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Quantitative computed tomography-based finite element analysis predictions of femoral strength and stiffness depend on computed tomography settings

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ABSTRACT

The aim of the present study was to compare proximal femur strength and stiffness obtained experimentally with estimations from Finite Element Analysis (FEA) models derived from Quantitative Computed Tomography (QCT) scans acquired at two different scanner settings. QCT/FEA models could potentially aid in diagnosis and treatment of osteoporosis but several drawbacks still limit their predictive ability. One potential reason is that the models are still sensitive to scanner settings which could lead to changes in assigned material properties, thus limiting their results accuracy and clinical effectiveness. To find the mechanical properties we fracture tested 44 proximal femora in a sideways fall-on-the-hip configuration. Before testing, we CT scanned all femora twice, first at *high* resolution scanner settings, and second at *low* resolution scanner settings and built 88 QCT/FEA models of femoral strength and stiffness. The femoral set neck bone mineral density, as measured by DXA, uniformly covered the range from osteoporotic to normal. This study showed that the femoral strength and stiffness values predicted from *high* and *low* resolution scans were significantly different ($p < 0.0001$). Strength estimated from *high* resolution QCT scans was larger for osteoporotic, but smaller for normal and osteopenic femora when compared to *low* resolution scans. In addition, stiffness estimated from *high* resolution scans was consistently larger than stiffness obtained from *low* resolution scans over the entire femoral dataset. While QCT/FEA techniques hold promise for use in clinical settings we provided evidence that further improvements are required to increase robustness in their predictive power under different scanner settings and modeling assumptions.

1. Introduction

A desire to reduce the level of mortality and morbidity due to hip fracture in the elderly population has fueled the advancement of techniques designed to provide fracture risk prediction using non-invasive methods (Center et al., 1999; Kanis et al., 2004; Morin et al., 2011). QCT/FEA subject-specific femur modeling was shown to provide high quality estimations of proximal femur strength, stiffness, and prediction of fracture location (Bessho et al., 2007, 2009; Dragomir-Daescu et al., 2011; Keyak, 2001; Keyak et al., 2001; Schileo et al., 2008). Its popularity is based on the ability to produce precise three-dimensional geometries from *high* resolution QCT images of the human femur (Viceconti et al., 2000, 2004) and to provide well-defined material property input to FEA models (Genant et al., 1999; Morgan et al., 2003; Taddei et al., 2006) – two variables essential for accurate results.

It has been shown that scanner type (single vs. dual source), image reconstruction algorithm, slice thickness/pitch, and power (changes in voltage and/or amperage) result in statistically significant differences in noise and contrast due to changes in gray scale values (Paul et al., 2012). It is therefore likely that changes in CT scanning parameters may lead to changes in FEA outcomes even when the same bone is scanned at varied settings. Clinical QCT scans are taken with the goal of minimizing tube current time (mAs) in order to decrease the amount of radiation to the patient, while in contrast, many research institutions developing techniques for fracture risk prediction with cadaveric bone tissue tend to select scanning parameters to provide for increased image quality (high mAs) for FEA input while disregarding the amount of radiation exposure to the tissue. Thus, information on how scanner parameters affect FEA outcomes would be valuable for researchers who desire to use QCT/FEA techniques in a clinical

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setting for fracture risk prediction in patients, but have developed their QCT/FEA technique using research quality scanner parameters at high mAs.

Though many researchers have provided extensive data comparing their QCT/FEA based results to experimental results, to our knowledge, none have examined the quality of the CT input data as a determining factor for the outcome of the FE analyses. The objective of our study was to compare if FE models whose gray scale values were obtained from low amperage scans reconstructed with smooth kernels (*low* resolution) are predicting strength and stiffness values comparable with models whose gray scale values were obtained from high amperage scans reconstructed with sharp kernels (*high* resolution) – the former representing the standard for clinical settings, and the latter representing the current standard in research settings. This will provide valuable information on whether QCT/FEA bone strength and stiffness predictions using lower quality clinical QCT scans are similar to those using techniques developed using research quality scans of cadaveric femora. We thus compared how finite element estimations of strength and stiffness for a sample of 44 cadaveric femora scanned at *high* and *low* scanner resolution settings were correlated to each other, and individually with experimental test results in a fall-on-the-hip configuration.

2. Methods

2.1. Experimental tests

All experimental procedures were approved by our Institutional Review Board and followed methodologies published previously. Some details on materials and methods relevant to the current study are briefly recapitulated (Dragomir-Daescu et al., 2011).

2.1.1. Femur specimens and QCT scanning protocol

Forty-four fresh frozen, transplant grade cadaveric femora were obtained from 44 individual donors (Table 1). The specimens were selected from a larger cohort of 100 cadaveric specimens based on femoral neck areal bone mineral density (aBMD) *T*-score (GE Lunar iDXA, GE Healthcare Inc., Madison, WI) such that the sample uniformly covered the range from osteoporotic to normal. All specimens were thawed to room temperature and scanned in air for maximum contrast using a Siemens Somatom Definition CT scanner (Siemens Healthcare, Forchheim, Germany). Each femur was scanned twice in the same position using two distinct QCT protocols for model comparison (Fig. 1).

2.1.1.1. High resolution research QCT protocol. Scanner power – 120 kVp and 216 mAs; image reconstruction – sharp (U70) kernel with in-plane pixel size 0.3–0.45 mm (Fig. 1A); slice increment and thickness – 0.4 mm; average number of QCT slices per femur – 1120.

2.1.1.2. Low resolution clinical QCT protocol. Scanner power – 120 kVp and 20 mAs; image reconstruction – body (B30) kernel with in-plane pixel size 0.3–0.45 mm (Fig. 1B); slice increment and thickness – 2 mm; average number of QCT slices per femur – 230.

A QCT scanning phantom (Mindways Inc., Austin, TX, USA) was placed in the field of view to convert Hounsfield units (HU) to equivalent K_2HPO_4 density, assumed to be equal to bone ash density (Cong et al., 2011)

$$\rho_{ash} = \rho_{K_2HPO_4} = -9 \times 10^{-3} + 7 \times 10^{-4} \bullet HU \quad (1)$$

2.1.2. Experimental testing protocol

Experimental testing was conducted using a Mini Bionix testing machine (MTS, Eden Prarie, MN, USA). Femora were tested to failure in a fall-on-the-hip loading configuration (15° internal rotation, 10° adduction) at a speed of 100 mm/s (Dragomir-Daescu et al. 2011). Data from a single axis load cell that measured the vertical reaction forces at the greater trochanter and a linear displacement sensor that measured actuator displacement at the femoral head were used for comparison to QCT/FEA estimated results. Experimental strength was determined as the peak load prior to specimen failure while stiffness of each bone was calculated from the most linear initial region of the experimental load–displacement curves.

2.2. Subject-specific QCT/FEA models

2.2.1. Image-based mesh generation

Finite element meshes were generated from QCT images using the Materialise Interactive Medical Image Control System – Mimics® 13.0 and 14.01 (Materialise, Plymouth, MI, USA). Dicom images obtained from the scans were imported into Mimics® software and the bone tissue was segmented using a threshold of 300 HU and each slice edited manually to ensure it included the entire cortical bone region. Since the *high* resolution QCT slices showed better contrast than *low* resolution QCT slices (Fig. 1A and B), we used the *high* resolution scans for segmentation and generation of the 3D geometry. Triangular surface meshes generated using the Mimics® FEA module followed a "smart" meshing technique with maximum element edge lengths of 4.0 mm (mid diaphysis), 2.5 mm (proximal diaphysis), and 1.5 mm (proximal metaphysis). Unstructured tetrahedral volume meshes were automatically generated from triangular surface meshes with ANSYS ICEM (ANSYS, Canonsburg, PA, USA) using 10-noded tetrahedral elements and an advancing front algorithm so that elements in the cancellous compartment were larger than elements in the cortex (Fig. 1C and D). These meshing parameters were shown to lead to converged results based on a previous mesh sensitivity study performed with *high* resolution scans (Dragomir-Daescu et al., 2011). The same 3D meshes generated were then imported into the *low* resolution scans in Mimics® models to assign material properties (Figs. 1C and D). A new sensitivity study was performed to confirm that the mesh derived from *high* resolution scans also resulted in mesh independent results for the *low* resolution models.

2.2.2. Material property assignment

Material properties, including bone ash density, elastic modulus and yield strain, were grouped into 42 discrete material property bins based on average HU number within the element and were mapped to the QCT/FEA models using the Mimics® FEA module. Each finite element elastic modulus (*E*, [MPa]) was obtained from literature based on a density–elastic modulus relationship established by

Table 1
Donor statistics for 44 femora data set.

Bone quality	Quantity	*T*-score	Mean age at death	Age range	Sex	Side	Mean (SD) femoral neck aBMD [g/cm^2]
Osteoporotic	14	≤ -2.5	75	53–97	12 Females, 2 males	7 Right, 7 left	0.592 (0.09)
Osteopenic	15	$-2.49, -1$	67	46–91	10 Females, 5 males	6 Right, 9 left	0.802 (0.061)
Normal	15	≥ -1	59	34–89	5 Females, 10 males	9 Right, 6 left	1.027 (0.147)