QCT/FEA Models of Proximal Femur Stiffness and Ultimate Load Using Experimentally Matched Boundary Conditions

INTRODUCTION
Assessment of proximal femur fractures requires accurate non-invasive estimates of proximal femur strength. However, the most available diagnostic tool, dual-energy X-ray absorptiometry (DXA), provides only modest estimations of strength because it does not assess bone geometry and trabecular structure nor can it incorporate the location and direction of impact from a sideways fall, the most common cause of proximal femur fractures. In contrast, quantitative computed tomography/finite element analysis (QCT/FEA) models can include such information, and have been shown to provide accurate estimates of fracture load, type, and location in the femur.

Clinical application of QCT/FEA methods requires validation by comparing model estimations to ex vivo experimental results. QCT/FEA models of sidewalk falls on the proximal femur have been developed [1, 2]. However, mechanical testing protocols are not yet standardized and may be difficult to compare results between studies. Moreover, various simplified boundary conditions (BC) have been used to improve computational efficiency [1, 2]. However, the models’ predictive power with simulation of complete experimental BC remains unknown.

The objective of our study was to investigate the capability of our in-house developed proximal femur QCT/FEA models, carefully modeled with full BC that match ex vivo experiments, in estimating stiffness and ultimate load under sidewalk falls loading conditions.

METHODS
Nine human cadaveric femora were studied (seven females, two males, 70.4 ± 10.3 years). Femoral neck aBMD was assessed (GE Lunar iDxA, GE Healthcare Inc., Waukesha, WI) and three each were classified as osteoporotic, osteopenic, and normal. QCT scans of the femora were obtained before testing (Siemens, Malvern, PA) operated at 120 kVp and 216 mA with in-plane resolution 0.30 ~ 0.45 mm and slice pitch 0.4 mm. The femora were kept hydrated at all times until the moment of fracture.

An anil mesh of each femur including a distal block was created (Mimics, Materialise, Ann Arbor, MI) (Fig. 1). The meshed block represented the cement block used to secure the distal femur during experiments. The meshes were more refined on the exterior and the proximal end and less refined on the interior and the distal end. Elements on the femur were grouped into 42 materials according to Houndfield units. The following laws were used for material properties:

1) Elastic modulus [3]: \( E = 1464 \rho \) GPa

2) Yield criterion (in-house): \( \epsilon_y = 0.0081 \rho \)

An uniform E (2 GPa) was used to represent dental cement elastic property for elements associated with the cement block. The nodes on the four lateral sides of the cement block mesh were connected with the rotation point by rigid beams to mimic the clamping effect of the fixture and the rotation about O (Fig. 1). Effective friction coefficients (\( \mu \)) were calculated for each femur using experimental data. The average \( \mu \) of the nine femora was used to model the friction between the bottom of the trochanter cup and load cell. The detailed BC are shown in Fig. 2.

A series of quasi-static analyses were performed. After each step (0.1 mm displacement), elements with the von Mises strain exceeding

Figure 1: Experimental setup. The distal end of the femur was embedded in a block of dental cement and clamped in a fixture. The femur was placed at 10° adduction and 15° internal rotation angles.

Figure 2. QCT/FEA model setup.

Figure 3. Experimental stiffness was estimated by A) QCT/FEA-estimated stiffness and B) aBMD. Experimental ultimate load was estimated by C) QCT/FEA-estimated ultimate load, and D) aBMD.

yield strain were "failed" by assigning a very small E (0.01 Pa). Stiffness was calculated from the linear portion of the QCT/FEA force-displacement curve. Ultimate load was determined as the estimated peak force on the trochanter. QCT/FEA estimations were compared with experimental data. The estimations based on the QCT/FEA and the femoral neck aBMD were then compared with experimental data.

RESULTS
Linear regressions showed strong correlations between QCT/FEA estimated and measured data for stiffness (R² = 0.77) and ultimate load (R² = 0.83) (Fig. 3). The correlations were weaker for neck aBMD (stiffness R² = 0.54, ultimate load R² = 0.67). The use of experimentally developed effective friction coefficient (\( \mu = 0.05 \)) led to excellent match between the estimated and measured friction force on the trochanter.

DISCUSSION
In this study we developed QCT/FEA models with BC fully matched to the experiments. The models accurately estimated both experimental stiffness and ultimate load in the proximal femur, and were shown to have better correlation with experimental data than aBMD.

A published modulus-density equation derived from trabecular bone was shown to provide good estimations of femoral stiffness. The use of a novel yield criterion based on density and von Mises strain distributions led to a strong correlation between experimental and estimated ultimate load. An experimentally derived effective friction coefficient provided better representation of the experimental conditions, highlighting the importance of carefully selecting model BC parameters.

Overall, this study shows that we have carefully crafted QCT/FEA models using a full set of experimental BC which provide accurate estimation of femoral stiffness and ultimate load under a sideways fall.

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REFERENCES