Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech Eng., 53(special issue 2) (2021) 289-292
DOI: 10.22060/mej.2019.16816.6450

Prediction of femoral fracture pattern using finite element analysis of dual-energy X-ray absorbptiometry-based model

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ABSTRACT: Osteoporotic bone fracture is a significant public health problem. Therefore, it has attracted several physicians' and biomedical researchers' attention. The main objective of this study is to predict hip fracture location under various loading conditions. The use of bone densitometry in clinics to evaluate and predict osteoporosis has been expanded. Therefore, in this research, finite element analysis is carried out using models based on images and reports of dual-energy X-ray absorptiometry system to predict the femoral fracture pattern. Initially, the finite element models were created based on the bone mineral density reported in four distinct regions including neck, greater trochanter, inter trochanter, and total hip. To improve the accuracy of predictions, the pixel by pixel bone mineral density map was extracted based on the raw data of the HOLOGIC bone densitometry device. Linear finite element analysis was performed using the maximum risk factor, which has been defined based on the ratio of the strain energy density to the yield strain energy density, and thus the location of femoral fractures was determined based on the location of critical elements. The results demonstrate that using the non-homogeneous distribution of bone mineral density in a finite element analysis of the 2D models based on dual-energy X-ray absorptiometry can be considered as a useful tool for predicting the location of the bone fracture.

Review History:

Received: Jul. 26, 2019
Revised: Sep. 18, 2019
Accepted: Dec. 09, 2019
Available Online:Dec. 30, 2019

Keywords:

Osteoporosis
Femur Fracture
Finite Element Analysis
Dual-Energy X-Ray Absorptiometry
Bmd Mapping

1. INTRODUCTION

Osteoporosis is the most common metabolic bone disease that causes the degradation of bone tissue quality and the loss of bone mass and consequently, bone strength is significantly reduced. Hip fractures due to osteoporosis have been recognized as a major and common health problem in the elderly population [1]. Thus, many researchers have used a 3D FE model derived from Quantitative Computed Tomography Images (QCT) to evaluate the risk of femoral fractures. The comparison made between the results of this noninvasive method with the experimentation has proved its reliability and accuracy [2]. However, high radiation exposure is the major obstacle of its clinical usage. Therefore a Dual-energy X-ray Absorptiometry (DXA) based Finite Element (FE) modeling was proposed to assess hip fracture risk. Several subject-specific DXA-based FE models were developed to estimate the bone strength and risk of fracture in the past few years. A few of them compared the DXA-based FE models predictions with experimental measurements [3, 4], which showed a good agreement with the experimental results (respectively R^2=0.59 and 0.77).

The purpose of this study is to evaluate the ability of DXA-based 2D FE model in the prediction of the fracture pattern of human proximal femur. This procedure was carried out by extracting a pixel-by-pixel map of the material property of femur such as aBMD using raw data of HOLOGIC DXA scanner and using high strain energy elements of the linear FEA results.

2. METHODOLOGY

Four patients were scanned with DXA (Horizon, Hologic Inc., USA). The aBMD from the total proximal femur, femoral neck, greater trochanter and intertrochanteric regions were obtained according to DXA report and a pixel-by-pixel BMD map (as shown in Fig. 1(a)) was extracted from raw data (.r file) of each DXA scan using MATLAB code (pixel size 0.901×1.008 mm^2). This file consists of the attenuation of X-ray beams at two distinct energies, which was used to calculate aBMD map (g/cm^2) at the total hip region. The details of this procedure are available in the literature [5, 6]. Each pixel of DXA images was converted into C3D8 element (element size 1×1×1 mm^3) and each model was assumed to be a plate with a constant thickness that was obtained using Eq. (1) for each patient [4].

$$t = \frac{3.5\pi D}{16} \tag{1}$$

D is the mean width of the femoral neck cross-section that is shown in Fig. 1(b).

In this linear analysis, the bone model was assumed to be an inhomogeneous isotropic material with linearly elastic properties. The aBMD of each element was converted to

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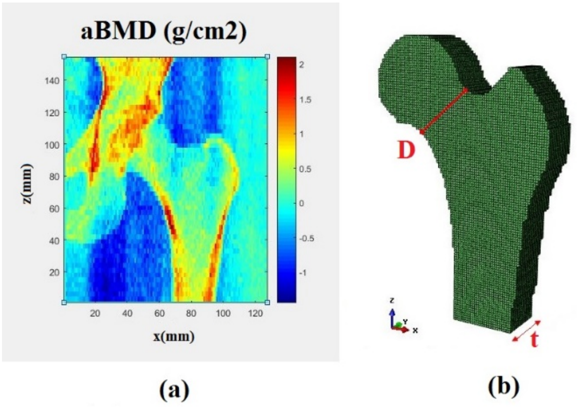

Fig. 1. (a) Pixel-by-Pixel BMD map (b) 3D FE model with a subject-specific constant thickness that meshed with a voxel size of 1×1×1 mm³

vBMD using empirical functions established by Luo [7]. For each element, Young's modulus of elasticity (E, MPa) and yield strength (S, MPa) values were computed from the vBMD of bone using the empirical equations developed by Keyak [8].

The boundary conditions in the finite element model were applied according to the conducted experiments which were reported in our previous study [2], i.e., the load of 2000 N was equally distributed among the nodes of the femoral head. The nodes of the distal of the shaft (2 cm) were fully restrained. In this study, two angles (α, β) were used for loading of the femur: α (the angle between the applied load and the sagittal plane) was varied from -30 to +30 and β (the angle between the load and the coronal plane) was assumed 0. All elements of boundary conditions and elements with the modulus below 5 MPa were assigned a low modulus of 0.01 MPa.

The linear FE models were analyzed using ABAQUS software. A python code was used to calculate and sort the elemental risk factor (RF) by computing the ratio of the strain energy density to the yield strain energy density for each element according to Eq. (2). The location of critical elements (elements with the most RFs) was considered as the failure initiation location. By increasing the percentage of screened critical elements, the fracture propagation was simulated as shown in Fig. 3.

$$RF = \frac{StrainEnergyDensity}{YieldStrainEnergy} \tag{2}$$

3. RESULTS AND DISCUSSION

The FE predicted femoral fracture pattern of the model with material properties according to pixel-by-pixel BMD mapping was compared with the model created using Hologic reported BMD. Fig. 2 shows an improvement in the prediction of failure pattern.

Fig. 3 shows the predicted failure patterns for one sample (number 1) under different loading orientations. It should be noted that this linear method can only predict just the location of damage initiation and limited growth. The trochanteric fracture of sample 1 is shown in this Figure and crack growth towards the lower trochanter in orientation (a) and (b), while in (c) when the hip is under normal loading at stance configuration, the fracture initiation would happen in the femoral neck region.

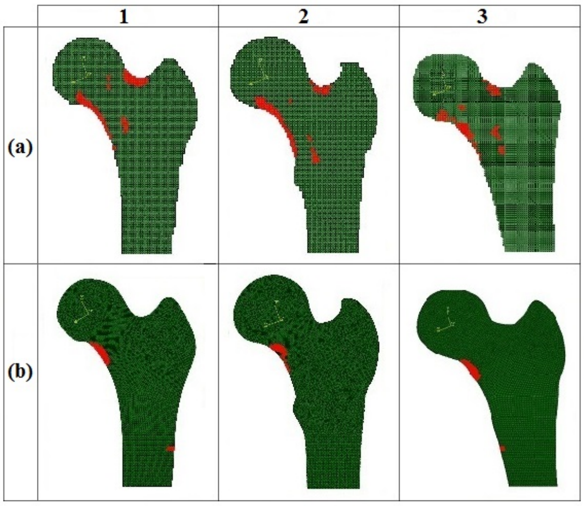

Fig. 2. Comparison of the femoral fracture pattern of three samples (a) voxel-based model (b) model with four reported material properties

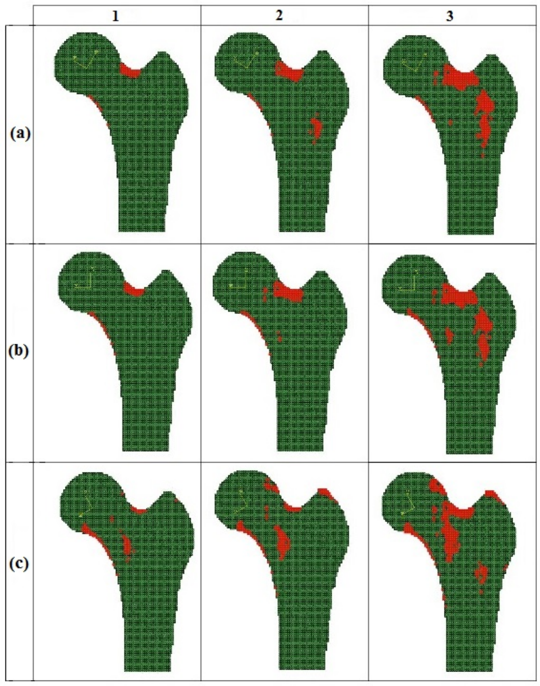

Fig. 3. Comparison of the development of the fracture pattern along 3 different orientations for specimen 1 a) α=-30, β=0 b) α =0, β=0 c) α =30, β=0

4. CONCLUSIONS

In this study, the mechanical behavior of femoral bone under different loading at stance conFiguration was simulated using a pixel-by-pixel DXA-based linear FEM. The results of this study show the ability of DXA-based FEA to predict femoral fracture location. Finally, it has been proposed as a suitable and clinically appropriate method to calculate the mechanical properties of the femur to assess hip fracture and predict failure initiation location.

5. REFERENCES

[1] J.A. Kanis, O. Johnell, C. De Laet, B. Jonsson, A. Oden, A.K. Ogelsby, International variations in hip fracture probabilities: implications for risk assessment, Journal of bone and mineral research, 17(7) (2002) 1237-1244.

[2] M. Mirzaei, M. Keshavarzian, V. Naeini, Analysis of strength and failure pattern of human proximal femur using quantitative computed tomography (QCT)-based finite element method, Bone, 64 (2014) 108-114.

[3] K.E. Naylor, E.V. McCloskey, R. Eastell, L. Yang, Use of DXA-based finite element analysis of the proximal femur in a longitudinal study of hip fracture,

[4] Journal of Bone and Mineral Research, 28(5) (2013) 1014-1021.

[5] E. Dall'Ara, R. Eastell, M. Viceconti, D. Pahr, L. Yang, Experimental validation of DXA-based finite element models for prediction of femoral strength, Journal of the mechanical behavior of biomedical materials, 63 (2016) 17-25.

[6] G.M. Blake, D.B. McKeeney, S.C. Chhaya, P.J. Ryan, I. Fogelman, Dual energy x-ray absorptiometry: The effects of beam hardening on bone density measurements, Medical physics, 19(2) (1992) 459-465.

[7] X.N. Dong, R. Pinninti, T. Lowe, P. Cussen, J.E. Ballard, D. Di Paolo, M. Shirvaikar, Random field assessment of inhomogeneous bone mineral density from DXA scans can enhance the differentiation between postmenopausal women with and without hip fractures, Journal of biomechanics, 48(6) (2015) 1043-1051.

[8] Y. Luo, Empirical functions for conversion of femur areal and volumetric bone mineral density, Journal of Medical and Biological Engineering, 39(3) (2019) 287-293.

[9] J.H. Keyak, Y. Falkinstein, Comparison of in situ and in vitro CT scan-based finite element model predictions of proximal femoral fracture load, Medical engineering & physics, 25(9) (2003) 781-787.

HOW TO CITE THIS ARTICLE

Z. Mohammadi, F. Alavi, Prediction of femoral fracture pattern using finite element analysis of dual-energy X-ray absorptiometry -based model. Amirkabir J. Mech Eng., 53(special issue 2) (2021) 289-292.

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