SYNCHROTRON-LIGHT TIME-LAPSED MICROSTRUCTURAL IMAGING OF THE ENTIRE HUMAN FEMORAL EPIPHYSIS UNDER LOAD

Saulo Martelli (1), Egon Perilli (1)

1. *Medical Device Research Institute, School of Computer Science, Engineering and Mathematics, Flinders University, Adelaide, South Australia, Australia*

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 and fracture mechanism. However, technological limitations 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 imaging chamber, have limited previous studies to either micro-CT imaging of the unloaded femoral epiphysis [1] or of small loaded femur cores [2]. We developed a protocol for time-elapsed micro-CT imaging of entire human femoral epiphyses under load at the Australian Synchrotron (AS) in Clayton (VIC).

Materials and methods

Twelve human femurs from elderly female donors (age range 56-91 y) were obtained (Science Care, USA). Finite element modelling of the fracture load: clinical CT images were taken (isotropic voxel size 0.7 mm) including a 5-sample calibration phantom (Mindways Software Inc., USA), the femur geometry was extracted (ScanIP, Simpleware Ltd., UK) and meshed (unstructured ten-node tetrahedral mesh, average edge length 1 mm). CT-based locally isotropic material properties and a nominal 1000 N hip force resembling a single-leg-stance hip force orientation were assigned, producing a strain pattern consistent with clinically relevant femoral neck fractures [3]. The models were solved using an iterative linear solver (ANSYS Inc., USA) and fracture loads estimated [3]. A custom-made compression stage (weight 14.2 kg) was manufactured featuring an aluminum compression chamber (245 mm diameter, 524 mm length), a 6-degree-of-freedom load cell (K6D68, ME-measurement sys. GmbH, Germany), a low-friction x-y table (THK Co., Japan), a vertical rail (SKF Inc., USA) and a screw-jack mechanism (Benzlers, Sweden). Femur samples, with the diaphysis potted in aluminum cups replicating the simulated loading conditions, were mounted inside the compressive stage and wrapped in wet tissue. 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 31 µm. One-fifth of the calculated fracture load was incrementally applied to the sample from the initial unloaded condition, with one scan taken at each load step. At each step, the total volume scanned was 150 mm in diameter and 160 mm in height, average scanning time 25 min. Four femurs were loaded to fracture, whereas 8 femurs were loaded to a single load step in the elastic region. The 6 component force over time was recorded for the duration of the experiment. Cross-section images of the femurs were reconstructed (32 bit .tiff) and examined. For each scan, projection and reconstructed images occupied 0.5 TB disk space.

Results

Fractures were experimentally induced by applying 5-6 load increments, with loads within the predicted range (1998-8636 N). The time-elapsed 2D and 3D micro-CT images clearly showed deformation and fracturing of the trabecular network and the cortex (Figure 1). Sub-capital femoral neck fractures were obtained, consistent with observed patterns of clinical fractures.

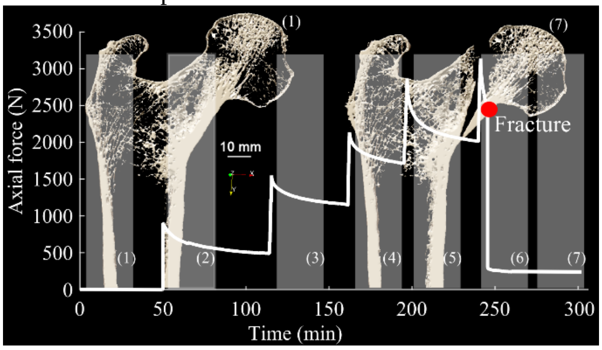

Figure 1: Load time history (white line), scanning time (gray bars) and time-elapsed micro-CT renderings (in yellow) of a femur unloaded (1) and once fractured (7).

Discussion

Time-elapsed synchrotron micro-CT imaging of the entire human femoral epiphysis with concomitant step-wise mechanical testing was successfully performed, at 31 µm pixel size. Clinically relevant fracture patterns were experimentally induced and identified in the micro-CT images. Morphometric and micro-finite-element analyses are being undertaken to investigate the contribution of the different microstructural compartments to withstand load. The testing protocol enables studying deformation and fracture mechanisms in the entire proximal femur, at micrometre resolution.

References

1. Nawathe et al, J Biomech 48:816-822, 2015.
2. Thurner et al, Bone 39:289-99, 2006.
3. Schileo et al, J Biomech, 47:3531-3538, 2014.

Acknowledgements

Australian Research Council (DE140101530).