TIME-ELAPSED MICRO-CT IMAGING OF HUMAN FEMORAL NECK FRACTURE AT THE SYNCHROTRON: SCAN ME BIGGER IF YOU CAN

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Summary: We performed time-lapsed synchrotron micro-CT imaging of entire human femoral epiphyses under incremental load up to fracture, at a pixel size of 30 µm. Fractures were experimentally obtained in 5-6 load increments as predicted by finite element analysis. The 2D and 3D micro-CT images showed first deformation, then fracturing of the trabeculae and cortex, with clinically relevant fracture patterns.

1. INTRODUCTION

The age-related microstructural deterioration of bone is an important co-factor to millions of fragility fractures occurring worldwide every year [1]. Time-lapsed micro-computed-tomography (micro-CT) with concomitant mechanical testing is increasingly used to study the bone deformation under load and fracture mechanism. Previous studies were limited, due to technological constraints linked to the size of the human femoral epiphysis (up to 130 mm width, 150 mm length) and the need of a dedicated mechanical stage for loading such a big specimen inside the CT scanner; these studies were restricted to either micro-CT imaging the unloaded femoral epiphysis [1] or small loaded bone cores [2].

We developed a protocol for time-lapsed synchrotron micro-CT imaging of entire human femoral epiphyses under incremental load at the Australian Synchrotron (AS), Melbourne (VIC), Australia.

2. EXPERIMENTAL METHOD

Femurs: Twelve human femurs from elderly female donors (age range 56-91 y) were obtained (Science Care, USA), with T-sores ranging from -4.57 (severe osteoporosis) to +0.77 (normal).

Prediction of fracture load: clinical CT images were taken (0.7 mm/voxel, isotropic). The femur geometries were extracted, meshed and finite-element (FE) models created. A 1000 N hip force resembling a single-leg-stance hip force orientation was assigned, producing strain patterns consistent with clinically relevant femoral neck fractures [3]. The FE models were solved (iterative linear solver, ANSYS Inc., USA) and the fracture loads estimated [3].

Compressive stage: A custom-made compression stage (weight 14.2 kg) was built featuring a cylindrical aluminium compression chamber (245 mm diameter, 524 mm length, 3 mm wall thickness), a 6-degree-of-freedom load cell, a low-friction x-y table, a vertical rail and a screw-jack mechanism to apply the load.

Specimen preparation: The femurs, with the diaphysis potted in aluminium cups replicating the simulated loading conditions, were mounted inside the compressive stage and wrapped in wet tissue.

Time-elapsed synchrotron scans: Micro-CT scans were performed at the AS Imaging and Medical Beamline using a 2560 x 2160 pixels detector ("Ruby", in shift mode), 60 keV beam energy, 360° projections, 0.1° rotation step, isotropic voxel size 30 µm. From the initial unloaded condition, one-fifth of the FE-predicted fracture load was incrementally applied to the sample, with scans taken at each load step. At each load step, the total volume scanned was 160 mm in diameter and 130 mm in height, scanning time 25 min. Four femurs were loaded to fracture, whereas 8 femurs were loaded in the elastic region. The 6 component force over time was recorded during the experiment. Cross-section images of the femurs were reconstructed (32 bit .tiff) and examined. For each scan (=load step), projection and reconstructed images occupied 0.76 TB disk space.

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3. RESULTS AND DISCUSSION

Fractures were experimentally obtained in 5-6 load increments as predicted by FE, with loads within the predicted range (1998-8636 N). The 2D and 3D micro-CT images showed first deformation, then fracturing of the trabeculae and cortex (figure 1). Sub-capital femoral neck fractures, consistent with observed patterns of clinical fractures, were obtained and were visible in the micro-CT images.

Time-elapsed synchrotron micro-CT imaging of the entire human femoral epiphysis with concomitant step-wise mechanical testing was successfully performed, at 30 µm pixel size. The dataset has been made freely available to the scientific community [4]. Digital volume correlation analyses are being undertaken to investigate the local internal strains and the contribution of the different microstructural compartments to withstand load. This will contribute to increase our understanding of femoral neck fracture mechanics, including the validation of FE models from micro-CT scale to clinical CT scale.

References

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[4] Micro-CT dataset for download: http://andspub.flinders.edu.au/rdr/martelli_femoral_epiphyses/

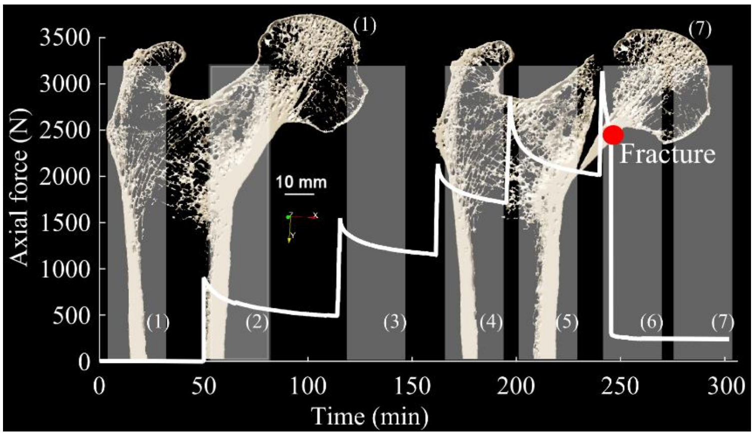

Figure 1: Load time history (white line), scanning time (gray bars) and 2 mm-thick 3D synchrotron micro-CT volumes (in yellow) of a femur unloaded (1) and once fractured (7).