Prediction on fracture risk of femur with Osteogenesis Imperfecta using finite element models: Preliminary study

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Abstract. Osteogenesis imperfecta (OI) is a genetic disease which affecting the bone geometry. In a severe case, this disease can cause death to patients. The main issue of this disease is the prediction on bone fracture by the orthopaedic surgeons. The resistance of the bone to withstand the force before the bones fracture often become the main concern. Therefore, the objective of the present preliminary study was to investigate the fracture risk associated with OI bone, particularly in femur, when subjected to the self-weight. Finite element (FEA) was employed to reconstruct the OI bone model and analyse the mechanical stress response of femur before it fractures. Ten deformed models with different severity of OI bones were developed and the force that represents patient self-weight was applied to the reconstructed models in static analysis. Stress and fracture risk were observed and analysed throughout the simulation. None of the deformed model were observed experienced fracture. The fracture risk increased with increased severity of the deformed bone. The results showed that all deformed femur models were able to bear the force without experienced fracture when subjected to only the self-weight.

1. Introduction

Osteogenesis imperfect (OI) is a genetic disease associated with a brittle bone due to less of collagen count. To date, it was reported that osteogenesis imperfecta could affect approximately 6 or 7 per 100,000 people and occur in approximately 1 in 20,000 births with no gender dependence or race dependence [1]. Bone mainly made up of collagen where type I collagen is the most abundant which cover up almost 95% of the entire bone format [2]. Type I collagen is the result of cross-link between two main gene named collagen type 1 alpha 1 (COL1A1) and collagen type 1 alpha 2 (COL1A2) where the alteration in one of these two genes will lead to abnormal structure collagen produced in bone where it causes low bone mass and bone fragility which leads to health condition such as OI [3], [4]. Generally, OI can be classified into four main types namely Type I, Type II, Type III and Type IV which basically based on clinical and radiology feature [5]. However, up to now, there is no specific cure for OI patients. OI patients are undergoing several treatments based on the severity of the disease recommended by their surgeons. Those treatments included fracture care, physical therapy, bracing, and medication. Thus, in this situation, the surgeons are having a limitation in order to predict the fracture risk of OI bone before the bone break. In general, the capability of bone to resist fracture risk
depend on the integrity of all levels in the bone principle which include the entire amount of bone material/mass, the size and shape of the whole bone, the microarchitecture of cortical and trabecular bone, trabecular bone volume per tissue volume, trabecular number and thickness, the intrinsic properties of the bone material, the constitution of the organic matrix and the interaction between mineral and organic phases [6]. Despite the medical treatment, the surgeon needs to perform the surgical procedure on OI patient as the last option to correct the bone deformity such bowing. For the past ten years, intramedullary rod implant had been become bone assist to ensure the long bone straight and prevent fracture [7], [8]. However, the drawback from this option is the rod itself might proximally and distally [9], [10]. Thus, it is very important to determine and to know the fracture risk of the long bone to help the surgeon to predict the occurrence. In doing so, the bone fracture risk of OI can only be predicted through the simulation which only can be done in finite element (FE) study. Finite element study had been extensively used in orthopedics biomechanics field for over almost a decade to study and investigate the behavior, process, mechanism, and properties biological system under the mechanical forces or also known as biomechanical phenomena [11]–[13]. Its ability to cope with biological structure especially non-linear material properties, irregular geometry, and complicated boundary condition are the main reason for its widely used among researchers [14].

Therefore, in this study, the fracture risk of femur associated with OI bone was investigated through FE analysis. Ten reconstructed femur models with variation of deformed angles were observed when directional force was applied vertically in the femoral head in static condition.

2. FE modelling of OI Bone

FE modelling of OI bone is the core process in this study in order to investigate the fracture risk associated with femur bone deformity. The load was applied vertically to the femoral head in sagittal plane of the femur model.

2.1 Standard Femur (SF)

The standard femur (SF) was obtained from Biomedtown website which was first proposed by Viceconti et al [15] to make it available for download. The length of SF is 409.4mm. The SF then imported into finite element software, ANSYS for simulation process. The SF was first modified in the design modeler to separate the femoral head and femur shaft part as shown in figure 1. The next was to develop ten different forms of bending angle where the middle of the femur shaft act as reference point to resemble the real OI bone.

![Figure 1. Femoral Head and femur shaft.](image)

2.2 Mechanical properties

Mechanical properties was assigned based on the work conducted by Fan et al [16], [17] using nanoindentation test performed on femur bone sample. Thus, the same mechanical properties were applied in this simulation which the SF was set as isotropic linear elastic with the Young’s Modulus of 19 GPa and Poisson ratio of 0.3.

2.3 Convergence Test

Convergence test was conducted to observe whenever the stress reached its consistency in response to the number of element providing those number of elements are the optimum element size. Ten convergence tests performed by varying the element size ranging from 10 mm to 1 mm. Figure 2(a) showed the number of element against Von Misses stress for convergence test graph. Figure 2(b)(c) and (d) showed the meshing result when the element size was set to 10 mm, 4 mm and 3 mm respectively. Compared to figure 2(b) and figure 2(c), figure 2(d) meshing seems more fine and able to
properly mesh around the curve and edge region of the geometry with the element size of 3 mm. The meshing number started to show consistency when stress reached the value of 13.845MPa when the element size was set to 3 mm. The bigger the element size will produce yield less complexity, however it will reduce the efficiency and effectiveness of the analysis as the distribution of stress among the bigger cell which made up of nodes and element is less accurate rather than smaller cell. Thus it is very important to choose the suitable element size as the meshing defines the model for the analysis. In this study, the suitable mesh for the SF geometry was consisted of 28105 number of nodes and 12745 number of elements of tetrahedron and hexahedron method when the element size was set to 3 mm.

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2.4 OI Bone modelling
The SF was then undergoing deformation process using ANSYS software to obtain the deformed shape of bone to resemble real OI bone. Equation (1) was applied to deform the SF model up to ten different angles of bending.

\[
\tan \phi = \frac{dx}{\left(\frac{L}{2}\right)}
\]

where \( \phi \) denotes as deformed angle, \( dx \) as deformed length and \( L \) is length of femur. The bone length was measured and divided by half, where this middle point was used as the reference point to deform the bone to represent the OI bone geometry. Hence all the deformed models have the same deformed point of reference. Figure 3 showed the radiography of OI bone geometry and figure 4 demonstrated deformed model of SF bone geometry to resemble the radiography image as shown on figure 3. Ten deformed angles ranging from 7.5° to 30.0° with different of 2.5° each was simulated to represent the severity of the deformed bone shown on Table 1. Each of the deformed SF geometry was then applied with force in vertical direction at the femoral head which act as upper body weight and fixed support at the end of the femur shaft to sustain the force applied.

Figure 2. Convergence Test. (a) Von Misses stress against number of element. (b) Meshing with 10 mm element size. (c) Meshing with 4 mm element size. (d) Meshing with 3 mm element size.
Table 1. Development of OI bones model.

| Angle | 7.5° | 10.0° | 12.5° |
|-------|------|-------|-------|
| ![Image](image1) | ![Image](image2) | ![Image](image3) |
| ![Image](image4) | ![Image](image5) | ![Image](image6) |
| ![Image](image7) | ![Image](image8) | ![Image](image9) |
| ![Image](image10) | ![Image](image11) | ![Image](image12) |
| ![Image](image13) | ![Image](image14) | ![Image](image15) |
| ![Image](image16) | ![Image](image17) | ![Image](image18) |

Figure 3. Radiography of real OI bone [18]

Figure 4. Deformed model of SF bone geometry
2.5 Boundary condition
The boundary conditions for the SF were set to be in static condition. The static condition is considered one of the crucial standing position for OI patients as this condition provide the greatest support specifically in femur to balance the whole body as the forces act mainly on hip. This force influenced the weight in static condition of OI patients. Thus to observed this behaviour, normal weight of 512 N was assumed to represent the average normal weight for normal person. In order to included only for upper body weight, based on de Leva's Segment Weight data [19], the percentage of upper body weight was calculated then divided by half to represent femur on both legs. The weight of 151.705 N was considered after calculation to represent as force acting on SF during simulation. The force was applied vertically at the femoral head in sagittal plane for all deformed models and the end of femur shaft act as fixed support as shown in figure 5.

![Force, Fz](image)

Figure 5. Anterior view of the SF with force acting on femoral head.

2.6 Fracture risk criteria
Fracture risk was calculated based on calculation develop by Keyak et al [20] as shown in Equation 2. Fracture strength of 115 MPa was assumed in this study based on the nanoindentation test done by previous study [21]–[23]. The femur bone considers undergo fracture if the value of fracture risk is equal or less than 1 (FR ≤1).

\[
\text{Fracture risk} = \frac{\text{Fracture strength}}{\text{maximum principle stress}}
\]  

(2)

3. Results and Discussion
Maximum principal stress against severity of the deformed angle was presented in Figure 6. However only the upper body weight was included into this study to observe does the OI femur bone is able to support the upper body weight in standing position without involved any body movement or others activities. Figure 6 showed that for the least deformed angle, which is 7.5°, generate maximum principle stress of 8.64 MPa. For the most deformed angle of 30.0°, the maximum principle stress was found to be 10.37 MPa. The maximum principle stress increased linearly with the severity of the deformed angle. The fracture risk was then calculated based on Equation (2) and the correspond value of fracture risk against deformed angle was presented in Figure 7. From the graph, the fracture risk recorded 11.09 for the most deformed angle (30°). None of the model experienced fracture throughout the whole simulation process. Table 2 presented the stress contour for all developed OI models. The maximum principle stress was seen to be accumulated at the deformed region, in the middle of the femur shaft for all deformed models, thus making this deformed region were able to withstand the most stress compared to other region when force was applied vertically to the femoral head. As the
severity of deformed angle increase, the stress was seen appeared getting larger at the middle point of femur shaft as indicated by red region in Table 2 for deformed bowing angles of $10^\circ$, $20^\circ$ and $30^\circ$.

![Graph showing maximum principal stress vs deformed angle.](image)

**Figure 6.** Effect on Deformed Angle on maximum principal stress.

![Graph showing fracture risk vs deformed angle.](image)

**Figure 7.** Effect of deformed angle on Fracture Risk.
Table 2. Stress contour for several deformed models.

This situation might lead to the possibility that static condition could bear the upper body weight by itself without fracture for all the severity level of OI. The fracture risk value was noticeable still high (11.089) even for the most deformed angle, 30°, however as mentioned early, the middle point of the femur shaft was used as reference point in this study to act as the bending point to estimate the fracture risk, meanwhile in real case, the bending angle might be slightly on different anatomical position which will produce different angle of bending and fracture risk. In addition, self-body weight was used as the force acting on femoral head in this study, thus, this result reflects that by the normal body weight, the OI bone was able to support the upper body on their own without fracture in standing position which involved no movement. Any external movement might actually cause fracture to occur. Nonetheless, this study was to provide preliminary result to show that the same approach could be applied when dealing with the similar issue in the real case.
4. Conclusion
The different OI bone models consisted of different severity of deformed bone have been developed and analysed in this FE study. The stress and fracture risk were observed against different deformed angle. Fracture risk associated with OI patients in femur bone could be fatal if there is no early detection. Thus, it very important to estimate and predict the fracture in femur in OI patient. In this study, it was noticed that in static condition, all the severity of the deformed bones were able to withstand the load in standing position. No fracture risk occurs for all the deformed angle in this position. On the other hand, this study also proves that modelling and simulation approach through finite element analysis could benefit to both the OI patients and medical support in order to predict the fracture in OI patients before surgical intervention.

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