Journal of Biomechanics 46 (2013) 2701–2709

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Finite element analysis and computed tomography based structural rigidity analysis of rat tibia with simulated lytic defects

John A. Rennick [a,c], Ara Nazarian [a], Vahid Entezari [a], James Kimbaris [a], Alan Tseng [a], Aidin Masoudi [a], Hamid Nayeb-Hashemi [c], Ashkan Vaziri [c], Brian D. Snyder [a,b,*]

[a] Center for Advanced Orthopaedic Studies, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, MA, USA
[b] Department of Orthopaedic Surgery, Children's Hospital, Harvard Medical School, Boston, MA, USA
[c] Department of Mechanical Engineering, Northeastern University, Boston, MA, USA

ARTICLE INFO

Article history:
Accepted 28 June 2013

Keywords:
Finite element analysis
Structural rigidity analysis
Metastatic disease
Lytic defect
Rat

ABSTRACT

Finite element analysis (FEA), CT based structural rigidity analysis (CTRA) and mechanical testing is performed to assess the compressive failure load of rat tibia with simulated lytic defects.

Twenty rat tibia were randomly assigned to four equal groups ($n=5$). Three of the groups included a simulated defect at various locations: anterior bone surface (Group 1), posterior bone surface (Group 2) and through bone defect (Group 3). The fourth group was a control group with no defect (Group 4). Microcomputed tomography was used to assess bone structural rigidity properties and to provide 3D model data for generation of the finite element models for each specimen.

Compressive failure load calculated using CT derived rigidity parameters (F_{CTRA}) was well correlated to failure load recorded in mechanical testing ($R^2=0.96$). The relationships between mechanical testing failure load and the axial rigidity ($R^2=0.61$), bending rigidity ($R^2=0.71$) and FEA calculated failure loads, considering bone as an elastic isotropic ($R^2=0.75$) and elastic transversely isotropic ($R^2=0.90$) are also well correlated. CTRA stress, calculated adjacent to the defect, were also shown to be well correlated with yield stresses calculated using the minimum density at the weakest cross section ($R^2=0.72$). No statistically significant relationship between apparent density and mechanical testing failure load was found ($P=0.37$).

In summary, the results of this study indicate that CTRA analysis of bone strength correlates well with both FEA and results obtained from compression experiments. In addition there exist a good correlation between structural rigidity parameters and experimental failure loads. In contrast, there was no correlation between average bone density and failure load.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

One third to half of all cancers metastasize to bone (Coleman, 2006). In addition, post mortem examinations of breast and prostate cancer patients show a 70% incidence of metastatic bone disease (Mac Niocaill et al., 2011). Pathologic fracture of bones occurs when they can no longer support the loads to which they are subjected to (Snyder et al., 2009), and approximately 30–50% of bone metastases lead to fracture or produce symptoms severe enough to require treatment (Jawad and Scully, 2010).

Fracture risk is commonly quantified through assessment of the size, location and type of tumor as well as through analysis of a patient's bone mineral density (BMD). In addition to conventional radiographic techniques, the Mirels' criteria is also commonly used by clinicians in the assessment of fracture risk in patients with appendicular skeletal metastasis (Damron et al., 2003; Jawad and Scully, 2010; Mac Niocaill et al., 2011). Conventional plain radiographic techniques generally lack sensitivity with regard to fracture prediction and while Mirels' criteria has been shown to be sensitive, it is not specific (91% sensitive, 35% specific) (Damron et al., 2003; Mirels, 1989).

In contrast, Computed Tomography based Structural Rigidly Analysis (CTRA) can be used to monitor changes in bone geometry and material properties by assessing axial, bending and torsional rigidities. While CTRA has been used to assess fracture risk in studies of benign and metastastic musculoskeletal lesion in both humans and rats, it has not yet been the subject of extensive studies to compare its efficacy to advanced techniques such as finite element analysis (FEA) (Keyak et al., 2007; Keyak and Rossi, 2000; Mann et al., 2008; Orwoll et al., 2009; Pistoia et al., 2002; Schileo et al., 2008; Silva et al., 1998; Varghese et al., 2011, Hojjat et al., 2012).

Osteolytic metastasis is commonly associated with significant bone resorption and frequently results in fracture (Bunting et al., 1985; Van der Linden et al., 2004). Furthermore, lytic lesions are

* Correspondence to: Center for Advanced Orthopaedic Studies, Beth Israel Deaconess Medical Center, 330 Brookline Avenue, RN 115, Boston, MA 02215, USA. Tel.: +1 617 667 2940; fax: +1 617 667 7175.
E-mail address: brian.snyder@childrens.harvard.edu (B.D. Snyder).

0021-9290/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2013.06.024

typically more likely to result in fracture than blastic or mixed tumor cases (Mirels, 2003). As a result, a simulated lytic model was chosen to simulate this condition and used as a basis to compare the CTRA and FEA fracture risk methodologies. The simulated lytic defect model allows defect sites to be strictly controlled whereas the use of a metastatic tumor model seldom results in predictable defect sites in the diaphysis of the tibia, even with the use of the intracardiac injection method (Harms and Welch, 2003). In these cases, tumor cell clusters typically form in the proximal or distal regions (Phadke et al., 2006). In the current study, defect sites in the diaphysis of the tibia were favored as a means to compare the CTRA and FEA methodologies and hence a simulated lytic defect model was chosen.

Since CTRA is related to both bone mineral density distribution and structural variations, we hypothesize that CTRA can predict failure load as reliably as FEA in a simulated osteolytic rat bone defect model. CTRA assessments′ of bone failure load are presented by comparing linear regression coefficients of FEA and CTRA predicted failure loads versus those from mechanical testing. Investigations into correlations between experimental failure load and (1) apparent density, (2) curvature and (3) the axial and bending rigidities at the weakest cross section are also undertaken.

2. Materials and methods

2.1. Specimen preparation

This study was approved by Beth Israel Deaconess Medical Center Institutional Animal Care and Use Committee (IACUC). Twenty female Sprague Dawley rats (~15 weeks old, mass: 250–275 g) were obtained from Charles River laboratories (Charles River, Charlestown, MA, USA). One tibia, selected at random, was excised from each animal and all attached soft tissue removed. The attached fibula was removed prior to scanning with a high speed dremel hand saw. The locations of the simulated lytic defects were chosen to emulate common sites of in-vivo metastatic cancer. Lytic defects were simulated by drilling a hole at the desired location. All defects were made at the apex of the curved section of the bone using a 60 gauge (1.016 mm diameter) carbide drill bit under copious irrigation. The defect diameter was chosen to yield a circular hole diameter to specimen diameter ratio of approximately 25% (Hong et al., 2004). The primary goal of this study was to compare the CTRA and FEA methods of fracture risk assessment and hence a single well defined defect size was used in this study.

The tibiae were randomly assigned to four equal groups ($n=5$). Three of the groups included a simulated defect at various locations: anterior bone surface Group 1; posterior bone surface Group 2; and through bone defect Group 3. Group 4 was a control group with no defect. Typical specimens from each group are shown in Fig. 1.

2.2. Imaging and image analysis

Sequential transaxial images through the entire bone cross section were obtained using micro computed tomography (μCT40, Scanco Medical, AG, Brüttisellen, Switzerland). 30 μm isotropic voxel size was chosen in order to provide the required resolution for creating a solid model to perform the FEA analysis. This guaranteed that the scan resolution would be below the size of the edge length of the elements in the finite element models. The samples were scanned using an integration time of 250 ms and tube voltage and current of 70 kV and 114 μA respectively. Hydroxyapatite phantoms of known mineral density (0, 100, 200, 400 and 800 mg HA cm^{-3}), supplied by the manufacturer, were scanned to convert the x-ray attenuation coefficient (μ) to the bone mineral density (ρ_{EQUIV} [g cm^{-3}])

2.3. Structural rigidity analysis

Structural rigidity analysis is a technique used to predict fracture risk by defining the bones weakest cross section (Entezari et al., 2011; Hong et al., 2004; Snyder et al., 2006, 2009; Whealan et al., 2000). The axial rigidity (EA) and bending rigidity (EI) for each transaxial cross-sectional image through each tibia were calculated by summing the modulus-weighted area of each pixel comprising the bone section by its position relative to the centroid of the bone (Fig. 2).

The CTRA derived rigidity parameters can be combined with simple beam theory (Boresi and Schmidt, 2003) to define a CTRA based failure load (F_{CTRA}), which is defined as

$$F_{CTRA} = \frac{\varepsilon_{CRITICAL}\{\Sigma E_{ij}(\rho)da\}EI_{MAX}}{(EI_{MAX} + (\{\Sigma E_{ij}(\rho)da\}yD))} \quad (1)$$

where, $\varepsilon_{CRITICAL}$ is the critical bone strain at failure, E_{ij} and ρ are the local elastic modulus and density at the ijth location of the cross-section respectively, E (N mm^{-2}) is the average elastic modulus of the weakest cross section, da is the incremental cross sectional area (mm^2); I_{MAX} is the maximum moment of inertia (mm^4) at the weakest cross section; y is distance from geometric centroid to the bone surface where critical stress is present; and D is the distance from the eccentrically applied load to the geometric centroid at the weakest cross section. The maximum bending rigidity was used to calculate F_{CTRA} as the bending moment in mechanical testing and FEA simulations was applied around the minor principal axis (that which exhibited the maximum moment of inertia). The minimum bending rigidity (EI_{min}) was calculated and correlated to the mechanical testing failure load (F_{MECH}) to account for the "worst case" scenario.

In defining a CTRA based failure load (F_{CTRA}), the critical strain which identifies the onset of fracture ($\varepsilon_{CRITICAL}$) was set to 1.2% strain in compression, and 1% strain in tension (Hong et al., 2004; Keaveny et al., 1994; Pistoia et al., 2002; Snyder et al., 2009).

2.4. Mechanical testing

Specimens were tested using an Instron 8511 (Instron, Norwood, MA, USA) load frame under displacement control condition. Specimens were loaded to failure under uniaxial compressive at an axial strain rate of 0.01 s^{-1}. Both ends of the specimens were embedded in Polymethylmethacrylate (PMMA) to provide support.

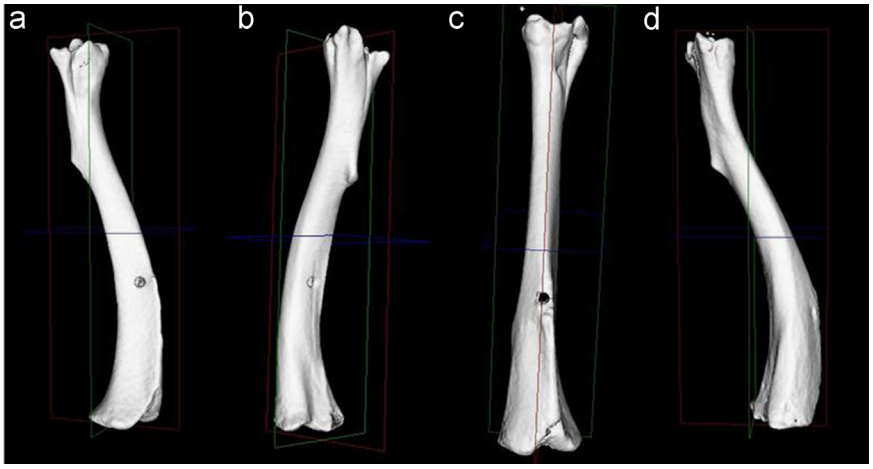

Fig. 1. Image of tibias, showing defect locations for the groups in the study: (a) Tibia from Group 1 (Anterior Defect); (b) Group 2 (Posterior Defect); (c) Group 3 (Through Hole Defect) and (d) Group 4 (Control). Sagittal (red), Coronal (Green) and Axial (Blue) Planes are shown. Fig. 2: Calculation of CTRA parameters for bone cross section. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Download English Version:

https://daneshyari.com/en/article/10432344

Download Persian Version:

https://daneshyari.com/article/10432344

Daneshyari.com