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ORIGINAL PAPER

Stress Interaction Analysis of Uniaxial Fixator Pins-Diaphysis Femur Bone Interface Subjected to Four-Point Bending

N.F.I. Ibrahim [a], R. Daud [a,*] N A M Zain[b], B. Izzawati[a], Y Bajuri[c]

[a] Fracture and Damage Mechanics SIG, School of Mechatronic Engineering, Universiti Malaysia Perlis, 02600, Arau, Perlis, Malaysia
[b] Institute of Mathematics, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia
[c] UKM Medical Centre, Department of Orthopedics and Traumatology, Universiti Kebangsaan Malaysia, Jalan Yaacob Latif, Bandar Tun Razak, Cheras, Kuala Lumpur, Malaysia

* Corresponding author: nurfatinizzati@hotmail.com

INTRODUCTION

Fracture happens when the bone cannot withstand the external impact or stress exerted upon them. One type of stress occurred is due to the four-point bending stress of the bone. At the proximal femur, a fracture can occur at three positions, trochanter, neck and head (Umadevi and Geetalaksmi, 2011). These fractures are treated by using internal fixation where surgeons will insert screws inside the bone. The amount and size of screws inserted are based on the type of fracture occurred. External fixation is usually used for the fracture occur at femoral shaft and distal femur. Most of the cases, external fixation will be installed at the broken femoral shaft but there are a few types of cases where surgeons are still using the internal fixation. There are also three main fractures occur at femoral shaft which are simple fracture, wedge fractures and complex fractures (Link an Babst, 2012). At the distal femur, most of the fracture had been majorly fixed by the internal fixation but there are still cases where the external fixator is installed. The types of fracture occur at distal femur are extra articular, partial articular and complete articular. After patients undergo surgeries and went through the healing process, the outpatients sometime will return back the hospital due to the pain they felt at the bone that they had surgeries on. The pain occurred due to the screws of the external fixation that hold the bone together to stabilize the broken bone undergo either fracture, loosening or tightening of the screws (Ramtani and He, 2014; Helito et al., 2014). In this study, a fracture analysis will be conducted on the interaction between the uniaxial fixator and femur bone that induces by four-point bending. A newly design of uniaxial external fixator has been introduced by Hospital Universiti Kebangsaan Malaysia (HUKM) and Universiti Malaysia Perlis (UniMAP) as a universal fixator for bone fracture treatments. Investigation for identifying and measuring strength or weakness of the performance of fixator is needed before applying to human body. Fracture sometimes failed to heal due to the load that the patient's body gives constantly to the fracture area. This load will cause bending to the bone and also the screws installed. The load will lead to the failure of external fixation that can make the implant undergo loosening or tightening. The implant installed should prevent such failures. Hence, this research was conducted to determine the performance of uniaxial external fixator based on geometry by different screw drilling techniques and biomaterials when angled uniaxial compression load subjected. This research will be focus on the transverse type of fracture. Therefore, in order to prevent failure of the implant, this research is needed to understand the effect of four-point bending on loosening and tightening of screws and analyze the stress-strain behavior of the bone and screws that can cause breakage and give pain to the outpatient. Thus, delay the process of osseointegration and bone remodeling.

MATERIALS AND METHODS

Computer aided design model of bone-implant

A computer aided design (CAD) model of the external fixation and the femur bone is developed using SolidWorks 2014. The length of an adult femur bone is 48 cm while the diameter of the cortical bone is 2.34 cm. The thickness of the cortical bone at the femoral shaft is 8 mm (Treece et al., 2010) . There are 4 pin screws to be attached to the femur bone where the distance of each screw was set to be 62 mm, 162 mm and 62 mm to each other, as depicted in Fig. 1(a). The fracture is assumed to be healed after 8 weeks of installment of the fixation. The assembly of the bone and fixation have two types of techniques of pins insertion that are pre-drilled pin and self-drill as shown in Fig. 1(b) and 1(c).

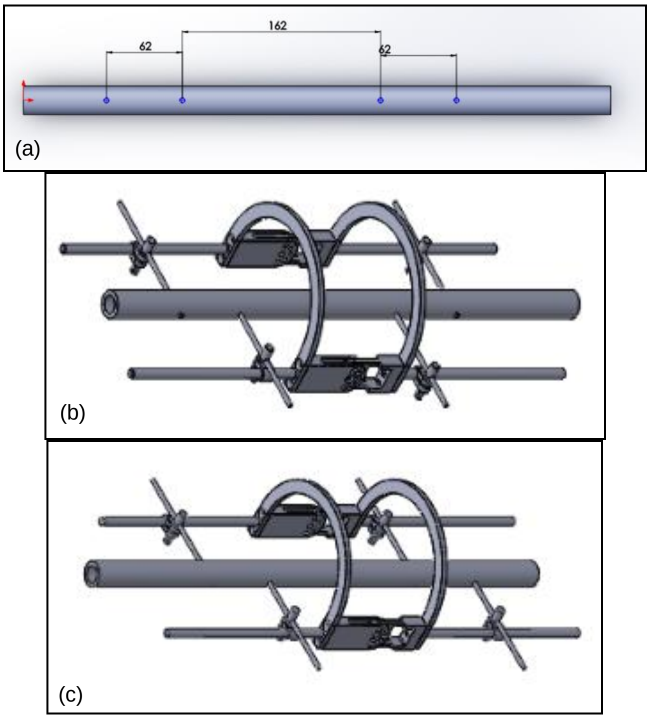

Fig. 1 CAD model of uniaxial fixator-femur cortical bone with (a) pin to pin distance, (b) pre-drilled pin screw, (c) self-drilled pin screw

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Finite element modeling

The simulation was designed to consider pins screw (pre-drilled pin screws and self-drilled pin screws) as the critical part in uniaxial external fixator. Finite element (FE) modeling is conducted using ANSYS 14.5 Workbench. The developed CAD model is imported to ANSYS enviroment. The FE models were meshed using sweep mesh method based on free meshed with tetrahedral elements, as shown in Fig.2.

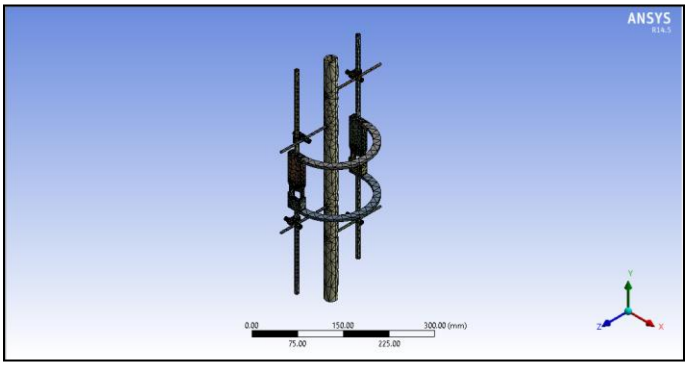


Fig. 2 Meshing scheme for uniaxial fixator-femur cortical bone model.

Two types of external fixation materials were used in this simulation, titanium alloy and austenite stainless steel. Details material properties were shown in Table 1 (Jade et al., 2013). The von Mises stress, von-Mises strain and deformation analysis were based on Elmadin et al. (2015). The maximum bending force is set at 500 N for a three point bending. Based on the bending force, the applied force used for the four-point bending analysis, is 250 N for each bending force at pin A and B. Boundary condition of pin D and C is fixed in x and y axis. Fig. 3 shows the forces that applied on the bone through the pin of the fixator to perform four-point bending analysis.

Table 1 Material properties (Jade et al., 2013)

Material	Elastic modulus (GPa)	Poisson's ratio
Cortical bone	12	0.33
Cancelous bone	0.1	0.33
Titanium alloy (Ti-6Al-4V)	116	0.34
Stainless steel AISI	190	0.29

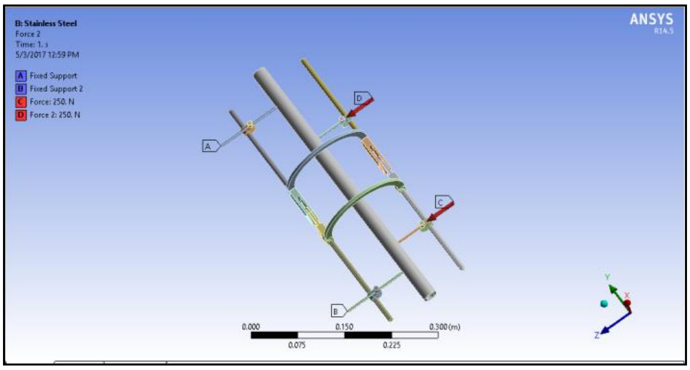


Fig. 3 Loading scheme and boundary condition of four point bending

Firstly, the convergence test was conducted to determine the meshing size that gives the converged results of the stress analysis. The evaluation of stress distribution is based on von Mises stress and 1st Principle Stress, von Mises stress can be expressed as

$$\sigma_e = \left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]^{1/2} \tag{1}$$

where

$$\sigma_1 = \tfrac{1}{2}(\sigma_x+\sigma_y) + [\tfrac{1}{2}(\sigma_x-\sigma_y)]^{1/2} + \tau_{xy}^2 \tag{2}$$

$$\sigma_2 = \tfrac{1}{2}(\sigma_x+\sigma_y) - [\tfrac{1}{2}(\sigma_x-\sigma_y)]^{1/2} + \tau_{xy}^2 \tag{3}$$

$$\sigma_3 = \sigma_z = 0 \tag{4}$$

The convergence test is performed by testing the different meshing size on the pins-bone. The convergence test was done to refine the mesh and reduces the size of element and increase the accuracy of the next iteration results.

RESULTS

Pre-drilled pin screws

Fig. 4 shows the highest von Mises stress, $\sigma_{e_{max}}$ for stainless steel is 36.033 MPa while the highest von Mises stress for titanium alloy is 34.3340 MPa. It can be seen that the von Mises stress tends to increase the intensity as the force increases to maximum of 250 N. Both materials are directly experienced proportional linear relationship. Fig. 5(a) and 5(b) show the location of the highest von Mises stress at the femur bone which are at the pin-bone interaction. The upper pin was identified as the most yield pins for both materials. The effect of Young's modulus of fixator materials is observed to be less significant at applied load lower than 100 N with the average error below 5%. As the applied load is increased more than 100 N, the error between two materials is obvious where the discrepancy average error is more than 6%.

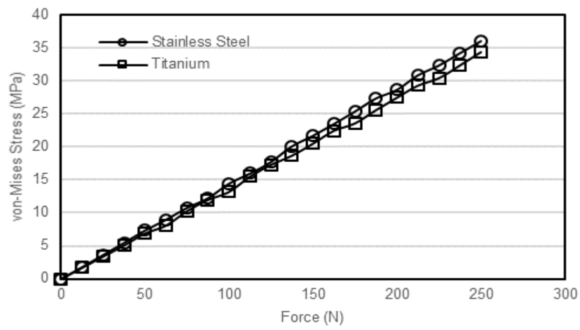
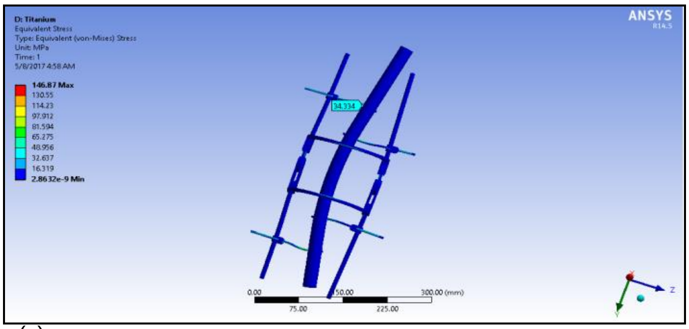


Fig. 4 von-Misses stress of pre-drilled pin



(a)

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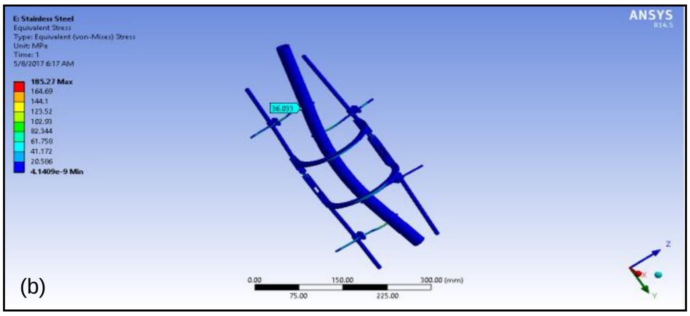


Fig. 5 Maximum von-Mises location of pin (a) Titanium alloy Ti=6Al-4V and, (b) Stainless steel AISI.

Self-drilled pin screws

Fig. 6 shows that the highest von Mises stress for stainless steel is 36.4460 MPa while the highest von Mises stress for titanium alloy is 39.2950 MPa. The stress of titanium alloy is slightly higher than stainless steel. Fig. 7(a) and 7(b) show the location of the highest von-misses stress at the femur bone which are at the pin-bone. In this case, the effect of Young's modulus of fixator materials is observed to be less significant at applied load lower than 100 N with an average error below 6%. As the applied load is increased more than 100 N, the error between two materials is obvious where the discrepancy average error up to 10%.

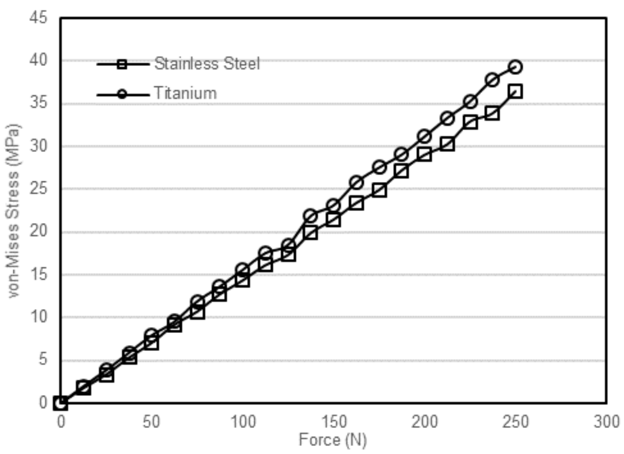
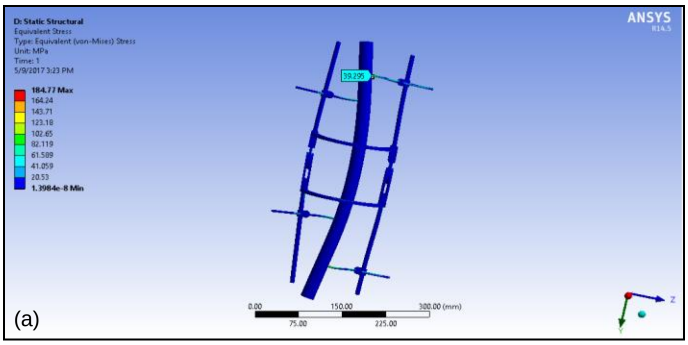


Fig. 6 Von Mises stress of self-drilled pin



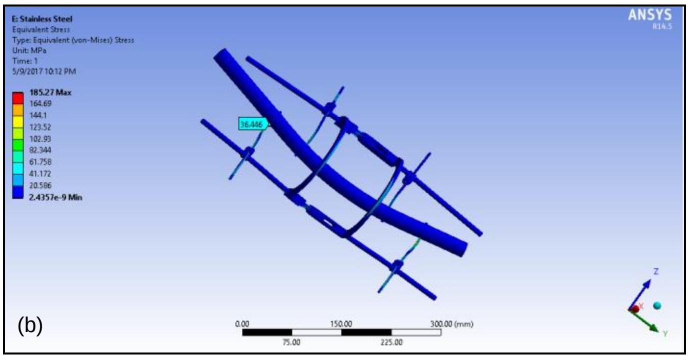


Fig. 7 Maximum von Mises location of self-drilled pin (a) Titanium alloy Ti=6Al-4V and, (b) Stainless steel AISI.

DISCUSSION AND CONCLUSION

The literature has mentioned that complex bone implant-interface from nano to microscopic level is essential in biomechanical optimization of implants. High strength, fracture toughness related to ductility need further investigation in term of elastic-plastic stress distribution (Shibata et al., 2015). Under compression loading, as the condition of four point bending was simulated, the uniaxial external fixation with four pins screw experienced different von Mises stress distribution. It is found that maximum von Mises stress, $\sigma_{e_{max}}$, at surrounding pin-bone interface is located in the first pin screw for both pre-drilled pin screws and self-drilled pin screws. This yielding point explained the insufficient of compression stress transfer from pin screws to bone which delay the bone healing process or initiates the pins breakage (Jade et al., 2013). In terms of pin strength and ductility, different used of pin screws resulted with significant behaviour of stress distribution. For pre-drilled pin screws, stainless steel material was found with higher σ_e for all applied force and $\sigma_{e_{max}}$ of stainless steel pin screws presented the highest $\sigma_{e_{max}}$, 5.8% higher than titanium alloy pin screws. Conversely, Self-drilled pin screws presented the highest $\sigma_{e_{max}}$ for titanium alloy, 7.6% higher than stainless steel where the stress distributions were slightly more than stainless steel for all applied forces. The present results demonstrated that titanium pins can also induce greater pin screw-bone yielding. These results are compatible with a previous FE study by Finn et al. (2012) where 60–65% more peri-implant bone yielding than stainless steel pins and predicted 25% higher contact stresses with titanium in comparison to stainless steel half-pins. As a conclusion, the use of titanium implants would therefore be expected to increase the risk of pin loosening particularly for self-drillled pins but not for pre-drilled pins. Inversely, the use of titanium implants would therefore be expected to reduce the risk of pin loosening particularly for pre-drilled pins but not for self-drilled pins.

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REFERENCES

Nur, H., Hayati, F., Hamdan, H. 2007. On the location of different titanium sites in Ti-OMS-2 and their catalytic role in oxidation of styrene. *Catal. Commun.* 8, 2007-2011.

Umadevi, N., and Geethalakshmi, S. N. (2011). "A Brief Study on Human Bone Anatomy and Bone Fractures." International Journal of Computer Engineering Science. 1(3): 93-56.

Link, B. -C., and Babst, R. (2012). "Current Concepts in Fractures of the Distal Femur." Acta Chirurgiae Orthopaedicae Et Traumatologiae Cechosl. 79: 11-20.

Treece, G. M., Gee, A. H., Mayhew, P. M., and Poole, K. E. S. (2010). "High resolution cortical bone thickness measurement from clinical CT data." Medical Image Analysis. 14(3): 276-290.

Ramtani, S., and He, Q. C. (2014). "Internal bone remodeling induced by metallic pin fitted into medulla of a long bone having cylindrical anisotropy: Theoretical predictions." International Journal of Engineering Science. 82(2014): 124-139.

Helito, C. P., Marcelo, B. B., Demange, M. K., Albuquerque, R. F. da M., Pecora, J. R., Camanho, G. L., and Angelini, F. J. (2014). "Screw Loosening and Iliotibial Band Friction After Posterolateral Corner Reconstruction." The Knee. 21(2014): 769-773

Elmedin, M., Vahid, A., Nedim, P., and Nedzad, R. (2015). "Finite Element Analysis and Experimental Testing of Stiffness of the Sarafix External Fixator." Procedia Engineering. 100(2015): 1598-1607.

Jade, S., Tamvada, K. H., Strait, D. S., and Grosse, I. R. (2013). "Finite element analysis of femur to deconstruct paradox of bone curvature." Journal of Theoretical Biology. 341(2014): 53-63.

Yo Shibata, Yasuhiro Tanimoto, Noriko Maruyama, Manamu Nagakura. 2015. A review of improved fixation methods for dental implants. Part II: Biomechanical integity at bone-implant interface.

Finn E. Donalson, Pankaj Pankaj, A. Hamish R.W. Simpson, 2012. Bone properties affect loosening of half-pin external fixators at the pin-bone interface, Injury International Journal Care Injured, 43, 1764-1770

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