fracture ends after performing the lag screw fixation.

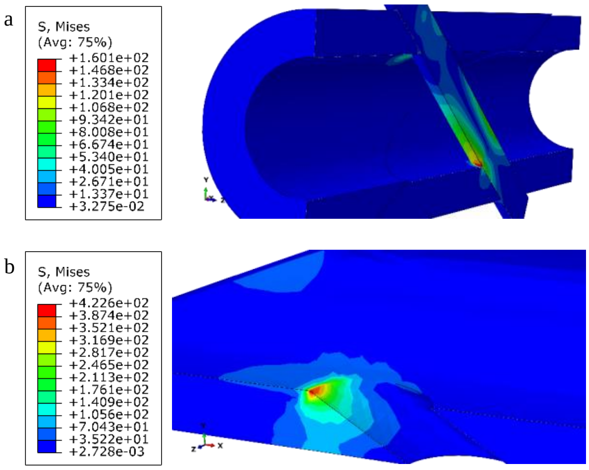


Figure 7. The maximum von Mises stress on screw (a) and bone (b) after performing lag screw fixation of model 60°

Table 3. Stability test under compression, bending and torsion conditions

Load	Model	Relative movement (µm)	Maximum stress (MPa)	
			Bone	Screw
Compression	0°	2.21	44.38	120.80
	20°	25.58	135.30*	320.60
	40°	293.33	196.80*	754.70
	60°	2827.16	491.09*	1,250.60*
Bending	0°	1.80	34.43	64.97
	20°	1.85	35.61	65.68
	40°	2.59	23.93	62.93
	60°	305.55	165.39*	421.18
Torsion	0°	4.93	43.24	97.31
	20°	4.73	42.39	76.20
	40°	93.44	47.05	151.43
	60°	689.96	206.79*	552.71

bone cortex (Arzimanoglou & Skiadaressis 1952). As well as under the compression, the 60° angle FE model provided the poorest performance among other models in withstanding torsion and bending load in terms of the highest relative displacement at fracture site and the highest maximum magnitudes of von Mises stress on both the lag screw and humeral bone. Moreover, the bones under both loading conditions in only the 60° angle FE model are likely to be damaged due to exceeding the yield values.

However, the lag screw is always used in combination with the neutralization plate in order to increase the fixation efficiency. The plate can reduce the compressive loading across the fracture and resist the shear and rotational loading by transmitting the load through the plate rather than the fracture site (Rüedi & Murphy 2000). Therefore, the maximum stress occurring in the practical case should be lower than in this study.

There are some limitations in our investigation. The 3D models used in this study were the simplification of the shaft of humeral bone and the cortical screw, which were different from real geometries of bone and screw in some details, such as the complex morphology of real bone model might affect the stress distribution and the fully constrained interaction between bone and screw could not perfectly represent the thread of cortical screw. The external force exerted by muscles and other soft tissues were not included, and the material properties assigned were assumed to be linear elastic, homogeneous, and isotropic which are different from the real behaviors of human bone. Furthermore, this study was investigated with only the aid of computational simulation. It may need to be validated with biomechanical experiments to ensure accuracy of the prediction outputs. These limitations lead to an enhancement of work in the future. A 3D model of real geometry of bone will be created based on CT data, and the screw model will include the detail of the thread. The real material properties and the external forces exerted by surrounding muscles and other soft tissues will be included in order to create a more realistic model. Finally, a validation with biomechanical experiment data will be performed to ensure the accuracy of the analysis results.

4. Conclusions

In this study, we investigated the effect of lag screw angle on fracture fixation stability and bone healing efficiency of oblique bone fracture fixation using finite element models of various lag screw angles fixation. For the screw model, it appeared that the FE model of the unthreaded screw provided comparable analysis results to the FE model of the threaded screw, while the analysis of unthreaded screw consumed less time and cost. In addition, the analysis results demonstrated that the 0° angle FE model provided the best performance in terms of generating the highest interfragmentary compression with lag screw tightened and performed the best stability when loads were applied. By contrast, the 60° angle FE model seems to have a high risk of fixation failure because the magnitudes of maximum stress occurring on both bone and screw exceeded the yield stress values of the materials. However, as previously mentioned, not only the lag screw is used for fixation but also in combination with the plate, which can decrease both loads transmitted through the bone and screw and stress occurred. These findings may provide the alternative angle options to the surgeon in the case which cannot insert the lag screw perpendicular to the fracture site. This experiment can be further researched by examination in real geometry models and validated with corresponding biomechanical experiments.

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