Fracture prediction on patient-specific tibia model with Osteogenesis Imperfecta under various loading direction

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Abstract. This study aims to predict the fracture of bone with osteogenesis imperfecta (OI) by considering the homogenization properties of real patient. A Type-III of osteotomy in OI femur was used as bone specimen. Nine representative volume element (RVE) models were developed based on μCT-images of bone specimen. Homogenized properties particularly the Young's moduli of the RVEs was obtained based on homogenization theory in Voxelcon software. The obtained homogenized properties were then assigned to the OI patient-specific model that was developed from CT-images of real patient. The fracture of OI bone was predicted based on linear static analysis and finite element method under loadings of activity daily living (ADL). The results found that the fracture might be happen to the patient under jumping load case, whereas the subject is expected to be safe under standing still and walking load case.

1. Introduction
Bone generally is known as porous, having complicated hierarchical design and heterogeneous material. The bone properties is dependent on the morphology of bone, bone tissue properties and bone volume fraction in microscopic scale [1]–[4]. However, most of the studies of OI bone were carried out in macroscopic level [5], [6]. The effective elastic properties of a bone is representing the stiffness at microscopic scale that can be calculated using homogenization method [7]–[9]. Homogenization method was originally used for predicting the effective elastic properties for periodic microstructure such as unidirectional fibre-matrix composite or cellular materials, but it has been validated that the method could also applicable for random microstructure such as bone and porous ceramics [10], [11]. Hence, the method could possibly use for predicting the effective elastic properties of bone with Osteogenesis Imperfecta (OI).

OI (also known as brittle bone disease) is a congenital and genetic disorder disease. Several studies on OI, particularly on fracture prediction using finite element analysis have been undertaken quite extensive recently[5], [12], [13]. Fan et al. [12] applied mathematical function to reflect different deformities of OI femur in model reconstruction. They concluded that deformity could deteriorate the stress and strain distribution. On the other hand, Caouette at al. [13] developed a reconstruction
method of the tibia for OI patients that used as input of a comprehensive finite element model to examine fracture risks. The FEM results showed the importance of patient-specific geometry modelling for fracture risk assessment. Recently, Albert et al. [5] characterized the macroscopic anisotropic cortical bone material properties and investigate the relationships with bone density measures in children with severe OI. They found that cortical bone in children with severe OI yields at the same strain as normal bone, and that their decreased bone material strength is associated with reduced volumetric bone mineral density.

Although several studies have investigated the fracture assessment on OI, none has applied the bone properties that considering the porosity of the microstructure. Hence, this study was undertaken to predict the fracture risk of femur with OI that considering the influence of bone porosity, by applying the homogenization method to obtain the bone elastic properties.

2. Finite Element Analysis

2.1 Reconstruction of Representative Volumetric Element (RVE) Model

In order to obtain the homogenized properties of OI bone model, RVE models were developed based on μCT-images of a patient (male, 19 years old). The series of images were binarized using Otsu method in MATLAB.

![Figure 1. A sample μCT image of OI bone specimen (left) before segmentation and (right) after segmentation.](image)

Nine RVEs were developed from three pieces of bone specimen using Voxelcon (Quint Corp., Tokyo) as shown in Figure 2. All RVEs were extracted from different locations of bone specimens with the same dimension of approximately 4 × 4 × 4 mm³. Bone volume fraction (BV/TV) for each RVE model was then calculated based the number of element over the total RVE volume.

![Figure 2. Nine RVE models that were extracted from bone specimens.](image)

2.2 Homogenized Properties
In order to determine the effective elastic (homogenized) properties of each RVE, the homogenization method was employed. Young’s modulus of 22 GPa and Poisson’s ratio of 0.3 was assigned as bone tissue properties. The influence of BV/TV on the effective elastic properties for the developed RVE was then investigated.

2.3 Development of OI Patient-specific Femur Model

OI patient-specific femur model was developed based on CT-images of real patient as shown in Figure 3. The element size was selected same as the image resolution in order to avoid argument on mesh size.

![Figure 3](image)

**Figure 3.** A patient-specific model of OI was developed (based on the CT-image before surgery). Three voxel models (right) were the osteotomy that been used for reconstruction of RVE models.

2.4 Fracture risk analysis

Fracture risk analysis was conducted based on static stress analysis. The obtained effective elastic property was then assigned to the OI femur. Analysis under various loading directions (as shown in Figure 4) and load cases that represent standing, walking and jumping was performed in Ansys [14], [15]. Body weight (BW) was taken as 62 kg. Fracture strength of 115 MPa was assumed [16] and the fracture risk for each load case was calculated as the fracture strength over the obtained von-misses stress.

![Figure 4](image)

**Figure 4.** The fracture load is in the direction of (a) lateral (b) medial (c) anterior (d) posterior (e) compression (f) tension.

3. Results and Discussion
Figure 5 shows the effect of BV/TV on the Young’s moduli in orthogonal axes. Obviously, the results show the increase of BV/TV has increased the average Young’s moduli. The effective elastic properties of the OI bone that consists of Young’s moduli, Poisson’s ratio and shear moduli are listed in Table 1. It seems that the effective elastic properties were strongly dependant on BV/TV.

| Load case          | Standing | Walking (3 × BW) | Walking (7 × BW) | Jumping (15 × BW) | Jumping (20 × BW) |
|--------------------|----------|------------------|------------------|-------------------|-----------------|
| Fracture risk      | 33.08    | 3.68             | 1.58             | 0.74              | 0.55            |

In the analysis of fracture risk, the OI femur was found safe (> 1.0) under standing and walking load cases, meanwhile it was expected to be fractured (< 1.0) under jumping condition. This indicates that the OI femur can bear high load under stationary condition like sitting and standing because it does not have excessive force. The fracture load in lateral/medial, anterior/posterior and compression/tension directions were obtained as 904.7 N, 1278.6 N and 2028.1 N respectively. Figure 6 shows the von-Mises stress distribution of the OI-affected femur under three orthogonal directions. The results found that the mid of femoral shaft is subjected to stress concentration and it is expected to initiate fracture under excessive load.

4. Conclusion
In this study, the RVE is well developed and the effective elastic properties of OI bone was obtained to be assigned as bone tissue properties of OI femur. The results found that the OI bone stiffness was strongly dependent on the BV/TV of RVE. Meanwhile in macroscopic scale analysis, the femoral
 shaft was spotted as the weakest area of the OI femur under all load cases and tend to experience fracture initiation. Loads under standing and walking activities were predicted to be safe for OI patient, whereas OI bone was expected to be failed under jumping activity.

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