Fracture risk prediction on children with Osteogenesis Imperfecta subjected to loads under activity of daily living

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Abstract. Children with Osteogenesis Imperfecta (OI) often vulnerable to fracture even on their daily basic tasks. The unpredicted fracture leads to intramedullary surgery. This study aims to investigate the fracture risk in children with OI in daily basic tasks including standing, walking, and jumping. Ten models of OI finite elements were reconstructed based on the radiography CT image of enrolled OI patients. An actual body weight of OI patient was used as the main force acting vertically towards the femoral head and then the fracture risk was observed. In standing and walking configuration, all ten OI models were found able to sustain the acted load. Whereas in jumping configuration, all OI models suffered to become fracture. Early prediction of fracture risk could help medical personnel and OI patients from fall or injury.

1. Introduction

Osteogenesis Imperfecta (OI) is a hereditary disease which causes the bone fracture to the patient. The unpredicted occurrence of fracture always becomes major issues discussed among the orthopedic, researchers and patients. The lack of type I collagen which covers up almost 95% of the entire bone formation lead to abnormal structure collagen produced in the bone where it causes low bone mass and bone fragility which leads to a health condition such as OI [1,2,3]. To date, once the fracture occurs, OI patient will be treated either with a surgical procedure or physical therapy. Surgical procedure involved the intramedullary nail insertion into the bone to join the fractured bone. However, this also does not solve the issue as the occurrences of unpredictable fracture might repeat in future.

Assessment of fracture risk in OI bone had been conducted by several researchers in the past [4,5]. The bone failure has been widely investigated where could be due to the physical properties at micro level [6,7] or macro level [8]. The finite element model of OI bone was presented with variation of bowing angles to resemble real OI bone [9]. The findings suggested that the gait cycle and various of load impacts influenced the risk of fracture. In order to develop the OI bone in the finite element method to presents the reliable model, there are several aspects should be taken into consideration. Geometrical model, bone properties and boundary conditions are the main parameters to be emphasised in finite element analysis. Commonly, the difficulty encountered by researchers is to develop the geometry of the finite element models to serve as the OI bone. Bone material properties must also be clearly defined considering the randomness of microstructures [10, 11]. The fragility of the bone largely affected by the porosity, crosslinking profile, mineralization distribution, or the collagen content which influence the
fracture risk. Fan et al. [8] suggested the Young’s modulus for OI bone is 19 GPa with isotropic linear elastic. This value based on experimental conducted on OI bone sample through nanoindentation technique.

In this study, the fracture risk with respect to activities of daily living (ADL) which is standing, walking and jumping was predicted using finite element analysis. Ten OI finite element models were reconstructed based on the radiography image of the real OI patient. The actual body weight opposed by OI patients was used as load acting on the femoral head.

2. Method

2.1. Standard femur (SF)
The “Standardised femur” (SF) model was first obtained from Biomedtown website proposed by Viceconti et al. [12] which make it available for download. The length of SF is 409.4 mm. SF was imported to finite element software, ANSYS for simulation purpose. First, the process of separating SF into two parts that consists of femoral head and femoral shaft takes place since the SF was imported in one full part thus separating its solid design into two parts is required for the selection of force region in the femoral head. The procedures are as follows.

i. At the origin, a perpendicular line with 45° was drawn in Z-plane to divide the femoral head and femoral shaft.

ii. Once divided, the femoral head and femoral shaft were bonded with same mechanical properties.

Once completing the separating process, convergence test was conducted to determine the optimum element size to ensure the accuracy of numerical results. The SF meshed with 28,105 nodes and 12,745 elements of tetrahedron and hexahedron types chosen based on the convergence test.

2.2. Finite element modeling of OI bone
Reconstruction of OI bones takes place in ANSYS. Ten OI models were reconstructed to resemble real OI bone geometry. CT scan image of enrolled OI patient obtained from the Hospital Universiti Sains Malaysia with patient’s consent was used as a guideline for this purpose. The bowing angles in sagittal plane were varied from 7.5° to 30.0° with increment of 2.5° for each model. 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. Figure 1 shows the radiography CT image from enrolled OI patient whereas Figure 2 shows the reconstruction of OI finite element model.

\[ \text{Figure } 1. \text{ CT scan image of real OI patient. Figure } 2. \text{ Reconstruction of finite element OI model.} \]

2.3. Material properties
Material properties of the reconstructed OI bone was set as isotropic linear elastic with the Young’s Modulus of 19 GPa and the Poisson ratio of 0.3 [13].

2.4. Boundary conditions
Boundary conditions were set to represent the standing, walking and jumping conditions. In standing, the compressive force was assumed as one-third of body weight. Walking takes approximately three to seven times of body weight, whereas jumping greatly affected on 15 to 20 times of body weight [14]. The body weight of real OI patient which is 37.5 kg was used as the main force acted upon the femoral head which indicated the children for age between 13 years old to 18 years old [15]. The constraint was set at the medial condyles, lateral condyles and intercondylar fossa of the femur. Figure 3 illustrates the force and constraint used throughout this study.

**Figure 3.** Setup of boundary conditions on femoral head (ADL load) and medial condyles (fixed).

2.5. Fracture risk analysis

Bone fracture risk is clinical risk used to determine the fragility of the bone. Fracture risk calculation was made based on formulation by Keyak et al. [16]. Fracture strength of 115MPa was considered into this study based on nanindentation test performed by previous study [13]. Maximum principle stress is a direct value obtained through the simulation for all boundary conditions.

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

3. Result & Discussion

Figure 4 presents the graph of fracture risk against ten OI models with variation of bowing angles. In Figure 4(a), for standing configuration, noticed here that the trend shows in decreasing pattern when the bowing angle increased. During the first three bowing angles which are 7.5°, 10.0° and 12.5°, fracture risk decrease as the OI bowing angles increase. When bowing angle reaches 15.0°, 17.5°, 20.0° and 22.5°, it is observed that there is a slight change of the trend which shows the constant pattern. However, at 25.0°, 27.5° and 30.0°, there is an increment in fracture risk. On the other hand, Figure 4(b) shows the fracture risk for walking and jumping configuration. The black line indicates the fracture risk level where the value less than one (FR<1), there is a fracture and vice versa. Discovered here that in both walking configuration, for minimum and maximum walking given the load possessed by OI patient, the result shows that all OI models have the ability to walk on their own without any aid as the fracture risk is above fracture risk value of 1. This result supported by previous study conducted by Fritz et al, in which during seven phase of gait cycle, all the OI patient able to perform gait cycle without fracture [5]. However, a precaution should be taken and the patient must be monitored even though the patients can perform this tasks on their own because any external impact from the surrounding might eventually
cause a challenge to them which lead to fracture. For jumping configuration, the analysis pointed that for minimum jumping where involve 15 times on body weight can actually have accomplished by the OI models. On the other hand, the maximum jumping will definitely cause fracture as all OI models show the value of fracture risk below 1. Highlighted here, for walking and jumping, the trend was different compared to the standing configuration. The trend which fairly remains at constant was observed for walking and jumping configurations indicated that there are only a slight difference in fracture load between each OI models when performing walking and jumping. The compressive force acting on the femoral head during all configurations seem to affect mostly at the femoral shaft region represented by the red contour. The stress concentration accumulated at the middle of femoral shaft part at the bowing angles region. The stress distributed among the femur region and at the femoral head and medial condyles, lateral condyles and intercondylar fossa of the femur do not seem to be affected by the compressive force acted upon standing, walking either jumping. On the other, the middle femoral shaft region is great suffering from a fracture. This circumstance can be related to the bone geometry itself. Well aware that in OI bone, the progressive deformities of long bones are heredity disease which mainly affected the porosity of bone and hence influence the mechanical strength of OI bone [17]. Thus far, the bending region of OI bone is considered as the most fragile region and will eventually break once vulnerable to an excessive amount of force.

![Fracture risk with variation bowing angles under loads](image.png)

**Figure 4.** Fracture risk with variation bowing angles under loads of (a) standing, (b) walking and jumping.
4. Conclusion

In conclusion, the ability of OI models to perform the daily basic tasks were clearly simulated through finite element analysis in this study. The finite element OI models used to represent the real OI patients conducted in this study proposed that in standing and walking configuration, all level of OI models were able to perform the tasks without fracture given the body weight of 37.5 kg. On contrary, the jumping configuration will experience fracture given the same load. However, minimum jumping barely able to endure under this circumstance. Overall, this study presents the activities of daily basic greatly influence the mobility of OI patients and risk of fracture.

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