Assessment of axial bone rigidity in rats with metabolic diseases using CT-based structural rigidity analysis

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Assessment of axial bone rigidity in rats with metabolic diseases using CT-based structural rigidity analysis

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Objectives
This study aims to assess the correlation of CT-based structural rigidity analysis with mechanically determined axial rigidity in normal and metabolically diseased rat bone.

Methods
A total of 30 rats were divided equally into normal, ovariectomized, and partially nephrectomized groups. Cortical and trabecular bone segments from each animal underwent micro-CT to assess their average and minimum axial rigidities using structural rigidity analysis. Following imaging, all specimens were subjected to uniaxial compression and assessment of mechanically-derived axial rigidity.

Results
The average structural rigidity-based axial rigidity was well correlated with the average mechanically-derived axial rigidity results ($R^2 = 0.74$). This correlation improved significantly ($p < 0.0001$) when the CT-based Structural Rigidity Analysis (CTRA) minimum axial rigidity was correlated to the mechanically-derived minimum axial rigidity results ($R^2 = 0.84$). Tests of slopes in the mixed model regression analysis indicated a significantly steeper slope for the average axial rigidity compared with the minimum axial rigidity ($p = 0.028$) and a significant difference in the intercepts ($p = 0.022$). The CTRA average and minimum axial rigidities were correlated with the mechanically-derived average and minimum axial rigidities using paired $t$-test analysis ($p = 0.37$ and $p = 0.18$, respectively).

Conclusions
In summary, the results of this study suggest that structural rigidity analysis of micro-CT data can be used to accurately and quantitatively measure the axial rigidity of bones with metabolic pathologies in an experimental rat model. It appears that minimum axial rigidity is a better model for measuring bone rigidity than average axial rigidity.

Article focus
- Use of CT-based Structural Rigidity Analysis to assess the average and minimum axial rigidities of cortical and trabecular femur segments from normal, ovariectomised, and partially nephrectomised rats
- Comparing the results to mechanical testing as the gold standard measure

Key messages
- Despite continued development of new therapies and treatments to prevent and treat fragility fractures, accurate, non-invasive assessment of fracture risk remains an elusive task
- Results of this study support the hypothesis that axial rigidity of bones with metabolic pathologies can be accurately and quantitatively assessed in a rat model by conducting structural rigidity analysis
- Axial rigidity measured non-invasively by micro-CT was well correlated with the results from mechanical testing as the gold standard measure

Strengths and limitations of this study
- Strength: animal study – where disease models are well controlled and mechanical testing can be conducted to confirm results
Introduction

Fragility fractures of the hip, spine or wrist resulting from osteoporosis and other bone diseases are common causes of disability, affecting up to 2 million Americans annually. While osteoporosis is assumed to be the cause of most fragility fractures, 25-OH-vitamin D deficiency is observed in 50% of postmenopausal women in the population who fracture their hip (not including those residing in retirement homes) and have no other cause for low bone mass. Vitamin D deficiency can result in osteomalacia, a bone material problem which has been diagnosed histologically (hypo-mineralized osteoid) in between 13% and 33% of patients with hip fractures.

Moreover, secondary hyperparathyroidism, as seen in patients with renal disease, can cause demineralization of both the cortical and trabecular bones and can increase the risk of fracture by compromising the material properties of bone. Currently, the World Health Organization (WHO) uses decreased bone mineral density (BMD), as measured by dual energy X-ray absorptiometry (DXA), in order to identify patients with osteoporosis and osteopenia in order to identify individuals at risk for fragility fracture. However, BMD, an areal projection, is not a true measure of bone density and has shown to be neither sensitive nor specific in its ability to predict future fragility fracture.

The strength of bone is determined by its material composition and structural organisation. DXA measurements are based on the areal projection of a two-dimensional construct, where trabecular and cortical bone components are integrated. In contrast, quantitative CT-based Structural Rigidity Analysis (CTRA), a three-dimensional imaging modality, can provide information about specific changes in bone material and structure for both cortical and trabecular bone. While DXA fails to distinguish changes in the composition of bone tissue from those changes occurring at the structural level, CTRA is capable of non-invasive assessment of axial, bending and torsional rigidities of bones from their trans-axial cross-sectional images. With this technique, modulus of elasticity (Young’s modulus) is treated as a function of bone material and bone geometry is represented by its cross-sectional area and moment of inertia. While CTRA has been used extensively to assess fracture in studies of metastatic musculoskeletal lesions, efforts have not been made to assess the efficacy of this technique in assessing fracture risk in metabolic musculoskeletal diseases.

The ovariectomized (OVX) rat model has been widely used to study the effects of menopause on bone mass, trabecular microstructure and fracture risk; and the partially nephrectomized (NFR) rat model has been used effectively to study the effects of renal osteodystrophy manifested as secondary hyperparathyroidism on bone metabolism. We have previously used the established ovariectomy model as a surrogate for an altered skeletal state in conjunction with the nephrectomy-induced renal osteodystrophy model and have demonstrated the deficiencies of DXA compared with quantitative computed tomography in detecting changes in trabecular bone microstructure in relation to changes in their mechanical properties. Our group has also described the relationships between the mechanical properties of normal, ovariectomized, and partially nephrectomized rat cortical and trabecular bone based on its mineral density, bone volume fraction and apparent density.

Given the ability of CTRA to detect structural and material changes within trabecular and cortical bone, we hypothesised that CTRA can accurately assess the average and minimum axial rigidities of cortical and cancellous bones affected by metabolic diseases. To that end, we used CTRA to assess the average and minimum axial rigidities of cortical and trabecular femur segments from normal, ovariectomized and partially nephrectomized rats, and compared the results with those obtained from mechanical testing as the gold standard measure.

Materials and Methods

Animal model. A total of 30 female Sprague Dawley rats (around 15 weeks of age, weighing between 250 g and 275 g) were obtained and divided into three equally sized groups: the animals in the control group (n = 10) were not subjected to any surgical or dietary interventions; the OVX group (n = 10) underwent ovariectomy a week prior to the start of the study in order to induce a state of low bone mass and micro-architectural deterioration; and the NFR group (n = 10) underwent 5/6 nephrectomy one week prior to the start of the study, in addition to being placed on a modified diet containing 0.6% Ca and 1.2% P for the duration of the study in order to induce renal osteodystrophy (normal rodent diet contains 1.35% Ca and 1.04% P) and severe secondary hyperparathyroidism.

Both surgical procedures were conducted at the animal supplier facility one week prior to the arrival of the animals at the laboratory. The control, NFR and OVX animals were killed by CO2 inhalation four months after they arrived at our laboratory, in order to allow appropriate time for the onset and progression of diseases. The femurs from each animal were excised and cleaned of all adherent soft tissues, a mid-diaphyseal (cortical bone only) and a distal metaphyseal (trabecular + cortical bone) specimen were cut from each femur perpendicular to the anatomical axis using two parallel diamond wafering blades on a low-speed saw (Isomet, Buehler Corporation, Lake Bluff, Illinois) under copious irrigation. The
cortical midshaft specimens (height: 5.99 mm (SD 0.28),
diameter at mid-length: 3.64 mm (SD 0.24)) were cut to
maintain an approximate 2:1 height to diameter ratio,15
while the distal metaphyseal segments (height: 6.22 mm
(SD 0.73), diameter at mid-length: 4.84 mm (SD 0.41))
were cut from the growth plate, as identified from antero-
posterior contact radiographs, in order to include the
distal metaphyseal trabecular micro-structure. The
metaphyseal cortex was shaved off at the laboratory
using diamond wafering blades under magnified viewing
and ample lighting in order to obtain trabecular only
specimens.13 The specimens were held by the operator’s
hand, allowing much greater freedom of movement than
using a jig.

**Micro-CT imaging.** Sequential transaxial images through
the entire cortical and trabecular bone sections were
obtained using micro-CT (μCT) (μCT40; Scanco Medical
AG, Brütisellen, Switzerland) at an isotropic voxel size of
30 μm, integration time of 250 ms and tube voltage and
current of 55 kVp and 145 μA respectively, while applying
a 1200 mg.cm⁻³ hydroxyapatite (HA) beam hardening
correction curve. Cortical and trabecular bone mineral
densities (ρ, g.cm⁻³) were calculated using a hydroxyapa-
tite phantom (0, 100, 200, 400 and 800 mg HA.cm⁻³),
supplied by the manufacturer, to convert the X-ray atten-
uation coefficient (μ) to volumetric bone mineral density.
Average and minimum cross sectional areas of the bony
components of the cortical and trabecular bone speci-
mens were calculated from the thresholded μCT images.

**Structural rigidity analysis.** Rigidity, the product of the
bone tissue modulus of elasticity and bone cross-
sectional geometry describes the structural behavior of a
bone and its resistance to deformation when subjected to
axial, bending or torsional loads. The bone tissue modu-
lus (E) depends on the bone mineral density. Axial com-
pressive relationships describing the mentioned
mechanical properties of rat bone as a function of μCT-
generated density were used to convert the densities to
their respective axial modulus value.13 These relationships
were generated from bones from a different group of ani-
mals as those used for this study. The bone geometry is
represented by the cross-sectional area. The axial (EA)
rigidity for each transaxial cross-section through the bone
was calculated by summing the density-weighted area of
each isotropic voxel (30 μm × 30 μm × 30 μm) by its posi-
tion relative to the density weighted centroid16 (Fig. 2).
Average (EAVG-CTRA) and minimum EA (EAMIN-CTRA) axial
rigidities were reported for each specimen. EAVG-CTRA rep-
resents the average axial rigidity of the entire segment,
whereas EAMIN-CTRA represents the axial rigidity of the
entire segment at its weakest cross-section. Given that a
bone is as rigid as its weakest section,7-9 and not as its
average rigidity, EAMIN-CTRA should provide meaningful
information into the fidelity of the normal and patho-
logical bone.

**Mechanical testing.** Specimens were thawed out to
room temperature and hydrated prior to mechanical test-
ing; otherwise, they were stored in saline soaked gauze
and stored at -20°C for the duration of the study. Circular brass end-caps (8 mm in diameter, 1 mm in thickness) were glued to both ends of each sample to reduce end-effect artifacts. Specimens were preconditioned, using a triangular waveform to 0.33% strain for 7 cycles at a strain rate of 0.005 s⁻¹, followed by uniaxial compression to failure at a strain rate of 0.01 s⁻¹ (Instron 8511; Instron, Norwood, Massachusetts). Yield load (Lₚ, kN) was assessed as the point where the load-displacement curve ceased to be linear, and ultimate load (Lₚₚ, kN) was assessed as the highest load point (Fig. 3). Stress data were calculated by dividing the load with average and minimum cross sectional areas of the bony components of the cortical and trabecular bone specimens as measured from μCT images. Strain data was calculated by dividing displacement with the intact height of each specimen as measured by a caliper (average of three measurements). Modulus of elasticity, (E, N/mm), was assessed by measuring the slope of the elastic region of the stress-strain curve for the cortical and trabecular segments. Average axial rigidity (Eₐᵥₐᵥₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚₚportion neglected.
Significant differences in EA data between different bone types (cortical versus trabecular, \( p < 0.0001 \)) and groups (\( p < 0.0001 \)) were observed (Table I). Post hoc analysis of the intra group differences revealed that \( E_{A\text{VG}} \) were not different between the OVX and NFR groups regardless of the data collection method (CTRA, \( p = 0.091 \); mechanical testing, \( p = 0.343 \)). The CTRA based \( E_{A\text{M}} \) results between the control and OVX groups were not significantly different from one another (\( p = 0.123 \)), whereas the mechanical testing based \( E_{A\text{MIN}} \) results between the control and OVX groups revealed a statistically significant difference (\( p = 0.004 \)) (Table I). Cortical bone axial rigidity distribution occupied the upper right hand quadrant of both regression figures, whereas trabecular bone axial rigidity distribution filled the lower left quadrant of both regression figures with cortical and trabecular bones from control animals providing the highest rigidity values.

**Discussion**

Despite continued development of new therapies and treatments to prevent and treat fragility fractures, accurate, non-invasive assessment of fracture risk remains an elusive task. The results of this study support the hypothesis that axial rigidity of bones with metabolic pathologies can be accurately and quantitatively assessed in a rat model by conducting structural rigidity analysis on serial axial images of the affected bone. Axial rigidity measured non-invasively by \( \mu \text{CT} \) was well correlated with the results from mechanical testing as the gold standard measure. Minimum axial rigidity produced a stronger correlation with mechanical testing based minimum rigidity results (\( R^2 = 0.84 \)) than their average counterparts (\( R^2 = 0.74 \)). Furthermore, intra-group and intra-type paired Student’s \( t \)-test showed no significant difference in axial rigidity as determined by CTRA and mechanical testing (\( p > 0.13 \) for all cases).

In the average axial rigidity model, the slope of the linear regression was 1.23 and the \( y \)-intercept offset was 3142, suggesting that CTRA using average axial rigidity consistently over-predicts bone rigidity. In the minimum axial rigidity model, the slope of the linear regression was 1.05 and the \( y \)-intercept offset was 69, indicating that CTRA is correlated without much skewness with mechanical testing results over the full range of the values tested. This data lends further support to the hypothesis that minimum rigidity is more accurate than average rigidity in predicting the overall rigidity of bone.

The cortical bone specimens predominantly make up the upper right quadrant of each regression model, corresponding to higher rigidity. Concurrently, trabecular bone specimens occupy the lower left quadrant of each regression model, corresponding to their lower rigidity distribution. In both cases, cortical and trabecular bones from partially nephrectomized animals comprise the lowest axial rigidity combination along the regression line of each bone type, while bones from ovariectomized animals comprise the mid-range for axial rigidity values from both bone types followed by bones from control animals.

In other studies, it has been shown that \( \mu \text{CT} \) and peripheral quantitative CT data in diabetic rats will identify changes in both bone densities and structure which then ultimately correlates with decreased structural strength and increased fragility in affected bones.\(^{17} \)
Another study used μCT to assess BMD in ovariectomized sheep and found that the corresponding change in the BMD and trabecular micro-architecture correlated with changes in the mechanical properties of the osteopenic bone; specifically the trabecular thickness and the bone volume fraction. Recently, one group used μCT in vivo to monitor the effect of zoledronic acid on the micro-architecture of ovariectomized rats; demonstrating the ability of μCT to detect crucial changes in bone volume fraction, trabecular number, and trabecular thickness, which ultimately correlate with bone strength.

This study proposes that not only is there a correlation between μCT-derived data and bone rigidity, but that structural rigidity analysis of μCT data can be successfully employed to non-invasively assess the axial rigidity of bones with metabolic pathologies. Ultimately, the advantage of this technique is that it uses structural engineering principles to calculate rigidity of bone, rather than using simple scalar measures such as density or morphometric indices that may provide good correlation but may not be based on theory.

The CTRA based average and minimum axial rigidities were compared to average and minimum axial rigidity values obtained from mechanical testing. This process entailed the assessment of E from the slope of the stress-strain curve followed by assessment of average and minimum bony cross-sectional areas from μCT images. This was done in order to generate equivalent rigidity indices to compare those that took into account changes in bone area measurement for both CTRA and mechanical testing methods. Failure load from mechanical testing, which have a unit of force as well, could have been used to correlate with the CTRA based average and minimum axial rigidity values, which would have been a more direct measurement. Additionally, torsional rigidity would have been a better option to use in a long bone setting. However, axial rigidity was chosen instead to generate rigidity data for both cortical and trabecular components of the bone, given that metabolic diseases affect the two bone types differently. The results suggest that the CTRA analysis was capable of differentiating between the bone types and groups as shown in Table I.

In summary, the results of this study suggest that structural rigidity analysis of μCT data can be used to accurately and quantitatively measure the axial rigidity of bones with metabolic pathologies in an experimental rat model. As shown, minimum axial rigidity appears to be a better model for measuring bone rigidity than average axial rigidity. It remains to be seen whether analogous CT images in human patients could also be used to predict fracture risk in those affected by metabolic bone diseases. Future studies across multiple disease models and imaging techniques involving larger sample sizes is warranted to evaluate the reproducibility and extensibility of these findings.
promising results. However, the results of this study suggest considerable potential in the use of μCT-based CTRA to quantitatively and non-invasively assess load bearing capacity of bones with metabolic diseases.

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