Experimental validation of finite element modelling on tibia with osteogenesis imperfecta

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Abstract. The paper aimed to determine the validity of finite element analysis of tibia bone affected by Osteogenesis Imperfecta (OI) under various angle of bowing of the bone. Finite element (FE) model of human tibia bones were developed with various degree of bowing to simulate different severity of OI, and then the geometrical models of these FE models were used to develop bone specimen using fused deposition method (FDM) rapid prototyping technique. Compression tests were conducted to the bone specimen and FE analysis were performed by simulating conditions of the compression test, and then results from the compression test and FE simulation were compared. It have been found that both of the results corresponded to each other, therefore it is concluded that FE analysis is able to simulate the mechanical response of tibia bone with OI.

1. Introduction
Osteogenesis Imperfecta (OI), also known as brittle bone disease, is a genetic bone fragility disorder characterised by skeletal deformities. It is one of the most commonly found bone fragility disorder among children, with a statistical incidence of 1 in 10,000 to 1 in 20,000 newborns [1]. OI is a heterogeneous disorder and is categorised into four main types, based on radiographic, genetic and clinical criteria [2]. There are type I, type II, type III and type IV. OI type II is one of the most lethal form of OI and is considered as one of the most common severe skeletal dysplasias [3].

There are several patient-specific models which evaluate the fracture risk in tibia under various loadings [4]–[6]. Caouette at al. [7] employed finite element analysis (FEA) to investigate the fracture risk with respect to tibia deformity in children affected by OI under lateral and torsion impacts loads.. The results suggested that fracture risk for lateral and torsion impact is correlated to the level of tibia bowing. In order to investigate the fracture risk of OI-affected bones using FE analysis, the accuracy of FE models involving bones with OI needs to be validated to verify its accuracy in simulating the mechanical behaviour of bone specimens with a certain bowing angle [8].

Validation of FE model is conducted by comparing the results of FE analysis to another experiment which is not performed numerically, usually a physical experimental test. The geometry of the FE model should reflect the geometry of the physical experimental specimen, and then the results of the numerical simulation and physical experiment is to be compared, and if the results agree to each other, then the FE model is said to be validated with accurate result that reflects real life situation. For the
physical experiment, it can be either by using the real bone such as what is performed by Dahan et al [9]. As an alternative, specimen fabricated using rapid prototyping technology to create a specimen that takes the shape of the bone meant to be studied as demonstrated by Johnson & Young and Hamblu [10][11]. Johnson & Young performed experiment on skull model fabricated using rapid prototyping, and found that the deformation closely matches to FE analysis result. On the other hand Hamblu did FE analysis on trabecular bone and compared the results with experimental results using real bone specimen, and managed to validate the accuracy of FE simulation as well. Both of these researches has shown that FE analysis is able to accurately predict the mechanical responses of complex geometries, this is very valuable because it would help to assist in pre-surgery evaluation on bones. Furthermore, research involving OI such as fracture risk prediction on femur has been done as well by Wanna et al [12]–[14] through the means of FE analysis.

Surgery involving bone of OI requires the prediction of when will the bent bone break to determine when to carry out orthopaedic surgery, such prediction is usually done by a doctor’s evaluation based on their experience, which might not be reliable, and therefore the ability of FE analysis to predict the point failure of bone will be highly valuable to determine the best time to carry out surgery for OI treatment. As of now, there is still a clutter with regards to the validation of OI bone FE models, there is a research gap in this field with regards to tibia affected by OI, and therefore there is an interest in the validation of OI tibia FE models to investigate the accuracy of such FE model in predicting the mechanical behaviours of OI tibia. Hence, this research aim to develop FE models based on tibia affected by OI and validate of the accuracy of the FE model on predicting the occurrence of failure for the model.

2. Materials and methods
For the validation of FE simulation results by comparing it to experimental outcome using physical model, 3 sets of tibia geometrical models with different bowing angles to simulate different conditions of OI was developed. The bowing angles imposed onto the bones are 10°, 14°, and 20°. This allows us to have a glimpse on the effect of large and small bowing angles in response to applied forces, the bowing angle 14° was selected to reflect the bowing angle of a patient (male, 18 years old).

2.1. Development of 3D models of tibia
A 3D geometrical model of a standard tibia (Turbosquid, U.S.) is modified in ANSYS Workbench to artificially impose a certain amount of bowing onto the bone. The boundary condition was set up by having the distal end of tibiotalar joint as a fixed support, and a compressive force applied on the distal end of tibiofemoral joint. Further boundary condition is added to restrict the displacement of bone so that it only moves along the vertical axis to help in forming a smooth bowing angle. The geometrical models created are then used in FE simulation and experiment.

2.2. Fabrication of physical model
For the fabrication of physical tibia model, the same 3D geometrical model used in FE simulation is used to create identical physical models through rapid prototyping approach. The rapid prototyping method used was fused deposition modelling (FDM). The material selected for the fabrication of test model is polylactic acid (PLA), the model was scaled to the same size with the size of model used in FE simulation.

2.3. Compression test of physical model
Each of the rapid prototyped models were used to carry out compression tests to determine the responses, and the deformation for each of the models were recorded. In order to cater to the irregular shape of bone specimen, custom jigs were created to provide support for the bone specimens during compression test. Figure 1 shows the setup of the compression test.
2.4. FE model validation
The FE analysis was set up to simulate the testing conditions of the compression test machine, the jigs which were used in the compression test were included into the FE analysis as well to further simulate the actual conditions of the compression test. The jig at the lower part of the tibia model was set as fixed support while force was applied from on the jig at the top part of the tibia model. The material properties of the FE model is set as isotropic linear elasticity, Young’s modulus and Poisson’s ratio of the PLA material which are 1.73GPa and 0.36 respectively was applied to the FE model set up.

For the compression test, only the results up to the point before yielding occurs is taken into consideration as the FE analysis is performed under the assumption that the material is linear elastic, therefore the compression testing results after the material undergone plastic deformation would no longer be reflected in the FE analysis. The forces recorded during the experiment at certain interval points of deformation was applied into the FE analysis, and then the responses of both FE simulation and compression are compared for validation, at least 5 points of interval was recorded for each of the experiments.

3. Results and discussion
The deformation due to compressive force is represented in the form of total displacement, the results both compression test and FE simulation of each tibia model samples were plotted against each other to evaluate how closely does the FE simulation predicts the outcome of experiment. Figure 3 to 5 show the plot for tibia with bowing angle of 10, 14 and 20 degrees respectively.
FE simulations gave perfectly linear predictions of total displacement as the force applied increases. On the other hand, the normalised data from the experiments appears to be linear with slight deviations at each point. The plotted lines for all three sets of experiments crossed each other and appears to be overlapping at certain points, which suggests that the difference between simulation predictions and experimental results are very small at certain points.

For tibia model with bowing angle of 10°, the percentage difference of experimental displacement over FE simulation displacement result ranged from as small as 0.12% to as large as 37.65%. On the other hand, for tibia model with bowing angle of 14°, the smallest percentage difference is 4.45% while the largest percentage difference maxed out at 15.08%. Lastly for tibia model with bowing angle
of 20%, the smallest percentage difference here is the smallest among all three sets of data which is 1.18%, while the largest percentage difference for this set of experiment is 20.08%.

It is worth mentioning that for all three sets of experiments, the largest percentage differences occurs at the first point of the plot where the deformation is the smallest, and once the deformation goes over 1mm and above the percentage differences for each of the points significantly drop to below 10%. The reason for higher errors at the lower end of the spectrum suggests that there are errors which occurred at the beginning of the experiment, as FE simulation is unaffected by such error, therefore the error likely lies in the earlier stages of the compression test. This is likely due to the pre-compressed force during the compression test setup that prevents the specimen from slipping away from the machine might induce a slight deformation during the initial stage, which is unavoidable, and therefore the initial readings up until 1mm contain larger errors.

Besides, due to the nature of FDM which has specific direction of printing, the specimen will be anisotropic instead of fully isotropic, resulting in slight difference in the behaviour of materials and cause some errors. Taking account of the slight errors due to FDM, and also the excess force during the setup for compression tests, percentage difference of below 10% between FE prediction and experimental results suggests that are highly correlated, and the errors are still tolerable. This finding is consistent with researches from other researchers who validates FE simulations with experiment, which the authors obtained percentage differences of 2% to 7% [15], [16], which considered that such results validate the ability of FE simulation to predict mechanical behaviours of complex 3D geometry with good accuracy. It is also worth noting that in Su et al’s finding, sub optimal set ups of FE simulation produced measurement difference of up to 49% for curved surfaces [15], suggesting that it is more complicated to predict complex shapes.

4. Conclusion
Even for geometry as complex human bone, FE analysis was able to predict the mechanical behaviour under compressive loading and produce results which matches closely with results from experimental tests. In order to achieve FE prediction with high accuracy, the simulation environment must depict the real environment as close as possible, by having appropriate boundary conditions. While the tolerance were high in the experiments of this paper, it was still able to produce satisfactory results, in the continuation of this work there are areas of improvement which might be able to further validate the usefulness of FE analysis, such as using rapid prototyping with smaller tolerance, minimizing parallax error in experimental set ups, and also fine tune the FE model by choosing more suitable type of mesh for different surfaces to further validate FE modelling results with higher confidence.

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