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Finite Element Prediction of Hip Fracture during a Sideways Fall

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Abstract**—**Finite element method was applied to model damage development in the femoral neck during a sideways fall. The femoral failure was simulated using the maximum principal strain criterion. The evolution of damage was consistent with previous studies. It was initiated by compressive failure at the junction of the superior aspect of the femoral neck and the greater trochanter. It was followed by tensile failure that occurred at the inferior aspect of the femoral neck before a complete transcervical fracture was observed. The estimated failure line was less than 50° from the horizontal plane (Pauwels type II).

Keywords**—**Femoral Strength, Finite Element Models, Hip Fracture, Progressive Failure, Sideways Fall.

I. Introduction

THE rate of hip fracture has been reported to be higher in elderly people. In the UK, half of all women over the age of 50 and 1 in 5 men will experience a fragility fracture [1].The increment is mostly associated with low femoral strength and high frequency of falling among elderly people. Bone fragility increases with increasing age, and generally correlated with low bone mineral density (BMD). However, measuring BMD alone is unable to predict 50% of these fractures [2], [3].

It has been suggested that the falling characteristics and femoral morphological features (hip axis length, neck shaft angle, neck width, thickness of neck cortices and bone density distribution) are other significant parameters that should be considered in order to predict the occurrence of hip fracture [4]. Falling to the side has been identified to increase the risk by almost five times. The risk would further increase by more than twenty times if the impact occurs directly on the hip [5]. Thus better prediction for femoral strength could be performed by incorporating information of bone density, femoral geometries and loading conditions. All these factors could be incorporated by using finite element (FE) method.

FE models of bone to predict femoral strength has significant advantage over other non-invasive tools [6]. The FE method has been used to analyze a response of three-dimensional anatomic structures of the femur [7-12]. Previous FE studies on prediction of femoral fracture estimated fracture load and failure patterns when at least one shell element or few solid elements exceeded yield stress or strain in the model [11], [12]. Recently, several authors investigated on complete femoral failure and the FE results correlated well with ex-vivo data [13] and clinical observations [14]. The studies, however, did not consider direction of strain in failure criterion or was modeled only for one-legged stance loading condition.

Previous experimental works indicated that compressive yield strain for bone was always higher than tensile yield strain [15]. During normal walking, the superior and inferior aspects of the femoral neck are subjected to tensile and compressive stresses respectively. The stress and strain distributions about the femoral neck, however, reversed during a sideways fall [16]. Therefore, the objective of this study was to simulate progressive failure in the femur during a sideways fall.

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II. Material and Methods

A. Computed tomography (CT) dataset and segmentation

The CT dataset of intact left proximal femur of a 69-year-old female was segmented using Avizo Standard software (Ver 6.3, Visualization Sciences Group, Burlington, MA, USA). Images of the femur were stored in 512 x 512 pixels, with a pixel size of 0.7 mm x 0.7 mm and a 0.7 mm slice thickness (Fig. 1 (a)). The segmentation was carefully performed to ensure that the soft tissue was excluded prior to generation of a three-dimensional triangular surface model of the femur.

B. FE model of proximal femur

Three-dimensional FE model of the femur was developed using Marc/Mentat 2010.1.0 (MSC Software Corp., Santa Ana, CA, USA from the triangular surface model. The model was meshed using linear 4-node tetrahedral solid elements with an element edge length of 1.5 mm. The mesh size was sufficient to achieve model convergence. The model contained of 56,959 nodes and 311,650 elements (Fig. 1 (b)).

C. Material properties assignment

Bone was assumed to be a linear and isotropic material. The elastic modulus of each bone element was determined from the CT data using an in-house program called Biomesh [17]. The program computes an average CT grey value (HU) from nine sampling points that are located in each element. Bone apparent density (ρ_{app} in g/cm^3) of each element then calculated from the grey value using a linear relationship [18]. The relationship was derived from the CT number of water, i.e. 1000 corresponding to 1 g/cm^3, and the maximum CT number for cortical bone found from the dataset, i.e. 2040 corresponding to bone density 1.8 g/cm^3. The resulting linear relation was ρ_{app} = 0.000769 HU + 0.230769. The Young's modulus (E in GPa) for each element was then calculated from the bone apparent density using the following relationship E = 6.850 $\rho_{app}^{1.49}$ [19]. This resulted bone model having heterogeneous material assignments that ranged from 0.2 to 16.4 GPa (Fig. 1 (c)). A constant Poisson's ratio of 0.3 was assumed for the bone.

D.Loading and boundary conditions

The femur was orientated to simulate a sideways fall [10]. The femoral shaft was orientated at 10° from the horizontal plane and the femoral neck was internally rotated in 15° posteriorly. Initially, 500 N was applied in a downward direction (negative y-axis) and was distributed on nodes in an area of approximately 3 cm diameter at the surface of the proximal head, where contact with acetabular cup occurs (Fig. 1 (d)). The load was then increased by 500 N in each load cases until it reaches a first yield (in compression/tension) and by 100 N increments until second yield limit was reached. Subsequently, once the second yield (in compression/tension) was reached, the applied load was reduced until a complete failure was observed. The distal end of the femur was restrained from axial movement and the lower part of the greater trochanter was prohibited from vertical displacement. [16].

E. Failure criteria

The femoral failure was predicted using the maximum/minimum principal strain criteria. The maximum and minimum principal strains for both cortical and cancellous bone were reported as 0.62% and -1.04% respectively [14]. After yielding occurs, element that failed in compression was

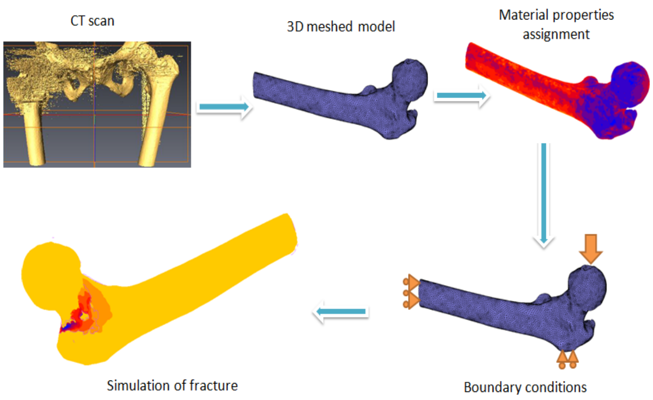

Fig. 1 Overview of FE modeling of proximal femur

assigned low elastic modulus of 0.1 GPa following the similar method as in [13]. The element failed in tension was removed from the model to simulate the broken zone [14]. The model was then updated and solved again until a complete fracture was observed. The iterative process is illustrated in Fig. 2. The curve of vertical reaction force at the greater trochanter vs. vertical displacement of the femoral head was plotted to explain the progression of femoral failure.

III. RESULTS

A typical load-displacement curve synchronized with the progression of femoral damage is shown in Fig. 3. The plot demonstrates that the damage was initiated at the junction of the superior aspect of the femoral neck and greater trochanter when elements began to exceed the yield compressive strain at approximately 4100 N. The compressive damages were

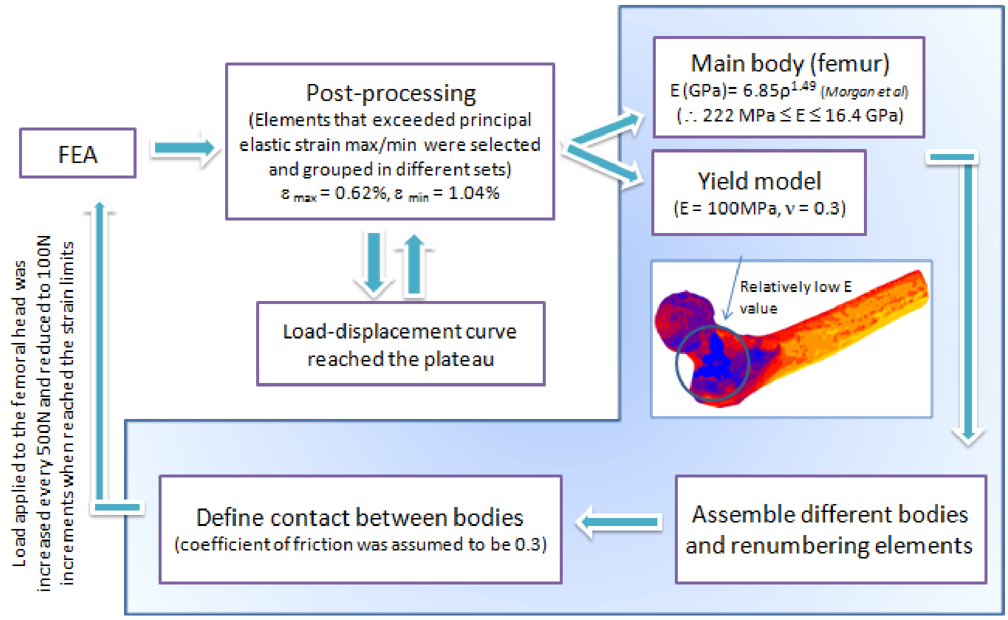

Fig. 2 The method used to obtain a complete failure within the proximal femur

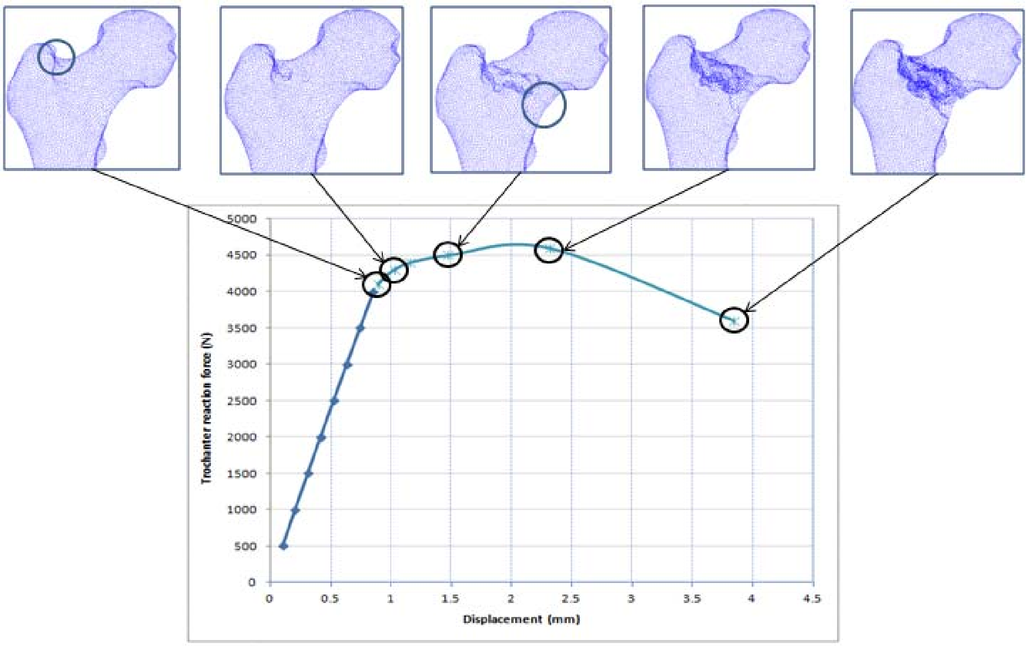

Fig. 3 Load-displacement curve synchronized with progressive failure in femoral neck

accumulated to anterior-superior medial femoral neck as the applied load was increased. Then some elements at the inferior aspect of the femoral neck exceeded the yield strain in tension which corresponding to crack initiation (4500 N). Finally, at the maximum displacement of 3.85 mm (corresponding to 3600 N), a complete transcervical fracture was observed, passing from superior aspect of the femoral neck down to the mid region of inferior aspect of femoral neck. Failure line was less than 50° from the horizontal plane (Pauwels type II), as shown in Fig. 4. The estimated ultimate load, femoral stiffness, i.e. slope of the curve, and work to fracture, i.e. area under the curve, was approximately 4650 N, 4663 N/mm and 14.5 J respectively.

IV. DISCUSSION

The purpose of this study was to investigate progressive femoral failure using subject-specific FE model during a sideways fall. The predicted fracture load was consistent with similar FE study [13] and experimental tests on elderly cadaveric femurs [16], [21]. In this study, a compressive failure initiates in the superior region. It was then accumulated and progressed toward anterior-superior medial femoral neck as the applied load was increased, then followed by a tensile failure in the inferior region prior to a complete transcervical failure. The similar evolution of damage was also reported in previous studies [13], [16].

The estimated ultimate load (4650 N) and work to fracture the proximal femur (14.5 J) of the present study compared very well to those commonly reported in literature.

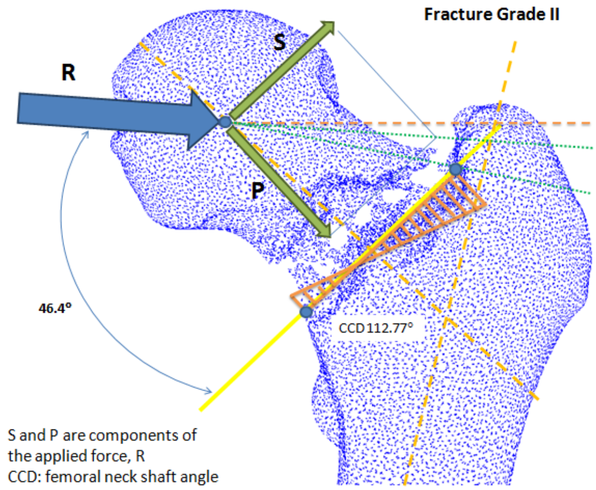

Fig. 4 The femoral neck fracture according to the Pauwel's classification

In comparison, the average fracture load for elderly cadaveric femur under similar falling condition was reported as 3440±1330 N and 3820±910 N by Courtney et al. [22] and Pinilla et al. [23] respectively. Lotz et al. [24] reported that the work to fracture of twelve fresh cadavera (mean age of 69±9 years) ranged from 5 to 51 J.

The method employed in this study has a potential to predict a complete femoral failure. The ability to predict the type of fractures depending on load direction to which the femur is most vulnerable may guide the surgeon and designers of orthopedic devices in developing such preventive action and any devices needed.

This study, however, has a number of limitations. The main limitation of this study is the small sample size (only one femur). The validation study was only qualitative. Therefore, further experimental validation using similar boundary conditions on human cadavers would be carried out. The study considered one boundary condition corresponding to sideways falling and does not include different configuration. It is likely that a fall might occur in other orientations such as posterolateral, backward or anterolateral sides and hence may results a different fracture pattern.

V. CONCLUSION

A complete femoral failure due to sideways falling was predicted from subject-specific finite element analysis study. The predicted ultimate load was found to be 4650 N and the fracture pattern followed Pauwels type II. The evolution of femoral damage was consistent with previous studies.

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