PREDICTING APPARENT ELASTIC MODULI OF VERTEBRAL CANCELLOUS BONE BASED ON APPARENT MORPHOLOGY: TOWARD PATIENT-SPECIFIC SPINE MODELS

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INTRODUCTION

Biomechanical assessment of the spine is clinically relevant in patients suffering from osteoporosis, disc bulging, degenerative disc diseases, scoliosis, back injuries and back pain. Patient-specific finite element (FE) modeling is a promising technology, which is expected to support clinical assessment of the spine in the near future. In order to allow rapid, robust and economic patient-specific modeling of large spine segments, it is practical to consider vertebral cancellous bone as a continuum material, but the elastic modulus of that continuum must reflect the quality of the patient's cancellous spinal bone. The morphology of trabeculae in vertebral cancellous bone varies considerably between patients, and this manifests in the mechanical properties of their spinal cancellous bone. Nowadays, quantitative computed tomography (QCT) can be performed on clinical CT scanners to determine bone mineral density (BMD) and apparent morphological properties, i.e. apparent trabecular thickness (Tb.Th) and apparent trabecular separation (Tb. Sp) of spinal cancellous bone in patients [1]. The objective of this study was to develop new biomechanical tools for predicting the apparent elastic modulus of cancellous bone (E_{cb}) - which is required in patient-specific continuum FE modeling of the spine - based on current clinical QCT scans.

METHOD

We extracted regression relations of E_{cb} to physiological and morphological properties of trabeculae: tissue BMD, apparent Tb.Th and apparent Tb.Sp, which can all be measured in patients *in vivo* using commercial QCT clinical imagers [1]. The resulting relations allow the determination of the continuum E_{cb} reflecting individual conditions of normal, osteoporotic or hypertrophic cancellous bone for application in patient-specific FE spine modeling. In order to obtain the E_{cb} regression equations, we developed computational orthogonal lattice models of cancellous bone (Fig. 1), which employ the single-trabecula generic 'building block' [2] as the basic structural unit. To analyze lattices of various sizes and with different trabecular qualities, we developed a custom-made FE code (Visual C++ 6, Microsoft Co.), which solves the apparent elastic modulus (E_{cb}) of any cubic orthogonal trabecular lattice under compression loading depending on tissue BMD, apparent Tb.Th, and apparent Tb.Sp. Being ideally orthogonal and under pure compression loading, these lattices best represent vertebral cancellous bone, which closely follow orthogonal paths and which supports mostly compression.

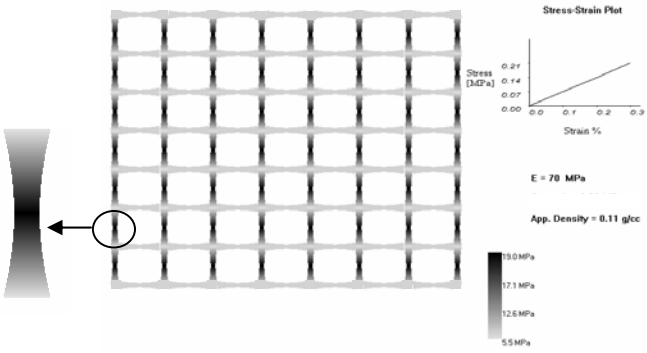

Figure 1. Screen capture from the FE simulations showing principal compressive stress distribution (stress scale at the bottom right) through a cross-section in the lattice, in the direction of loading during a virtual compression test. A single trabecula is magnified to show the stress distribution.

We ran 5000 cases, using cubic lattices that contained 1344 trabeculae. Apparent elastic modulus (E_{cb}) of the lattice was obtained for each computational compression trial. We used multiple linear regression to allow calculation of E_{cb} from Tb.Th, Tb.Sp and tissue BMD, without needing to use the FE model (Fig. 1) directly. For sufficient accuracy, we fitted different regression equations to three thickness ranges. In order to validate the FE model and the E_{cb} regression relations based on that model, we conducted uniaxial compression tests (Instron 5544) on cubic cancellous bone specimens extracted from the C7 vertebra of dogs. Specimens were prepared from

vertebrae frozen immediately after sacrificing the dogs, and thawed to room temperature on the day of testing (less than 3 months from euthanasia). Smooth cubic geometry of the specimens (face length 8-9 mm) was obtained using a diamond coated rotating disk saw (Dremel Co.). Contact surfaces of the specimens were gently lubricated to allow unconfined compression, and a rigid hemisphere was placed above the specimens during the tests to ensure surface parallelism. From each vertebra assigned for compression testing, we also extracted a smaller cancellous bone sample for digital microscopic analysis (magnification X300), to measure the means and standard deviations of Tb.Th and Tb.Sp (for ~30 trabeculae per specimen). We fed the measured apparent Tb.Th and Tb.Sp and their variations (quantified as ±½standard deviation) to the FE lattice model to obtain a confidence interval of predicted E_{cb}, and checked (separately for each specimen) whether experimentally measured E_{cb} fell within the interval of predictions. We also calculated E_{cb} of human vertebral bone using Tb.Th and Tb.Sp reported in the literature [3,4] and compared our predictions with experimental E_{cb} reported for these specimens in the same human studies.

RESULTS

The FE calculations of E_{cb} based on tissue BMD (range: 0.5-0.75 g/cc at intervals of 0.01 g/cc), Tb.Th (70-150 μm at intervals of 5 μm), and Tb.Sp (400-1000 μm at intervals of 50 μm) are shown in Fig. 2. Piecewise-linear (3-segment) regression was fitted to these calculations with sufficiently high correlation ($R^2 > 0.9$), as:

$$E_{cb} = a_1 + a_2 BMD + a_3\left[\frac{\rho_t}{Tb.Sp^2}\pi\frac{(\beta - 2\cdot Tb.Th)^2}{4\gamma(1+\alpha)^2}(11\gamma + \sin 2\gamma - 12\sin\gamma)\right] \quad (1)$$

$$\gamma = \cos^{-1}\left[\frac{1}{2}\left(3 - \alpha - \frac{\beta(1+\alpha)}{2Tb.Th - \beta}\right)\right]$$

where the trabecula curvature constants are α=1.3736 and β=40.9 μm [2], the tissue density of trabeculae is ρ_t= 1.99 g/cc, and the regression coefficients a_1, a_2 and a_3 depend on the Tb.Th regression segment as detailed in Table 1. Comparison of E_{cb} regression calculations (Eq. 1) to direct FE modeling (Fig. 2) shows very good visual agreement and regression errors not exceeding 12%.

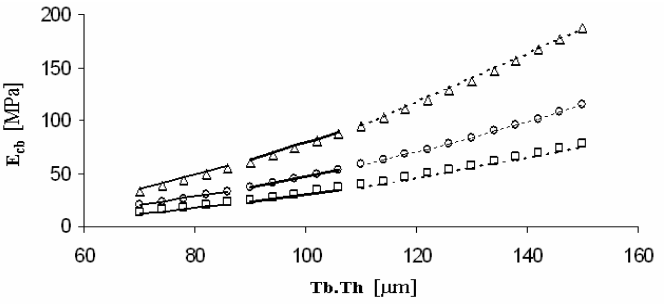

Figure 2. . Regression (lines) and direct finite element (FE) calculations (marks) of E_{cb} versus Tb.Th. FE calculations are shown for a mean value of vertebral Tb.Sp = 700 μm (○), mean Tb.Sp + standard deviation = 850 μm (□) and mean Tb.Sp – standard deviation = 550 μm (Δ).

Table 1. Coefficients of the E_{cb} regression (Eq. 1)

Tb.Th [μm]	a_1 [MPa]	a_2 [MPa·cc/g]	a_3 [MPa·cc/g]
70-90	-55.01	80.95	643.08
90-110	-89.44	136.84	639.02
110-150	-165.4	258.1	645.8

Table 2. Comparison of experimental to model-predicted apparent elastic moduli of vertebral cancellous bone

	Mean **Tb.Th** (SD) (from Microscopy) [μm]	Mean **Tb.Sp** (SD) (from Microscopy) [μm]	Measured E_{cb} (Comp. Tests) [MPa]	Predicted E_{cb} (Regression) [MPa]	Predicted E_{cb} (Direct FE) [MPa]
Dog #1	175.8 (37.5)	482.96 (110.5)	218	225-531	216-540
Dog #2	110 (29.25)	367.29 (92.1)	148	144-370	122-364
Dog #3	150 (37.12)	475.41 (124.5)	128	158-421	146-427

Comparison of model-predicted E_{cb} to experimentally-obtained E_{cb} in 3 dogs (Table 2) shows that generally, measured E_{cb} were within the range of predicted E_{cb}, with tendency of measurements to be close to the lower limit of predicted ranges. Model predictions of E_{cb} are also in good agreement with literature reports of human vertebral cancellous bone morphology and properties. For example, Majumdar [3] found that specimens with Tb.Th=170±20 μm (mean ± SD) and Tb.Sp= 1100±70 μm had superior-inferior E_{cb} of 66±63 MPa under compression, while our Eq. 1 resulted in E_{cb} of 57 ± 30 MPa and direct FE calculation provided E_{cb} of 61 ± 22 MPa. Cendre [4] found that lumbar specimens with Tb.Th=261±43 μm and Tb.Sp=1348±744 μm had E_{cb} of 134 ± 81 MPa, while our Eq. 1 resulted in E_{cb} of 95 ± 31 MPa and direct FE calculation provided E_{cb} of 100±36 MPa.

DISCUSSION

FE modeling is the tool of choice in numerous stress/deformation analyses of musculoskeletal structures. Whole or large segment spine analyses are expected to be introduced for clinical use in the near future, through automatic generation of patient-specific models. Considering spatial resolution of current clinical imaging modalities it seems most practical – at least for the first stage of development of such automatically generated models - to consider cancellous bone as a continuum material. The continuum assumption will allow fast, straightforward FE model construction and robust, economical simulations in the clinical setting. In this abstract, we introduce regression equations generated by numerical modeling, to calculate the elastic modulus of the continuum representing cancellous bone (E_{cb}) in patient-specific spine models, based on physiological (tissue BMD) and morphological (apparent Tb.Th, Tb.Sp) bone properties which can be extracted from clinical QCT scans. When compared with morphological measurements and mechanical property tests performed on the same C7 canine vertebral specimens, our model generally showed good predictive ability. Data collection from additional dogs is currently underway to fine-tune the model parameters.

ACKNOWLEDGMENT

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