CT-based Finite-Element Analysis and Structural Rigidity Analysis to assess Failure Load in Bones with Simulated Lytic Defects

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INTRODUCTION

In clinical practice, there is urgent need to improve the prediction of fracture risk for cancer patients with bone metastases. Pathological fractures that result from these tumors most frequently occur in the femur. It is extremely difficult to determine the fracture risk even for experienced physicians. Although evolving, fracture risk assessment is still based on inaccurate predictors estimated from previous retrospective studies. As a result, many patients are surgically over-treated, whereas other patients may fracture their bones against expectations.

We have previously demonstrated the effective use of non-invasive imaging techniques using quantitative computed tomography (QCT) for the assessment of structural rigidity and prediction of failure loads in ex-vivo and in-vivo models.[1, 2] Additionally, using the same principle, we have shown that finite element (FE) computer models are capable of simulating the mechanical behavior of bones under an axial loading condition with a high level of precision.[3]

The aim of this study is to assess and establish statistical comparisons between our proposed QCT structural rigidity analysis (CTRA) and the FE computer models, in their accuracy for the estimation of fracture risk prediction.

METHODS

Ten pairs of human cadaveric femurs (obtained with institutional approval) were mechanically tested to failure under uni-axial loading. The load was increased by 10 N/sec from 0 N until failure. In one femur of each pair one or two holes were drilled to simulate metastatic lesions. The location and size (22, 30, 40, 45 mm diameter) of each hole varied amongst the bones and were realistic to the metastatic lesions found in patients. During the experiments, the failure forces and the course of failure were registered.

Before testing, the femurs were CT-scanned (Philips, 120kV, 220mAs, 3mm slices) in a water basin on top of a solid calibration phantom (Image Analysis), which included 0, 50, 100 and 200 mg/ml calcium equivalent densities. From the scans, 20 finite element (FE) models were generated using tetrahedral elements with edge lengths of approximately 2 mm. The mineral density of each element was computed from the calibrated CT scan data and non-linear isotropic mechanical properties were implemented.[4] The exact boundary conditions of the experiments were simulated in the FE-models, in which plastic deformation simulated failure of the bones.[3]

For the CTRA, gray scale values in the CT-scan were converted to mineral density by using the linear relationship between Hounsfield units and mineral density as established by the hydroxyapatite phantoms scanned with each bone. The mineral density of each pixel was converted to either modulus of elasticity (E), for axial (EA) and bending (EI) rigidity measures, or to shear modulus (G), for torsional (GJ) rigidity, using empirically derived constitutive relationships for cancellous and cortical bone. For each trans-axial image, EA, EI and GJ were calculated by summing the modulus-weighted area of each pixel within the bone contour by the position of the pixel relative to the centroid of the bone cross-section. The cross-section through the affected bone that had the largest reduction in rigidity is the weakest and assumed to govern failure of the entire bone.

The accuracy of the failure loads predicted by CTRA and FE analysis were regressed on the experimental failure loads. Furthermore, we compared the two modeling techniques by regressing CTRA predictions on the FE predictions. Statistical analyses were performed in SPSS (version 17.0, SPSS Inc., Chicago, IL, USA).

RESULTS

The simulated FE-failure predictions showed good correlation with values obtained from the experimental mechanical testing ($R^2=0.89$, $p<0.0001$). Similarly, values obtained through CTRA correlated well with those obtained from mechanical testing, all achieving statistical significance ($p<0.0001$). For axial rigidity (EA), $R^2=0.82$; for bending rigidity (EI), $R^2=0.86$; and for torsional rigidity (GJ), $R^2=0.79$. Linear regression with FE simulation analysis and CTRA showed moderately high correlation coefficients (FE with EA, $R^2=0.77$; FE with EI, $R^2=0.76$; and FE with GJ, $R^2=0.8$).

DISCUSSION

By quantitatively comparing the predictions of FEA and CTRA to the experimental testing conditions, we have shown that both methods provide good correlating results. Regression analysis between the estimated rigidities and the failure loads as calculated by the FE method showed good correlation coefficients as well.

Unlike previously proposed radiographic guidelines, the main advantage of both methods in predicting fracture risk remains in their capability of delivering objective data that considers every aspect of bone tissue as a three-dimensional structure governed by its material and geometric properties.

Analyzing such results leaves room for us to compare and establish the differences between both methods based on technical and practical parameters. Thus, the advantage of CTRA remains in its comparatively reduced computational time, approximately 30 minutes. Advantages of FE analysis include the possibility of applying daily loading conditions so that a physician can give patient-matched advice on daily life activities.

Limitations of our study are shared with many previous works done in the field using *ex-vivo* models for the assessment of fracture risk prediction using non-invasive imaging methods. Evident differences in geometry exist between the artificial metastatic lytic lesions simulated in this study and those seen in real-life patients. Although these features were not included in this study, QCT would be readily able to detect these irregularities and incorporate them into the algorithmic analytical processes.

Further research should focus on *in-vivo* validation and modeling under more realistic and complex loading conditions. This will allow clinical experts to implement the proposed techniques as useful tools for fracture risk prediction in patients suffering from metastatic bone disease.

In conclusion, the results of our study support the fact that non-invasive fracture risk assessment techniques currently developed both correlated well with actual failure loads in mechanical testing. We believe that the choice of the most appropriate technique should be mainly determined by the personnel capabilities and preferences of the physician and/or center.

SIGNIFICANCE

CTRA and FE-model analysis have proven to yield results that are highly correlated with actual mechanical testing results. These non-invasive methods introduce potentially powerful options for the clinicians to objectively predict fracture risk and take the most appropriate therapeutic approach in patients with metastatic bone disease.

ACKNOWLEDGEMENTS

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