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Numerical simulation of the femur fracture under static loading

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Abstract. Bone is a living material with a complex hierarchical structure that gives it remarkable mechanical properties. Bone constantly undergoes mechanical. Its quality and resistance to fracture is constantly changing over time through the process of bone remodeling. Numerical modeling allows the study of the bone mechanical behavior and the prediction of different trauma caused by accidents without expose humans to real tests. The aim of this work is the modeling of the femur fracture under static solicitation to create a numerical model to simulate this element fracture. This modeling will contribute to improve the design of the indoor environment to be better safe for the passengers' transportation means. Results show that vertical loading leads to the femur neck fracture and horizontal loading leads to the fracture of the femur diaphysis. The isotropic consideration of the bone leads to bone fracture by crack propagation but the orthotropic consideration leads to the fragmentation of the bone.

Keywords: extended finite element method (X-FEM); crack/damage detection/identification; structural design; simulation

1. Introduction

Each year, more than 1.17 million people die in circulation accidents in the world. 65% of deaths are pedestrians. In 2005 mortality after 1 year hip fracture are approximately 22% for men and 14% for women (Brauer, Coca-Perraillon *et al*. 2009). On the other had 90% of fractures are the result of fall with provoke mostly the fracture of the inter-trochanterienne region of the femur (Cummings and Melton 2002).

The extended finite element method (X-FEM) first introduced by Belytschko and Blackard (1999). Numerical approaches to study (Giambini, Qin *et al*. 2015, Li 2013, Adel A. Abdel-Wahab, Maligno *et al*. 2012, Li, Abdel-Wahab *et al*. 2013).

Finite element modeling is a tool increasingly used to study the behavior of the human body, and more particularly the fracture bones.

This study compares the fractures predicted using different material properties (Isotropic/Orthotropic) and loads (resembling different falls).

This analysis was carried out taking into account two types of materials for the cortical bone:

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the first is isotropic and in the second one take the diaphysis and the femoral neck as orthotropic material.

2. Method

2.1 Geometrical model

The obtaining of the 3D solid model of the patient's femur is done by taking images of the interesting regions using the medical imaging technique (CT-scan). The thickness of each slice is about 1 mm for the proximal part until the small trochanter and 8mm from the small trochanter to the most distal of the shaft.

Using the brightness of the tomographic shots, two regions can be distinguished: Cortical bone and cancellous bone. The three dimension reconstitution of both parts is realized separately. (Fig. 1(a)) shows the steps of the 3D reconstitution of the femur.

Bone composed of two components (cortical and cancellous) which differ in their behavior. FE model of the human femur was subject to three loads in three different directions (Fig. 1(b)). The applied load is 18 KN on the head of femur and the fixation of the femoral epiphysis was considered Hambli, Bettamer *et al*. (2013).

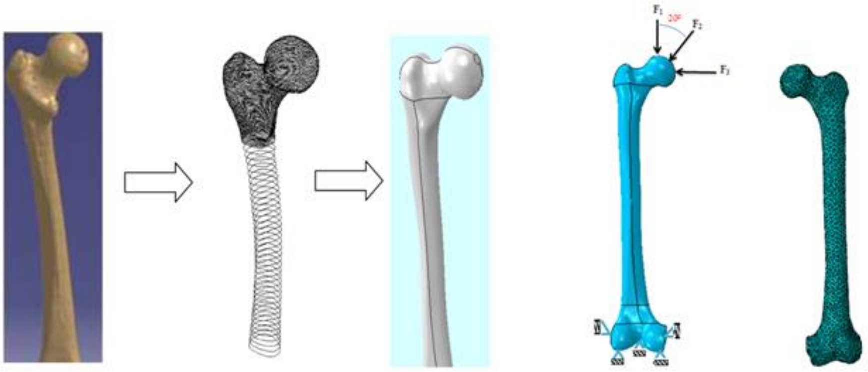
The Fracture is modeled with the X-FEM, which is based on the maximum principal stress criteria to determine the location of the crack initiation and propagation. This criterion can be represented as follows

$$F = \{< \sigma_{max} > / \sigma^0_{max}\} \tag{1}$$

Here, σ^0_{max} represents the maximum authorized principal stress. The symbol $< >$ represents the Macaulay bracket with the usual interpretation that is

$$< \sigma_{max} > = 0 \text{ if } \quad \sigma_{max} < 0 \text{ and } < \sigma_{max} > = \sigma_{max} \quad \text{if} \quad \sigma_{max} \geq 0.$$

Compressive stress does not initiate the damage. When the boot $f \geq 0$ criterion is met. Developed



(a) (b) (c)

Fig. 1 (a) Femur 3D reconstitution procedure, (b) Applied Boundary Conditions and (c) mesh on the model

Table 1 Elastic properties of isotropic bone

	E (Mpa)	υ	σ_y (Mpa)	ε_y (%)	ρ (kg/m3)
Cortical	17000	0.3	117	3.3	2000
Cancellous	0.6	0.3	45	0.65	0.45

E: Young's modulus; υ: Poisson's ratio; σ_y: elastic limit; ε_y: elastic Deformation limits; ρ: density.

Table 2 Elastic properties of orthotropic bone

E1(Gpa)	E2(Gpa)	E3(Gpa)	G12(Gpa)	G23(Gpa)	G31(Gpa)	υ13	υ23	υ12
16.6	17.0	25.1	7.2	8.4	7.1	0.237	0.247	0.334

Directions 1, 2, 3 show radial, circumferential and longitudinal directions, respectively.
E: the modulus of elasticity; G: the shear modulus; υ: Poisson's ratio

Table 3 X-FEM damage parameters

Bone properties		
σ_{nc} (Mpa)	G_{nc} (N/mm)	G_{sc} (N/mm)
116	1.16	2.97

σ_{nc}: the normal strength; G_{nc}: fracture toughness for opening mode; G_{sc}: shear mode

in commercial finite-element software-Abaqus (Dassault Systèmes 2013).

A static analysis was conducted to assess the distribution of the bone deformations and identify the regions of fracture risk. A mesh of approximately 20000 types of linear tetrahedral elements is generated to get better the results' approximation (Fig. 1(c)).

2.2 Materials

The mechanical properties of the materials are taken from previous studies (Ali, Abdelkader *et al*. 2015, Yoon and Cowin 2008, Benbarek, Bouiadjra *et al*. 2007). For the first step, the cortical and cancellous bone has been defined as isotropic linear material in Table1 and linear orthotropic for the second step in Table 2.

The parameters required by the X-FEM for models were selected on the basis of experimental data from the literature Table 3. Mischinski and Ural (2013).

Modelling will be carried out using finite elements method by ABAQUS 6.11 software.

3. Results and discussion

This latter carry out tests on five cadaveric femurs (3 men, 2 women) with an average age of 75,2 and average weight of 69,9 kg. The Fig. 2 presents boundary conditions applied to its specimens. Our numerical model presents a similarity to his experimental result.

These indicate where the femur experiences high principal stress levels and show deferent tensile and compressive stresses areas in the longitudinal direction under load F2, F1 and F3.

The simulation results show that with the X-FEM we detected the crack initiation and follow its propagation in the femur subjected to efforts representing the max strength will last undergo

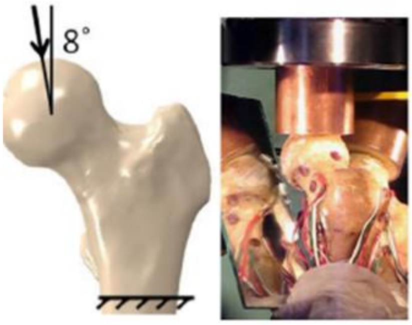
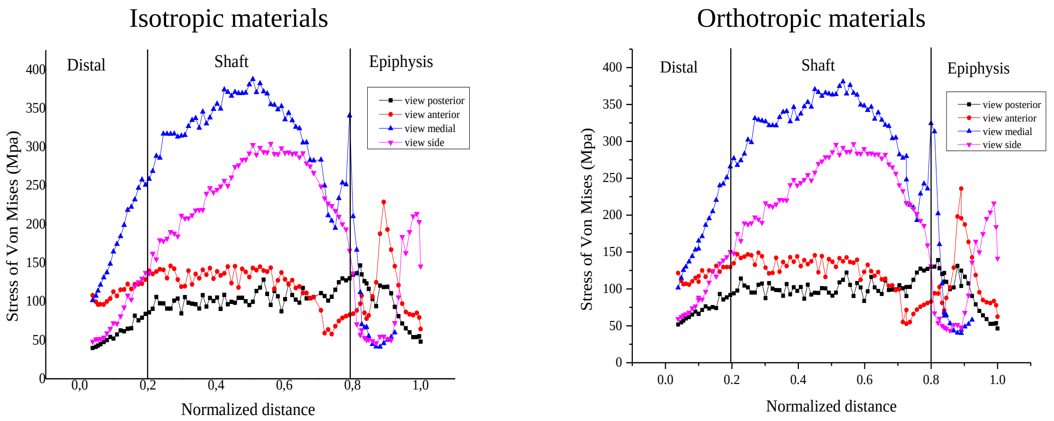


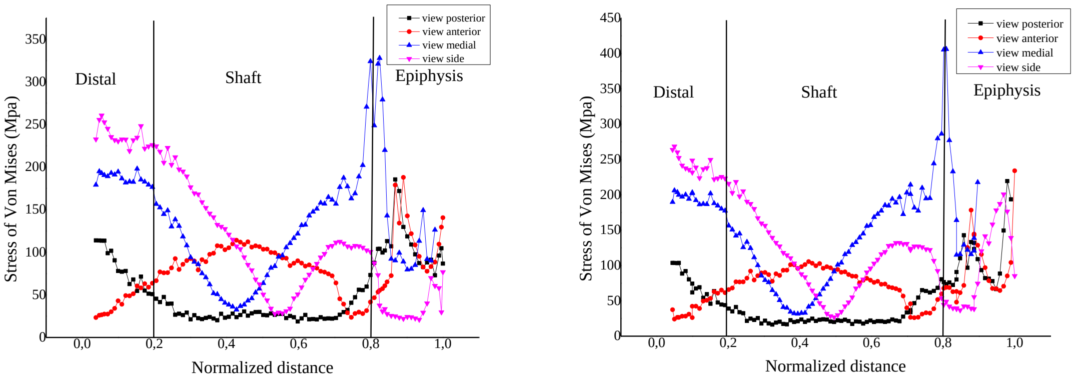
Fig. 2 Applied loading condition of the experimental tests

during an impact depending on the boundary conditions, femoral bone geometry and properties.

Fig. 3 show the variation of the Von mises stresses for different view: lateral, anterior, posterior and medial and for different and different regions: Proximal part, shaft part and Distal of the femur.

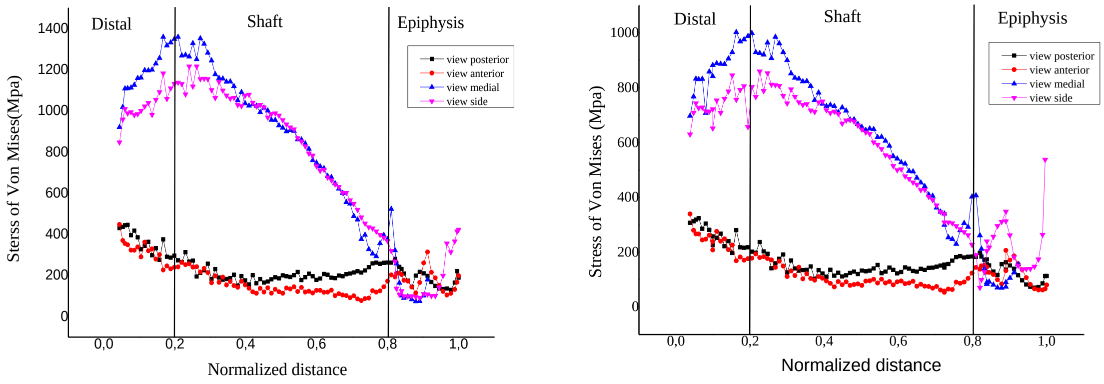


Load F1



Load F2

Fig. 3 Distribution of the von mises stress in the femur between the two materials for three load cases

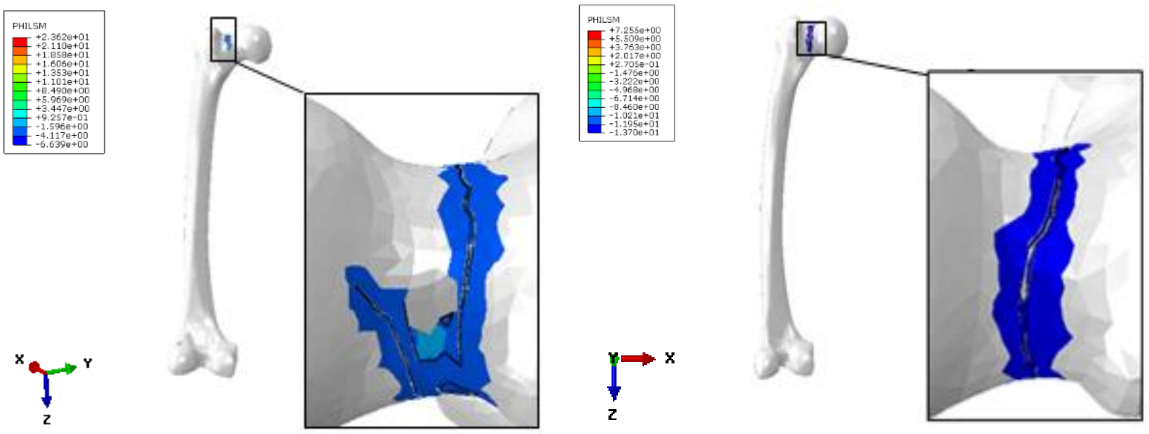


Load F3

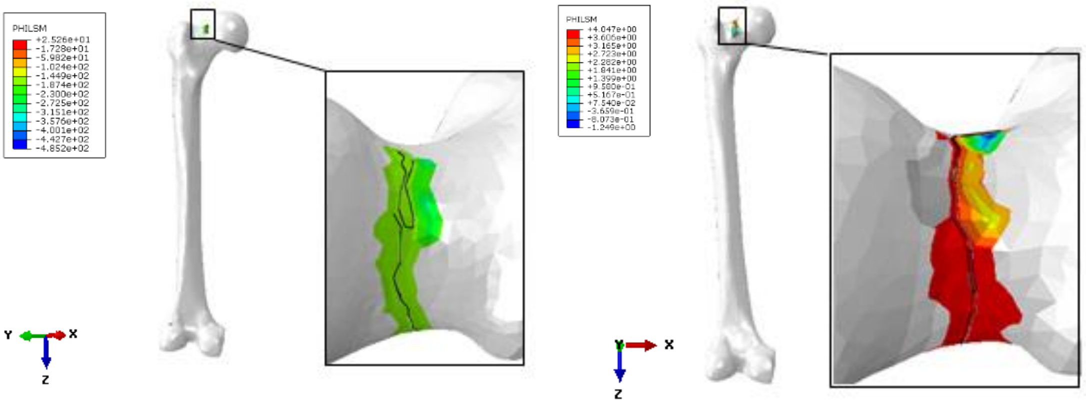
Fig. 3 Continued

Orthotropic materials

Isotropic materials

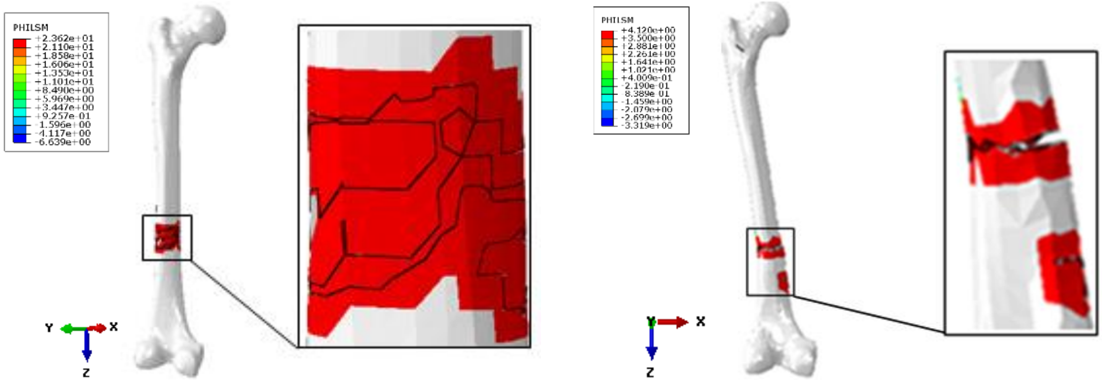


Load F1



Load F2

Fig. 4 Comparison of the femur fracture between two materials for three load cases



Load F3

Fig. 4 Continued

When the load is transferred to the different regions of the femur, the highest stress is observed in the medial side for loads F1 and F3. On the other hand the load F2, product the higher stresses in the epiphysis area.

For the orthotropic case the bone strong in one direction and very weak for the remaining two directions. This difference leads to the bone torque around the main direction under the different loading. This torque combined the bending tension is the responsible parameter of the femur fragmentation.

Our results are shown in Fig. 4 according to the three deferent loading directions (F1, F2, F3) and both kind of assumed materials (isotropic, orthotropic).

For the load case F1, one can see the crack initiation in the femoral neck region in a plane parallel to the femoral neck section leading to a complete fracture of the femoral neck.

For the case of orthotropic material, the crack initiates in the femoral neck but this time we see two cracks. The main one propagates in the section of the neck and the second crack propagate in the same neck with an offset from the first as shown in Fig. 4 (charge 1).

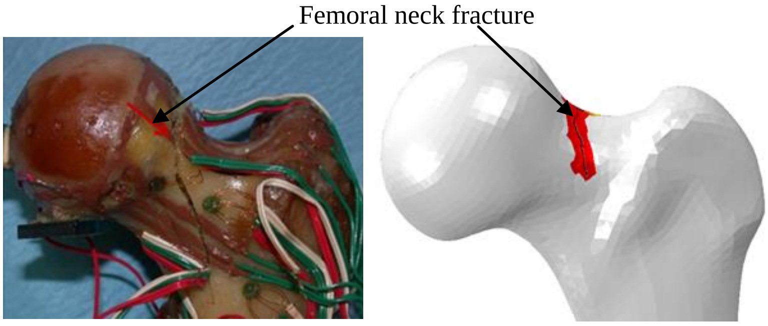
For the case of the second loading, we found that the initiation of the fracture takes always the region of the femoral neck as an initiation area. This type of force slightly affects the behavior of the fracture. One notices a slight difference of the fracture relative to the first case, which approximates the femoral head.

In the case of orthotropic material, we see the initiation and propagation of a single fracture close to the femoral head.

Load F3: in the last case, the fractures propagate through the femoral diaphysis in its lower third part flowing horizontal path in the diaphysis section and resulting to the complete fracture of the femur diaphysis. For orthotropic materials, a complex fragmentation is observed in the femur diaphysis.

In this case we consider that, in reality there is a complete detachment of bone fragments from this area. Fig. 5 comparison of the femur fracture between two materials for three load cases We compared our numerical results (Fig. 5(b)) to experimental tests (Fig. 5(a)) directed by (Ali, Cristofolini *et al*. 2014). Our numerical model presents a similarity to his experimental result.

Previous results have been compared with real measurements in some cases, such as a fall or collision (Park, Lee *et al*. 2016, Schwarzkopf, Oni *et al*. 2013), This is what justifies that XFEM Provided simulate real results of bone fracture.



(a) (b)

Fig. 5 Comparison between the location of the fracture with (a) experimental and (b) simulation results

4. Conclusions

The development of a FE model to predict human femoral fractures is a novel treatment and preventative care approach for this population. A fracture prediction model should provide clinicians and therapists with an accurate representation of what loading conditions have potential to cause fracture in human as well as the fracture location and type.

- X-FEM allows the prediction of the initiation and propagation of cracks without prior knowledge of the path of the crack.
- Modeling results of the femur fractured show that the considered material’s properties (isotropic - orthotropic) of cortical bone affected the nature of the fracture type (fragmentation our fracture).
- The location of the fracture has a relationship or depends on the nature of shock.
- The direction of loading influences the value of the load break orientation of the load (20° - vertical - horizontal), and suggested the possibility the direction of loading to determine the exact cause of the fracture trauma. The extent in which the direction of shock affects fracture injuries is little heard in actual clinical conditions.

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