Prediction of proximal femoral fracture by using Quasi-brittle damage with anisotropic behaviour model

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PREDICTION OF PROXIMAL FEMORAL FRACTURE BY USING MECHANICAL QUASI-BRITTLE DAMAGE COUPLED WITH ANISOTROPIC BEHAVIOUR LAW

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Introduction

A femoral fracture caused by the osteoporosis becomes increasingly important goal for both clinicians and biomedical researchers in order to evaluate and to prevent the risk of neck femur fracture.

Over the last years, a large number of 3D FE models based on quantitative computed tomography (QCT) which can account for the three-dimensional proximal femur and bone density distribution have been developed to predict proximal femur fractures [1-3]. Most previously published models employed simple uncoupled failure criteria to linear and non-linear with isotropic and anisotropic material behaviour. The authors focused their attention on the failure initialization stage, and not on the prediction of failure propagation. The fracture load is determined as the load at which at least one solid element had exceeded the threshold value of the fracture criteria. Such 3D representations enhance the proximal femurs geometries. Nevertheless they are not able to predict the progressive cracks initiation and propagation. Until now, direct comparisons of predicted and measured force-displacement curves and complete fracture profile of the proximal femur have not been performed. Recently, several authors investigated the fracture of cortical bone based on fracture mechanics concepts [4-7]. Fracture mechanics approach combines applied stress, fracture toughness to determine the crack initiation and crack propagation behavior in a material [7].

The purpose of this study was to develop a computed tomographic (CT) 3-D anisotropic model based on isotropic damage to simulate the force-displacement curve and to profile the fractured area of proximal femur. The model was developed in term of anisotropic coupled behaviour law (strain-quasi-brittle damage) to describe the progressive crack initiation and propagation within proximal femoral. To illustrate the potential of the current approach, the right adult human femur previously investigated by Keyak et al. [8], (Model B: male, age 61) was simulated till complete fracture under one-legged stance load. The femur fracture profile was predicted and compared to similar clinical observed results. Good agreements were obtained and different fracture patterns were predicted. The obtained results show that the proposed damage model could be used correctly to simulate the fracture type.

Method

To model the progressive development of damage of bone through the decrease in its elastic stiffness, a homogenized measure of damage is introduced, which in the simplest case is represented by a scalar D, called the damage variable

$$\sigma_{ij} = (1-D)M(C)\varepsilon_{ij} \qquad 0 < D < 1 \tag{1}$$

Where σ_{ij} the Cauchy stress components, ε_{ij} the linear strains and C_{ij} are the components of elasticity tensor. To distinguish between tension and compression, a way to consider the problem is to add a term to the damage law weighting the damage accumulation based on the local stress state. A well suited variable to include such effect is the well known hydrostatic stress σ_H.

$\sigma_H < 0$ indicates a compressive state.

$\sigma_H > 0$ indicates a tensile state.

Combining Nagaraja's [9] experimental law and the dependence of damage growth to the hydrostatic pressure, a quasi-brittle damage law can be expressed by:

$$\begin{cases} D = 0 & ;\varepsilon_{eq} \le \varepsilon_0 \\ D = \left(\dfrac{\varepsilon_{eq}}{\varepsilon_f}\right)^n & ;\varepsilon_0 < \varepsilon_{eq} < \varepsilon_f \\ D = 1 & ;\varepsilon_{eq} \ge \varepsilon_f \end{cases} \tag{2}$$

ε_f : denotes the strain at fracture given by:

$$\begin{aligned} \varepsilon_f &= \varepsilon_f^T \quad if \quad \sigma_H > 0 \\ \varepsilon_f &= \varepsilon_f^C \quad if \quad \sigma_H < 0 \end{aligned} \tag{3}$$

Results

The predicted load-displacement curve based on Keyak et al. [8] proximal femur specimen is provided in (Fig.1) for two different values of strain at fracture representing two different level of bone fragility. Both curves start yielding for force amplitude of about (6 kN). Exceeding this point, the predicted FE-based curve for "brittle bone $\left(\varepsilon_f^C = 1\%\right)$" exhibits a sharp drop in force until total failure. In the case of "quasi -brittle bone ($\varepsilon_f^C = 0.9 - 1.2\%$)", one can notice that significant non-linearity observed in the load-displacement curve after the yielding.

Under excess load deformation, during the yield phase, the overall maximum stress as presented in (Fig.1) started at the inferior root (basal) of the femoral neck. The strain of femur tissue is increased as a result of the presence of bone damage,

The damage subsequent to the ultimate predicted force of (18 kN) if bone with the assumption of brittle bone with ($\varepsilon_f^C = 1\%$) with a brittle bone ($\varepsilon_f^C = 0.9 - 1.2\%$) result in a reduction of the mechanical properties in bone strength and stiffness of bone material that caused by the apparition of microcracks corresponds to crack displacement of (1mm). Under excess load deformation, during the yield phase, the overall maximum stress as presented in (Fig.1) started at the inferior root (basal) of the femoral neck. The strain of femur tissue is increased as a result of the presence of bone damage and continues towards the greater trochanter causing as a consequence a complete failure which occurs at a displacement of (3.5 mm).

Different profiles corresponding to different cracks propagation level and damage accumulation within the proximal femur in relation with the curve are reported. As expected, for the brittle material, the cracks propagate faster compared to quasi-brittle material.

Discussion and conclusion

The propagation is observed advancing in a slower behavior due to the effect of the anisotropic modulii which resist in the transverse directions of crack propagation and also due to the relatively higher value of the transverse shear modulus (up to 2000 MPa). The propagation under the effect of the successive load follows an oblique path based on an the angle with the horizontal plane greater than 60° (Pauwels type III) from the inner surface of the neck (basal) to the outer surface towards the greater trochanter (Fig.1). This behavior fracture can be represented in different ways depends on the assumption of behavior.Our results predict different fracture profile compared to the simulation model previously proposed by Keyak et al. 2003 [8]. Such differences can be explained by two features (i) Uncoupled isotropic behaviour assumption was applied. (ii) the anisotropic effects of the bone strength.

The proposed damaged model leads to good predictions can be made more precise results concerning the shape of the force-displacement curve (yielding and fracturing). A comparison between predicted fracture patterns (Fig. 2a) and a radiographs of basicervical fractures from [10] is given in (Fig. 2b). Although loading conditions (unknown for the radiograph) and femurs geometries are different, a quite good agreement is obtained between both results. The current developed model predicts plausible fracture profile. It succeeds to predict the fracture profiles, Garden undisplaced fracture (stages 1 and 2), and as in the current case predicts Garden displaced fracture (stages 3 and 4).Our limits are affected by the assumption of the homogeneity of the bone structure. Higher order tensorial damage must be implanted to increase the potential of prediction simulation.

We have developed a computational method based on continuum damage to predict the profile of the four different types of Garden femoral neck (subcapital) fractures and to investigate the force displacement curve.

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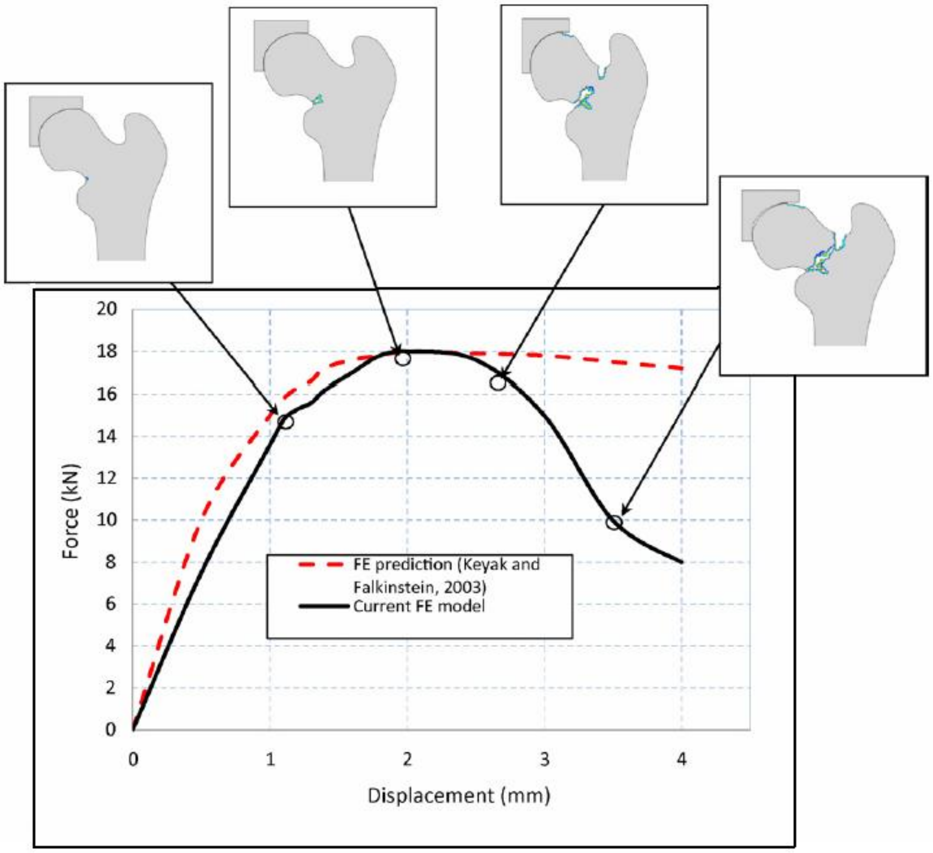

Figure 1. Predicted force–displacement curve obtained by the proposed model, comparison with Keyak and Falkinstein results [8]. The cracks propagation within the proximal femur in relation with the curve is reported. Solid arrows correspond to the profiles sequences related to the brittle bone and dashed arrows correspond to the profiles sequences related to the quasi-brittle bone

(a) **(b)** **(c)**

Figure 2. Qualitative comparison between predicted fracture patterns and examples of typical basicervical fracture (a) Predicted fracture profile (anisotropic behaviour law with isotropic damage) (Garden-stage 1: incomplete femoral neck fracture). (b) Example of a radiograph of a 33-year-old man with a type-C displaced fracture from [10]. (c) Keyak's predicted model