Displacement response of femur with various deformity angles under vertical load: FEA and experiment

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Abstract. Osteogenesis Imperfecta (OI) is a disease that affect the bone in terms of deformity and brittleness. It is known that after certain deformation angles, OI bone cannot sustain the excessive stress that resulting to bone fracture. Although several studies have been undertaken to analyse the fracture prediction on OI bone due to deformity angles using finite element analysis, however none of them has validated experimentally. Hence, the main objective of this study was to investigate the validity of finite element analysis in predicting the fracture risk of OI-affected femur. For experimental works, the bone specimens were prepared using polylactic acid material through Fuse Deposition Material method at 15°, 20° and 25° deformation angles. Findings of this study show a promising result as the deformation response for the FEA was agreed to experimental result. Hence, it proves that prediction of finite element analysis on bone fracture risk of OI is acceptable. This study also found that femur bone with 25° deformation angle tend to fracture under minimum load. Therefore, patients that have femur bone at 25° deformation angles should be advised to undergo surgical intervention.

1. Introduction

Osteogenesis imperfecta (OI) is a disease that can affect human bone characteristics. Bone with OI is brittle due to low amount of type I collagen which is normally consist of 95% from entire human bones [1]. Approximately, 6 to 7 per 100,000 peoples suffer from OI and it is occurring in approximately 1 in 20,000 births without gender or race dependence [2]. Cross-link between collagen 1 alpha 1 and collagen 1 alpha 2 will produce type I collagen. Abnormal condition of any one of these two genes will lead to distorting the structure of type I collagen in the bone. This condition causes the bone mass decrease and contribute to brittleness and fragility [3]. OI patient suffers several bone break throughout their lifetime due to the brittle condition. Currently, there are no special treatments that can cure OI disease. Alternatively based on severity of the disease, surgeon will be advised to patients for treatment such as fracture care, physical therapy and bracing parallel with normal medication. Due to lack of studies on OI bone fracture, surgeon do not have any guidance to predict the fracture quantitatively. Surgeon will depend on their experience as there are no quantitative indicators to do the surgical intervention [4]. The past decade has seen the rapid development of finite element analysis (FEA) [5]–[7] in many engineering area as it produces fairly accurate result. Hence, this study was
carry out to validate the result from FEA with experiment by utilizing the rapid prototyping technique. Although the number of cases on OI in Malaysia is low, however there is need to address the OI bone fracture problem as its secondary effect to the patients is severe. The focus of this research will be on the femur bone as the femur bone fracture incident is high due to this bone endures the highest mechanical stress during performing daily activities.

2. FEA modelling of OI bone and experimental work

2.1 Reconstruction of OI femur model

A standard femur model of healthy person was obtained from Biomedtown website in .igs format. ANSYS was used in this study to analyse the OI deform femur bone. First, the downloaded standard femur model was imported to ANSYS software. Then, the femur shaft length was measured to determine the displacement required at the middle of the shaft to create OI femur model. The shaft length was found as 347 mm. An adequate displacement was then applied to the middle of the shaft as shown in Figure 1. Three angles of deformation which is 15°, 20° and 25° was created to mimic femur bone of OI patients by using tangential rule.

![Figure 1. Deformed model of the femur](image)

Once the deformation shape as showed in Figure 2 were obtained, the shape was scaled to 1/4 in order to accommodate FDM machine before being export to .stl file format for rapid prototyping process.

![Figure 2. OI femur models with three deformity angles of (a) 15 degree, (b) 20 degree, and (c) 25 degree.](image)
2.2 FEA on OI bone

All OI femur models were then reset its stress value to create a situation where the OI femurs are under zero loading. Instead of using bone properties, the material properties of the FEA model was assigned with PLA in order to ensure consistency between experiment and FEA. Then, boundary conditions were set as a force at the femoral head was applied in the vertical direction at the load same with the experiment. The load was increased at increment of 5 N for every step until 50 N. The load was limited to 50 N as to maintain the analysis within the elastic region of PLA material. In this FEA, displacement of the femur head at the highest point was recorded to be compared with the experimental results.

2.3 Experimental work on OI

All three types of OI femur model in the form of .stl file were transported to CURA software. The model was sliced using a certain algorithm to create a numerical control coding that will be used by the FDM machine. The coding was required to move its nozzle in three axes to create the physical OI bone specimen, as shown in Figure 3. A set of PLA print cap was fabricated to partially encase both ends of the printed OI femur bone in order to make sure vertical force that will be exerted on the specimen spread along a wider area. This is to prevent concentration of force on a small area resulting local material failure and the specimen from slipping during experimental work.

![Figure 3. Preparation of OI bone specimen using rapid prototyping.](image)

For the experimental work, the test specimen was mounted on the UTM vertically with both ends was capped with prefabricated PLA material as shown in Figure 4. A small preload was applied to the specimen at 10N to prevent any mechanical damage such as hysteresis. Then the specimen was compressed for 10 mm at speed of 3 mm per minute. The specimen material begins to yield when the machine recorded decrease of load value. The displacement of the highest points of the femur head was recorded to build a displacement versus load graph.
3. Results & Discussion

Figure 5 shows the deformation contour distribution under compression load. It was found that the maximum displacement values are increase with respect to the increasing of OI deformity angles. The maximum displacement was located at the femoral head for all cases.

Figure 5. Displacement contour distribution on OI femur models for (a) 15 degree, (b) 20 degree, and (c) 25 degree.

Figure 6 shows the displacement response of OI bone for the selected deformity angles under experiment and FEA. According to the both graphs, it indicates that OI bone model with deformation angle of 25° is the weakest among all models as its femur head displacement was found highest at all load values. As the bone deformation angle decrease, the displacement of the femur head decrease as expected. Furthermore, the displacement value for the experiment is nonlinear as the slope changing over load values, whereas the FEA results show almost linear. The results also show that the risk for bone fracture was increased as the deformation angle increased. It seems that both results are agreed well.
Figure 6. Displacement response under compression load for all deformity models based on (a) experiment and (b) FEA.

4. Conclusion
In general, the results of displacement response of OI bone under compression load was in agreement between experiment and FEA. The maximum displacement was found increased with respect to the increase of deformity angles. Therefore, the finding of this study shows OI bone analysis using FEA has predicted very well since it was agreed with the experimental results.

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