Quantitative Computed Tomography-Based Finite Element Models of the Human Lumbar Vertebral Body: Effect of Element Size on Stiffness, Damage, and Fracture Strength Predictions

This study investigated the numerical convergence characteristics of specimen-specific “voxel-based” finite element models of 14 excised human cadaveric lumbar vertebral bodies (age: 37–87; M=6, F=8) that were generated automatically from clinical-type CT scans. With eventual clinical applications in mind, the ability of the model stiffness to predict the experimentally measured compressive fracture strength of the vertebral bodies was also assessed. The stiffness of “low”-resolution models (3×3×3 mm element size) was on average only 4% greater (p=0.03) than for “high”-resolution models (1×1×1.5 mm) despite interspecimen variations that varied over four-fold. Damage predictions using low- vs high-resolution models were significantly different (p=0.01) at loads corresponding to an overall strain of 0.5%. Both the high (r²=0.94) and low (r²=0.92) resolution model stiffness values were highly correlated with the experimentally measured ultimate strength values. Because vertebral stiffness variations in the population are much greater than those that arise from differences in voxel size, these results indicate that imaging resolution is not critical in cross-sectional studies of this parameter. However, longitudinal studies that seek to track more subtle changes in stiffness over time should account for the small but highly significant effects of voxel size. These results also demonstrate that an automated voxel-based finite element modeling technique may provide an excellent noninvasive assessment of vertebral strength. [DOI: 10.1115/1.1589772]

Introduction

Researchers continue to seek improved methods for diagnosis and tracking of osteoporosis, assessment of fracture risk, understanding the effects of damage, and predicting bone strength [1]. One promising method is the use of finite element computer models of vertebral bodies generated from quantitative computed tomography (QCT) scans. Such models can be used to assess vertebral body mechanical properties [2–4] and to determine the regions of damage and probable failure in the bone [5]. The voxel-based finite element modeling technique is clinically feasible because it can be highly automated [6]. However, the numerical convergence characteristics of voxel-based finite element models can be complex and difficult to predict [7–10] and may confound any clinical predictions if not controlled. Understanding the numerical convergence characteristics of voxel-based finite element models of the vertebral body is therefore an important first step if this technology is to be used reliably to assess vertebral strength in both research and clinical settings.

Previous research has shown that convergence characteristics of voxel-based models vary widely depending on the output parameter and model geometry [7,8]. In a study of the proximal femur, the convergence of the total strain energy did not translate into convergence of elemental stress and strain values [7]. In a study of an idealized cylinder, total strain energy and peak deflection rapidly converged as the number of elements increased while the stress converged at one location and diverged at a different location [8]. Another study on idealized structures concluded that the suitability of the voxel-based technique must be evaluated in the context of the specific application [9].

The thin shell on a vertebral body introduces a number of issues that render the convergence characteristics of a voxel-based finite element model of the human vertebra unique compared to other applications. First, QCT scans overestimate the shell thickness by at least a factor of 2 due to partial volume averaging, beam hardening, and edge effects [11]. Second, the shell—on the order of 0.4 mm [11,12]—is thinner than the anticipated finite element size. This difference requires that finite elements containing only part of the shell must provide a composite representation of multiple tissues with potentially different material properties. How these two factors combine to influence the convergence characteristics for the whole vertebral body is unknown. A third issue is the scanning resolution. Clinical QCT scan resolution is controlled by two independent settings: in-plane resolution and slice thickness. Thus, in anticipation of eventual clinical applications, it is impor-
tant to independently establish the sensitivity of the model convergence characteristics as a function of element size in the in-plane and slice thickness (axial) dimensions.

The overall goal of this study was to determine the convergence characteristics of a series of voxel-based finite element models of the human lumbar vertebral body, focusing on stiffness and measures of damage because of their clinical relevance. The specific objectives were to assess the effects of element size on: (1) the convergence characteristics of stiffness and damage distribution; and (2) the correlation between model-derived stiffness and experimentally measured strength.

Methods

Seventeen vertebral bodies in a previous study that were QCT scanned and then tested in compression past their ultimate point were selected for use in this study (see Ref. [13] for details). Prior to the testing, quantitative computed tomography scans (GE 9800; General Electric, Milwaukee, WI, U.S.A: 140 kV, 70 mA, 1.5 mm slice thickness, bone algorithm) were taken of the vertebral bodies held in an acrylic fixture and submerged in a water-filled container approximately the size of a human torso. A liquid K$_2$HPO$_4$ calibration phantom (Mindways Software, Inc., San Francisco, CA) was located in the prospective image field of view. Retrospective images were constructed from the prospective images at 0.25 mm/voxel in-plane resolution, 256×256-pixel field-of-view, and 1.5 mm slice thickness. To provide clinical measures of bone density for osteoporotic classification, an average value of trabecular bone mineral density of each vertebra was calculated according to typical clinical protocols using commercial densitometry software (QCT PRO, Mindways Software, San Francisco, CA).

For biomechanical testing, the vertebral bodies were molded to endplates using a 1–3 mm layer of polymethylmethacrylate (PMMA). The specimens were loaded in compression at a rate of 0.15 mm/sec between the platens of a screw-driven load frame (Instron Corporation, Model 5583, Canton, MA) and displacement, strain, and load were recorded for each specimen. Experimental stiffness was defined as the maximum slope in the load-displacement curve over a sliding range of 0.2% strain. No adjustments were made to the experimentally determined stiffness and strength values as a function of minor differences in the strain rate between tests because the effect was determined to be negligible (<1%) [14].

Preliminary analysis showed that the model stiffness values were highly sensitive to element size when the vertebral bodies were misaligned by more than 15 degrees along the cranio-caudal axis during QCT scanning. Two vertebral bodies exceeded this level of misalignment and their model data were excluded from these results. The QCT file of one vertebral body was corrupted and no model data were generated for this specimen. Thus, data from 14/17 vertebral bodies were analyzed further (L1–L4; age: 37–87; M=6, F=8). Six of the 14 vertebral bodies that represented a range of experimentally measured stiffness values (L1–L3: age: 70–80; M=4, F=2) were selected for use in addressing the first objective whereas all 14 specimens were used for the second objective.

A semi-automated segmentation technique was developed to isolate the vertebral body from the surrounding water in each QCT image. A rectangular area of water surrounding the vertebral body was manually selected (NIH Image, Version 1.62, NIH, Bethesda, MD) and the mean and standard deviation of the Hounfield unit (HU) value in the region were calculated. The QCT image was then thresholded at one standard deviation below the mean value, and the edge of the vertebral body was traced automatically using an outlining tool. Each voxel in the QCT data was converted from HU to a QCT mineral density value ( Dit, Version 5.4, Research Systems, Inc., Boulder, CO) using a scan-specific linear regression of the calibration phantom mineral density values. The resulting mineral density data were averaged to establish a single mineral density value for each element over 1×1×1.5 mm$^3$ volumes, the latter dimension corresponding to the slice thickness.

Custom code was written to automatically generate a mesh for the vertebral body using eight-noded brick elements (Fig. 1). A thin layer of PMMA (0–2 voxels high) was modeled on the superior and inferior endplates to mimic the experimental conditions (E = 2500 MPa; ν=0.3 [15]). QCT mineral density values of each voxel ($\rho_{\text{QCT}}$, g/cm$^3$) were converted into a longitudinal (or axial) compressive modulus ($E_{z\z}$, MPa) using the following [16]:

$$E_{z\z} = -34.7 + 3230\rho_{\text{QCT}}.$$  (1)

Any negative values in $E_{z\z}$ (caused by regions of air or fat) were set to 0.0001 MPa, and the remaining engineering constants were then assigned using assumptions of transverse isotropy [17,18]. The Poisson’s ratio $\nu_{yz}$ denotes the strain in the $y$ direction divided by the strain in the $x$ direction in response to a load in the $x$ direction:

$$E_{xx} = E_{yy} = 0.33E_{z\z},$$  (2)

$$\nu_{xy} = 0.381,$$  (3)

$$\nu_{xz} = \nu_{yz} = 0.104,$$  (4)

$$G_{xy} = 0.121E_{z\z},$$  (5)

$$G_{xz} = G_{yz} = 0.157E_{z\z}.$$  (6)

The strong correlations between vertebral trabecular bone modulus, yield stress [19,20], and strength [19,21,22] and the reduced computer processing involved in linear finite element models led us to use whole vertebral stiffness as a surrogate for whole vertebral strength. The superior surface of the model was subjected to a uniform vertical displacement and constrained from any displacement in the lateral directions. The inferior surface was constrained in all degrees of freedom. A linear analysis (ABAQUS, Version 5.8, HBK, Pawtucket, RI) was used to compute the whole vertebral stiffness—calculated as the resultant force on the inferior surface divided by the applied displacement.

Similar procedures were repeated for in-plane resolutions of 2×2, 3×3, and 4×4 mm$^2$ at slice thickness values of 1.5 and 3 mm for the six aforementioned vertebral bodies. An analysis of covariance was conducted with whole vertebral stiffness as the dependent variable; resolution and slice thickness as continuous variables; and donor as a categorical variable (IM, Version 5, SAS Institute Inc., Cary, North Carolina).

Regions of damage were quantified based on element-level strains [23,24]. The average principal strains were calculated in each element for the applied load that produced an overall strain on the vertebral body of 0.50%. A failure threshold was defined as a principal strain exceeding either 0.70% in tension or −0.77% in compression based on reported yield strains for human vertebral
trabecular bone [20]. A failed or damaged element was defined as one in which either the maximum or minimum principal strain exceeded the established failure threshold. The percentage of failed elements in the six aforementioned vertebral bodies was compared at “high” resolution (1×1×1.5 mm element size) versus “low” resolution (3×3×3 mm) using a paired t-test.

Whole vertebral body stiffness values were computed for the complete data set of vertebral bodies (n=14) at both the low (3×3×3 mm) and high (1×1×1.5 mm) resolutions. A linear regression was conducted between these stiffness values and the experimentally measured fracture strengths.

Results

The analysis of covariance indicated that in-plane resolution (p<0.0001), slice thickness (p=0.0036), and donor (p<0.0001) possessed significant effects on finite element model stiffness. A positive linear correlation was identified between in-plane resolution and stiffness for all of the vertebral bodies at both slice thickness values (0.90<r²<0.99; p<0.05; Fig. 2). The slope of these relations at 1.5 mm slice thickness was on average 33% greater than the slope at the corresponding 3.0 mm slice thickness.

The percentage of failed elements in the high-resolution model at loads corresponding to a total strain of 0.5% was 3% greater (n=14, p=0.01; paired t-test) than in the low-resolution model. Strain values were relatively uniform throughout the central portion of the vertebral body (Fig. 3a). Toward the top and bottom endplates, elements representing the shell of the vertebral body frequently demonstrated low strain because the curvature of the vertebral body resulted in the loss of a continuous vertical load path for those elements. The highest stresses typically occurred in those elements that formed the first complete endplate-to-endplate vertical column nearest to the vertebral body shell because they possessed the largest moduli due to their higher densities (Fig. 3b). Elements that exceeded the assumed failure criterion did so almost exclusively by exceeding the principal strain in compression (Figs. 3c and d).

For all 14 vertebral bodies, the experimentally measured vertebral body ultimate strength was highly correlated with the finite element model-predicted stiffness for the both the high and low resolution models (high: r²=0.94; low: r²=0.92; Fig. 4). One vertebral body had severe osteophyte formation and demonstrated a substantially higher ultimate strength than the other 13 vertebral bodies (15,906 N versus 2,004–8,126 N). A separate stiffness-strength regression conducted without this specimen still resulted in strong correlations (high: r²=0.82; low: r²=0.76; Fig. 4). For all models, the stiffness at low resolution (3×3×3 mm³) was on average 4% greater (p=0.05; paired t-test) than at high resolution (1×1×1.5 mm³); by contrast, stiffness varied over fourfold across specimens.

The mean (±SD) QCT bone mineral density was 87±36 mg/cm³ (range: 31–164 mg/cm³) with 10 of the 14 specimens possessing values below the clinical fracture threshold of 110 mg/cm³ [25]. Thus, the range from 31–164 mg/cm³ represents bone mineral density values that span from osteoporotic individuals with high probability of fracture to the young normal range.
Discussion

We sought to determine the effects of element size on the output of voxel-based finite element models of the human vertebral body and to assess the potential of this technology for predicting vertebral strength. As in previous studies [7,8], we found that the numerical convergence characteristics depend on the choice of output parameter. Element size can significantly affect the amount of damage that the voxel-based model predicts. By contrast, the effect of element size on vertebral stiffness, on average only 4% over the range of sizes studied here, was negligible compared to the observed fourfold variation across specimens. As such, these results indicate that cross-sectional studies of whole vertebral body stiffness will not be significantly influenced by the choice of voxel size in the range studied here. However, the small but systematic difference in stiffness values necessitates that longitudinal studies utilize identical voxel sizes if they are to have the ability to track the subtle changes in the bone properties that can occur over time in a given individual—changes that sometimes involve fractures of a percent [26]. Taken together, these results suggest that consistency of voxel size is more important than the choice of any specific size. Regardless of element size studied, the models prospectively predicted vertebral strength in an excellent manner for the specified boundary conditions, indicating that voxel-based finite element modeling may be an excellent tool for noninvasive assessment of vertebral strength.

This study contains several features that support these conclusions. First, multiple vertebral bodies that included osteoporotic and nonosteoporotic donors as defined by a clinical bone mineral density criterion were used. The trends were consistent across the specimens and thus we expect these results to be quite general. Second, the model used material properties for the trabecular bone that were measured without end artifacts [27] and also accounted for material anisotropy. Even though we did not model the shell explicitly, the excellent correlation with experimental strength indicates that such explicit modeling may not be required. Third, comparisons of model stiffness versus measured strength were truly predictive in that no calibration of the model was performed. Thus, the predictive abilities of the model for strength are well validated.

Despite these strengths, there are some caveats. First, even though this study establishes important numerical convergence characteristics of voxel-based models, the repeatability of this modeling technique was not investigated. A study of a similar modeling technique applied to the femur found the variation and repeatability of the technique to be similar to that for QCT bone mineral density of the femur [28]. The 0% difference in stiffness values for over the range of voxel sizes studied here is similar to the 2.6% coefficient of variance that has been reported for QCT bone mineral density of vertebrae in vitro suggesting that voxel-size choice is important in longitudinal studies [29]. Further studies are required to address these issues. Second, the damage regions of the vertebral body were computed using linear analyses. A more accurate damage model would account for the nonlinear, post-yield compressive behavior of bone. However, the use of low level apparent strains minimized the effects of nonlinear material behavior, and the results from the linear model are considered a first-order approximation of damage and damage location. Third, while finite element stiffness was found to be a strong correlate with experimental fracture strength, the correlation of model stiffness with experimental stiffness was not as strong (n = 14: “high” resolution $r^2 = 0.71$, “low” resolution $r^2 = 0.75$; n = 13: “high” resolution $r^2 = 0.45$, “low” resolution $r^2 = 0.53$). This finding is attributed to experimental artifacts that affect strain measurement but not force measurement [22], e.g., end constraint design, system compliance, and inhomogeneous vertebral body strain. Finally, the loads were applied via a polymethylmethacrylate layer and only in compression. In vivo conditions involve an intervertebral disc and perhaps a bending load. While the specifics of convergence characteristics may change with different boundary conditions, we expect that the general trends would persist since the discretization of the vertebral structure would not change.

It should be noted that the density-modulus relationship Eq. (1) was used in this study over a different density range and at a different physical scale from which it was originally developed [16]. The density-modulus relationship was derived from bone volumes of approximately 1000 mm$^3$ (8-mm-diameter specimens) and QCT mineral densities that ranged from 0.015–0.215 g/cm$^3$. It was applied here to element volumes of 1.5–48 mm$^3$ and over densities of 0.000–1.056 g/cm$^3$. While the majority of the element densities fell within the validated range, the percentage of elements falling outside this range increased as the element size decreased, e.g., 19% and 27% of the elements fell outside the validated range in the 3×3×3 mm$^3$ and the 1×1×1.5 mm$^3$ models, respectively. The high correlations observed between finite element model-derived stiffness and measured fracture strength indicate, however, that this modeling approach worked well. Thus, issues related to the continuum assumption do not appear to be important for this application.

Based on the results of this study and others in the literature [2,4,30–33], it now appears that voxel-based finite element models are a powerful research tool for a variety of applications and may well be a superlative tool for noninvasive assessment of vertebral strength and damage. Faulkner et al. [2] demonstrated that voxel-based finite element models of the vertebra showed a greater diagnostic accuracy than traditional QCT methods for separating patients with and without osteoporotic fractures. Homminga et al. [4] used voxel-based models to provide insight into how disc and bone quality may affect loading sharing and damage distribution within the vertebra. Our study complements these efforts by establishing the numerical convergence characteristics of these models and by demonstrating that finite element model-derived vertebral stiffness is strongly correlated with in vitro measures of vertebral body strength. Other studies have demonstrated that QCT voxel-based finite element models of the proximal femur can predict fracture strength better than clinical densitometry.
modalities such as DXA and QCT [30,31]. Given our findings that potential complications with modeling of the shell may not be important in voxel-based modeling of the vertebra, this modeling technique may have great potential for clinical noninvasive assessment of vertebral strength.

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