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Research Paper

Nonlinear quasi-static finite element simulations predict in vitro strength of human proximal femora assessed in a dynamic sideways fall setup

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ABSTRACT

Osteoporotic proximal femur fractures are caused by low energy trauma, typically when falling on the hip from standing height. Finite element simulations, widely used to predict the fracture load of femora in fall, usually include neither mass-related inertial effects, nor the viscous part of bone's material behavior. The aim of this study was to elucidate if quasi-static non-linear homogenized finite element analyses can predict in vitro mechanical properties of proximal femora assessed in dynamic drop tower experiments. The case-specific numerical models of 13 femora predicted the strength (R^2=0.84, SEE=540 N, 16.2%), stiffness (R^2=0.82, SEE=233 N/mm, 18.0%) and fracture energy (R^2=0.72, SEE=3.85 J, 39.6%); and provided fair qualitative matches with the fracture patterns. The influence of material anisotropy was negligible for all predictions. These results suggest that quasi-static homogenized finite element analysis may be used to predict mechanical properties of proximal femora in the dynamic sideways fall situation.

1. Introduction

Osteoporosis-related fragility fractures of the proximal femur are associated with high morbidity and mortality, and often result in decreased patient quality of life (Cummings and Melton, 2002; Johnell and Kanis, 2006; Roth et al., 2010). Worldwide occurrence of these injuries was reported to be as high as 1.6 million per year and is known to increase with age (Johnell and Kanis, 2006; Melton, 1996). Falling is a dynamic event involving high strain rates. Material properties of bone tissue are not only volume fraction dependent and anisotropic (Helgason et al., 2008; Morgan et al., 2003), but are also visco-elastic and visco-plastic (i.e. stiffer and stronger, but more brittle) under impact compared to quasi-static

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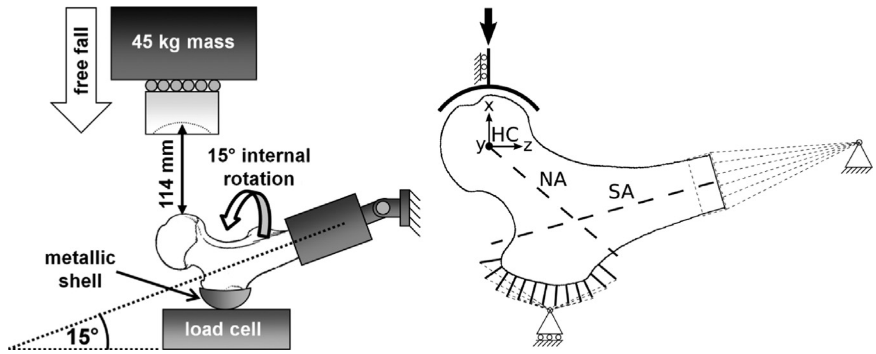

Fig. 1 – Schematic illustration of the experimental test setup (left) and its representation in the numerical model (right). HC: head center, NA: neck angle, SA: shaft angle.

loading conditions (Carter and Hayes, 1977). Accordingly, the stiffness and fracture force of whole bones are strain rate dependent (Courtney et al., 1994). Additionally, in drop-tower test configurations that aim to better mimic sideways falling accidents, the rate of loading is a function of the sample's stiffness (Gilchrist et al., 2014).

Numerous previous studies used finite element (FE) analysis to predict fracture properties of bones via virtual mechanical testing (Ariza et al., 2015; Cody et al., 1999; Dall'Ara et al., 2013a; Dragomir-Daescu et al., 2011; Keyak et al., 2001; Luisier et al., 2014). In order to avoid the above mentioned complexities related to the dynamic event, most FE models aim at predicting the quasi-static behavior of bones. Accordingly, such models neglect mass-related effects and utilize material models that are calibrated based on low strain rate experimental testing of small bone cores (Helgason et al., 2008). These models are validated by means of quasi-static destructive testing of whole bones. It is, however, not known if such models would accurately predict the mechanical properties of bones subjected to accident-relevant dynamic failure or if the viscous material behavior of bone tissue and the inertial effects would be required. However, several previous experimental studies (Carter and Hayes, 1976; Linde et al., 1991) suggested that the influence of loading rate on bone elasticity and strength, associated with the organic constituents, was independent of bone density and therefore relative differences of bone strength were independent of loading rate. We therefore hypothesized that numerical models, which utilize a material model of bone that was validated on the whole bone scale at a specific loading rate, would predict elasticity and strength on another loading rate.

The aim of this study was therefore to investigate if stiffness, ultimate load, energy to failure and fracture pattern of intact proximal femora tested in vitro using a dynamic drop tower test to simulate sideways fall could be predicted with a finite element approach that was previously developed for and validated under quasi-static conditions.

2. Materials and methods

2.1. Sample preparation and imaging

Fourteen fresh frozen (−20 °C) human cadaveric femora (left/right: 5/9) were obtained from individual donors (female/male: 10/4, age: 85.3±7.1 ys, range: 72–95 ys). The bones were obtained from the Department of Pathology of the Kantonspital Basel, Switzerland, with appropriate consent of the relatives. The bones were cleaned of all soft tissues except the articular cartilage. The proximal part of each femur, bounded by the distal end of the lesser trochanter, was scanned with high resolution peripheral quantitative computer tomography (HR-pQCT, XtremeCT, Scanco Medical AG, Brüttisellen, Switzerland). Scanning settings were 60 kVp voltage, 900 μA current, and 123 μm isotropic voxel size. Osteoporosis status (6 osteoporotic, 6 osteopenic, 2 healthy) was estimated based on the areal bone mineral density (aBMD) assessed by projecting the HR-pQCT image along the anterior–posterior axis and correcting using an established relationships accounting for the difference between QCT-based and dual X-ray absorptiometry (DXA)-based aBMD values (Khoo et al., 2009).

2.2. Experimental testing

The femora were tested in vitro according to a previously described protocol (Fliri et al., 2013) using a drop tower setup that simulates a sideways fall on the hip (Fig. 1, left). In brief, following thawing at room temperature for 24 h, the proximal 160 mm of each femur was cut. The distal 50 mm part of the shaft was embedded in a cylindrical poly(methyl methacrylate) (PMMA) block and attached to a hinge joint allowing rotations only around the horizontal axis, perpendicular to the bone axis. The bone was rotated around its longitudinal axis to 15° internal rotation and the location of the hinge joint was adjusted to provide a 15° angle of the shaft axis with respect to the horizontal plane. The greater trochanter was shallowly embedded (approximately 10 mm) in a metallic spherical cap using PMMA to distribute the ground reaction force.