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Short communication

How accurately can subject-specific finite element models predict strains and strength of human femora? Investigation using full-field measurements

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ABSTRACT

Subject-specific finite element models have been proposed as a tool to improve fracture risk assessment in individuals. A thorough laboratory validation against experimental data is required before introducing such models in clinical practice. Results from digital image correlation can provide full-field strain distribution over the specimen surface during in vitro test, instead of at a few pre-defined locations as with strain gauges. The aim of this study was to validate finite element models of human femora against experimental data from three cadaver femora, both in terms of femoral strength and of the full-field strain distribution collected with digital image correlation. The results showed a high accuracy between predicted and measured principal strains ($R^2 = 0.93$, RMSE = 10%, 1600 validated data points per specimen). Femoral strength was predicted using a rate dependent material model with specific strain limit values for yield and failure. This provided an accurate prediction ($<2\%$ error) for two out of three specimens. In the third specimen, an accidental change in the boundary conditions occurred during the experiment, which compromised the femoral strength validation. The achieved strain accuracy was comparable to that obtained in state-of-the-art studies which validated their prediction accuracy against 10–16 strain gauge measurements. Fracture force was accurately predicted, with the predicted failure location being very close to the experimental fracture rim. Despite the low sample size and the single loading condition tested, the present combined numerical–experimental method showed that finite element models can predict femoral strength by providing a thorough description of the local bone mechanical response.

1. Introduction

Fragility fractures due to osteoporosis are a huge problem in Western society (Burge et al., 2007). Pharmacological treatment can increase strength of osteoporotic bones and reduce fracture risk (Kanis et al., 2013) but should be targeted to individuals whose risk of fracture is highest (Lindsay et al., 2005).

Osteoporosis is diagnosed based on bone mineral density measured in the proximal femur or lumbar spine using Dual-Energy X-ray absorptiometry. By including epidemiological parameters, fracture risk is estimated (Cummings et al., 2006; Kanis et al., 2005). This method has a relatively poor accuracy (30% false negatives (Järvinen et al., 2005; McCreadie and Goldstein, 2000)), and is ethnic-specific (Watts et al., 2009). Subject-specific finite element (FE) models from computed tomography (CT) scans can increase the prediction accuracy by providing a comprehensive description of the bone's mechanical response. Although the prediction accuracy is considerably high both for strains ($R^2 > 0.95$ (Schileo et al., 2008; Yosibash et al., 2007)) and femoral strength (standard error of estimation(SEE) < 400 N (Koivumäki et al., 2012)), FE models have not yet been introduced in clinical practice. This is due to several reasons including concerns about validation (Henninger et al., 2010; Viceconti et al., 2005). Typically, validation against ex-vivo measurements with strain-gauges is performed. This limits the data to ~10–15 measurements at pre-selected spots (Grassi and Isaksson, 2015). Optical methods like digital image

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correlation (DIC) (Gilchrist et al., 2013; Helgason et al., 2014; Op Den Buijs and Dragomir-Daescu, 2011) provide a more comprehensive validation benchmark. We recently collected DIC measurements at a physiological loading rate on three femora (Grassi et al., 2014), suited for reliable validation of FE models.

Therefore, the aim of the present study was to predict fracture load in human femora using subject-specific FE models. Validation was performed for strains calculated with FE against strains measured experimentally with DIC, and for femoral strength calculated with FE against the maximum force recorded experimentally.

2. Material and methods

Three male cadaver human proximal femora were harvested fresh at Kuopio University Hospital, Finland (ethical permission 5783/2004/044/07). None of the donors had any reported musculoskeletal disorder. Height, weight, sex and age at death are reported in Table 1. The specimens were CT scanned (Definition AS64, Siemens AG, 0.4 × 0.4 × 0.6 mm voxel size).

2.1. Mechanical testing

The three femora were mechanically tested to failure in a single-leg-stance configuration, and strains were measured using DIC. The experimental protocol was reported in detail by Grassi et al. (2014). Briefly, the specimens were cleaned and resected 5.5 cm below the minor trochanter. The femoral shaft below the minor trochanter was embedded in epoxy and constrained. A stainless steel cap was applied on the femoral head to distribute the load and avoid local crushing. The gap between the cap and the femoral head was filled with epoxy. The anterior surface was prepared for DIC by applying a random black speckle pattern over a matt white background. Mechanical tests were performed in a single-leg-stance configuration, with the load applied on the femoral head parallel to the shaft axis. Specimens were loaded at 15 mm/s until macroscopic failure. DIC was performed on the acquired images (two Fastcam SA1.1, Photron, Inc., 3000 frames per second; VIC 3D v7, Correlated Solutions, Inc., 25 px subset, 5 px step, 100 Hz low-pass displacement filter), and the Green–Lagrange strains were retrieved at each frame (~10,000 uniquely traceable points per specimen) (Grassi et al., 2014).

2.2. Finite element modelling

FE models were generated using a consolidated procedure (Grassi et al., 2013; Schileo et al., 2008). Femur geometry was semi-automatically segmented from CT (threshold, dilation/erosion, and manual correction, Seg3D2, University of Utah). The geometries were reverse-engineered (Rhinoceros 4.0, Robert McNeel & Associates, USA, and RhinoResurf, Resurf3d, China), and a second-order tetrahedral mesh (~140,000 nodes, ~100,000 elements, Hypermesh v13.0, Altair Engineering) was created. Elements in the epoxy pot were assigned an isotropic Young's modulus of 2.5 GPa, (Technovit 4071, Heraeus Kulzer). Elements belonging to the femur were assigned Young's modulus based on the Hounsfield Unit (HU) values. CT images were reconstructed using a sharp convolution kernel (B60f). Each axial slice was filtered using a mean filter of 4 × 4 px size to compensate for the HU overestimation due to this kernel. Bonemat_V3 (Taddei et al., 2007) assigned inhomogeneous isotropic material properties to the elements, based on the HU values of the volume enclosed by each element. HU values were converted to equivalent radiological density (Model 3CT, Mindways Inc.), and the Young's modulus was derived using the relationships proposed by Schileo et al. (2008). Poisson's ratio was set to 0.4 (Reilly and Burstein, 1975). The geometry of the epoxy pot was used to identify the experimental reference system (Fig. 1). The load was equally distributed among the 10 most superior surface nodes on the femoral head. FE simulations were solved using Abaqus (v6.12-4, Dassault Systèmes).

Table 1
Patient information (sex, age at death, height, weight, and leg side) for the three specimens used in this study.

Specimen ID	Sex (M/F)	Age [years]	Height [cm]	Weight [kg]	Side (L/R)
#1	M	22	186	106	L
#2	M	58	183	85	R
#3	M	58	183	112	L

2.3. Strain prediction accuracy

Strain prediction accuracy was evaluated at a force of four times the body weight (BW). The predicted principal strains were compared to DIC measurements. A registration and data comparison method was adopted, based on a procedure that earlier provided good results for composite bones (Grassi et al., 2013). The DIC point cloud was registered over the FE model using an iterative closest point approach. For each surface element, the smallest sphere circumscribing it was calculated. All DIC data lying within the sphere were averaged, and the obtained value compared to the FE element strain. A robust regression analysis with bisquare weighting function of the major and minor principal strain magnitudes was performed to assess the accuracy. Bland–Altman plots (Bland and Altman, 1999) provided a visual interpretation of the agreement between predicted and measured principal strains.

2.4. Femoral strength prediction accuracy

The FE models implemented a rate-dependent material model, with different strain limit values for yield and failure (Fig. 2). Each element was assigned its specific initial modulus (E_{elem}^{ref}) as described above. A strain rate correction factor: $\mathrm{SRCF}_{elem} = (\dot{\epsilon}^{elem}/\dot{\epsilon}^{ref})^{0.006}$was defined, where $\dot{\varepsilon}_{elem}$ is the absolute major principal strain rate, and $\dot{\varepsilon}_{ref}$ is the strain rate at which yield values and density–elasticity relationship were obtained (5000 με/s (Bayraktar et al., 2004; Morgan et al., 2003)). The tangent modulus was defined as: $E_{elem}(\mathrm{SRCF}) = \mathrm{SRCF}_{elem} * E_{elem}^{ref}$.

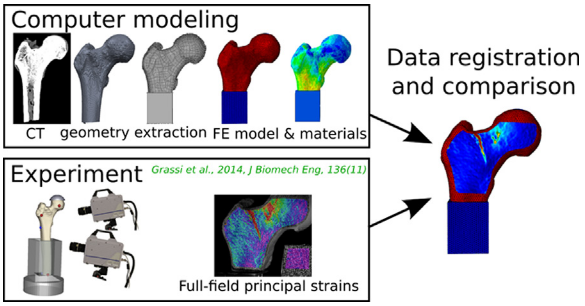

Fig. 1. Overview of the study. Top left: the subject-specific FE models were built starting from the CT scan through a process of segmentation, reverse engineering, tetrahedral meshing, and material property mapping based on the calibrated CT values. The origin of the experimental reference system was set in a base corner of the epoxy pot, with x-axis and y-axis aligned to horizontal and vertical side, respectively. The load was applied along the negative y-direction on the femoral head. Bottom left: schematic of the experimental setup. The specimens were tested until fracture in a single-leg-stance position, and deformations measured using 3D surface digital image correlation (Grassi et al., 2014). Right: the FE predictions were compared to the measured principal strains by registering the experimental point cloud over the FE model, and then averaging the experimental values within each element's volume of interest.

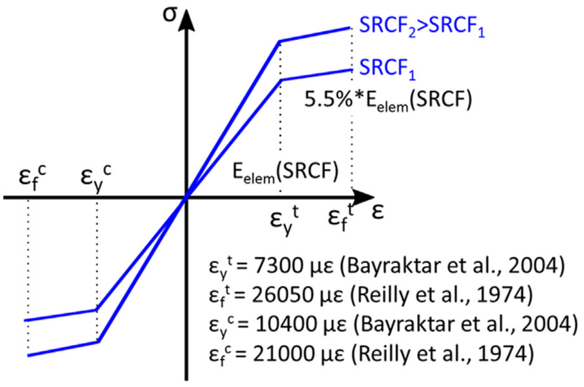

Fig. 2. The material model implemented in the FE models to predict bone strength. The response was strain rate dependent, according to the defined strain rate correction factor (SRCF). The behaviour of one element for two different values of SRCF is shown in the stress strain diagram. Bone strength was predicted using threshold strain values for yield (ε_y) and failure (ε_f). Different thresholds were chosen for tension ("t" superscript) and compression ("c" superscript). The post-yield modulus was set to 5.5% of the modulus in the elastic range, as extrapolated from the measurements reported by Reilly et al. (1974).