

MRI-based Finite Element Analysis of the Femur compared to Mechanical Testing for Evaluation of Fracture Risk

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INTRODUCTION: Hip fractures are a serious health problem that often affects older patients. These injuries have a high rate of morbidity and mortality and are repeatedly seen in people with osteoporosis. However, in vivo evaluation of fracture risk continues to be a challenge. DXA is the clinical standard for assessment of osteoporosis and fracture risk, yet many patients who sustain fragility fractures are above the diagnosis threshold. Conventional MRI-based Finite Element Analysis (FEA) has been shown to provide a more accurate evaluation of bone mechanical competence. Recently, ultrashort echo time (UTE) MRI sequences have been shown to directly image signal from cortical bone water that is invisible with conventional MRI due to its short T_2^* decay. UTE -derived cortical bone imaging biomarkers have been shown to predict porosity, collagen density, and whole-bone mechanics. Therefore, the objective of the present study was to conduct a preliminary investigation into the efficacy of UTE MRI FEA for predicting bone strength as a clinically viable, non-invasive method for evaluating fracture risk.

METHODS: 11 cadaveric femur specimens (age 72.1 ± 14.9 years) were stored at -30°C and thawed for 12-16 hours prior to experimentation. Specimens were imaged with a Prisma 3T clinical MRI scanner (Siemens, Erlangen, Germany) with an 18-channel flexible body coil array wrapped tightly around the femurs. A custom dual-echo UTE sequence was acquired with $TE_1=50\text{ }\mu\text{s}$, $TE_2=2400\text{ }\mu\text{s}$, TR 7 ms, $(280\text{ mm})^3$ field-of-view, flip angle 12 degrees, 120k center-out spokes, dwell time 2 μs , and off-line reconstruction resulting in a reconstructed matrix size of $480 \times 480 \times 480$. The TEs were chosen such that the first echo acquires signal from the long- T_2 components of marrow and soft tissue, as well as the short- T_2 species in bone, whereas the short- T_2 signal has entirely decayed by the second echo. Therefore, to generate a bone-specific image I (Fig 1) where cortical bone is the brightest component, Eq 1 was used:

$$I_{bone} = \frac{S_{TE1} - S_{TE2}}{S_{TE1} + S_{TE2}}$$

An 8mm slice of the proximal femur shaft was selected. For input into the FEA, each femur section of I_{bone} was rescaled between 0 and 100 with the maximum and minimum values being set to the average intensity values within the cortex and marrow respectively.

Masks were used on the background as well as the marrow, so the final axial image included only the cortical bone (Fig 1). Once preprocessed, the virtual bone sections were run through a custom linear FEA (AU) to simulate stiffness under uniaxial compression in the superior-inferior direction.

Specimens underwent uniaxial compression tests using a servo-hydraulic material testing machine (Instron 8874, Instron, Norwood, MA) equipped with a 100 kN load cell. The 8 mm proximal femur segments were placed loosely between two parallel steel plates and compressed under displacement control at a rate of 0.06 mm/sec. Samples were cycled 3 times to a load of 10,000 N, followed by a compression to 25,000 N. The linear portion of the load-displacement curves from the 25 kN ramp were used to determine stiffness (N/mm).

Once stiffness measurements were obtained both computationally and experimentally, a linear regression model was created, and the correlation coefficient and p-value were calculated using MATLAB.

RESULTS: See Figure 2. The R-value equals .8009 with a p-value of .0031.

DISCUSSION: The stiffness results from the FEA performed on MRI UTE scans show a significant and strong correlation with mechanical testing measurements. Our results indicate the potential for MRI to be used in the clinical evaluation of fracture risk. Ongoing work is exploring additional ways to leverage UTE measurement of cortical bone composition to further improve FEA models. However, the present study does have limitations. First, our relatively small sample size provides challenge when drawing conclusions, and further investigation should be done with more specimen. In addition, we performed a linear FEA, which simulates a fracture in the superior inferior direction, yet many hip fractures do not occur in just one plane. Simulation of a sideways fall should also be done to analyze its correlation with mechanical measurements as this may be a more rigorous representation.

CLINICAL RELEVANCE: The clinical significance of this work is the ability of our MRI-based analysis method to provide a more comprehensive and accurate assessment of fracture risk compared to current clinical methods such as DXA. This will help reduce the morbidity and mortality from hip fractures, as well as improve quality of life for patients with osteoporosis.

IMAGES:

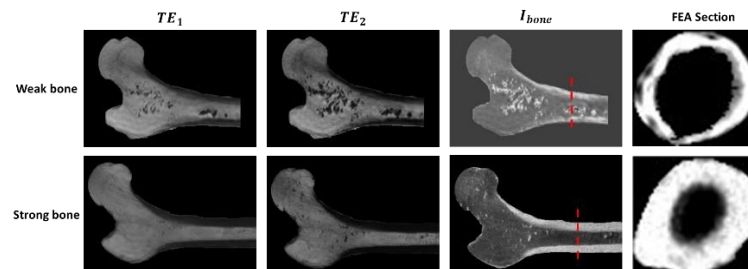


Figure 1: UTE images obtained during MRI protocol as well as calculated I_{bone} . The far-right images depict the preprocessed femur sections used in analysis. The top row of images demonstrates a specimen with low mechanical testing and FEA results, while the bottom row represents a specimen with high mechanical and computational testing. Note that in the weak bone (top), the bone shows higher porosity and lower cortical thickness.

$R=.8009, p<.0031$

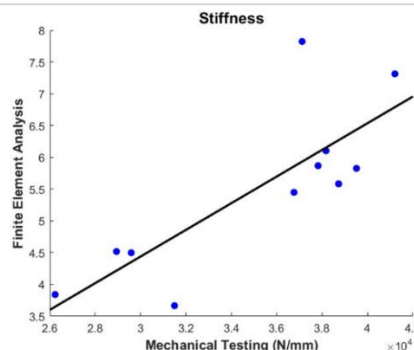


Figure 2: Linear correlation plot of FEA results vs. mechanical testing.