INTRODUCTION

Currently, the best tool to predict osteoporotic fractures is femoral neck (FN) areal bone mineral density (aBMD) by dual-energy x-ray absorptiometry (DXA). FN aBMD is correlated with bone stiffness and strength but does not account for three-dimensional bone geometry and spatial distribution of mineral. Our aim is to develop a better method to predict osteoporotic fractures using clinical Quantitative Computed Tomography (QCT). Previously, we successfully developed QCT-based finite element models (QCT/FEA) for cadaveric proximal femora [1]. In the current study, we extended this methodology to in-vivo data.

METHODS

Sixty proximal femur QCT scans from 29 women and 31 men (mean age, 71±12 years; range, 51-96 years) were selected from a larger population sample [2]. FN aBMD of each subject was also measured. Based on WHO criteria, the sample consisted of 20 subjects with normal FN aBMD (1.005±0.123 g/cm²), 20 with osteopenia (0.821±0.059 g/cm²), and 20 with osteoporosis (0.659±0.097 g/cm²).

QCT scans were performed with a slice thickness of 2 mm and average pixel size of 0.814 mm. A calibration phantom (Mindways Software, Inc., Austin, TX) was simultaneously scanned in order to convert grayscale values to ash density. Scans from one femur for each subject were studied, and a 3-dimensional model was generated from the QCT-Surfaces using Mimics (Materialise, Plymouth, MI). A surface was created and imported into ANSYS ICEM software (ANSYS, Canonsburg, PA) to generate a uniform volume mesh with 4 mm maximum element edge length. Forty-two discrete elastic modulus values were assigned to elements based on calculated ash density [1].

Each femur mesh was then imported into ANSYS Mechanical APDL for FEA. For simulations, bone models, generated from in-vivo scans, were oriented in a fall-on-hip position similar to our prior cadaver models (10° adduction, 15° internal rotation) (Fig. 1). To mimic the knee, a rotation node was added to the model distally and was attached with rigid beam elements to nodes in the bone mesh. Selected nodes in the trochanter were fixed in the vertical, z-direction, while vertical loads were applied in 100N increments to selected nodes on the head.

Femoral stiffness and strength were significantly lower in subjects classified as being osteoporotic when compared to those with osteopenia or normal FN aBMD (p<0.002 for all) (Table 1). Femoral stiffness, but not strength, was significantly different between osteopenic subjects and those with normal FN aBMD (p=0.013, =0.126, respectively).

There was a significant relationship between WHO classification and ranked tertiles for femoral stiffness and strength (p<0.001; =0.002, respectively) (Table 2). This association was stronger for stiffness than for strength (Cramer’s V: 0.54 for stiffness vs. 0.38 for strength).

DISCUSSION

In this study, we extended our previously developed FEA models for femoral stiffness and strength estimations to in-vivo resolution QCT scans. The results showed clear and significant differences between groups with one exception; although the average femoral strength for subjects with normal FN aBMD (9201 N) was larger than the average strength for subjects with osteopenia (8000 N), the difference was not statistically significant. This may be attributed to the limited capability of aBMD by DXA to correctly represent femoral stiffness and strength. Furthermore, we ranked the subjects based on FEA-calculated femoral stiffness and strength to classify them using tertiles (Low, Medium, and High). The number of subjects in these three categories tended to agree relatively well with the WHO classification of osteoporotic, osteopenic, and normal. The misclassifications observed could be due to limited discrimination capacity of aBMD.

The values calculated for femoral stiffness and strength were higher than those obtained in our prior cadaveric models which produced an average stiffness of 2495 N and strength of 4542 N for six normal aBMD femora [1]. Comparatively, the values obtained for the subjects in this study were higher: ~75% for stiffness and ~100% for strength. This was likely due to element elastic modulus values being twice as large as in the cadaver models. These differences are currently being investigated. Despite these differences, our QCT/FEA models were able to discriminate well between groups for both calculated femoral stiffness and strength. Further work on their utility in fracture prediction is underway.

SIGNIFICANCE

Our QCT/FEA models show promise to achieve more accurate predictions of proximal femur strength when compared to aBMD, and consequently improve clinical estimations of osteoporotic fracture risk.

REFERENCES


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