A SYNTHETIC MODEL FOR MECHANICAL EVALUATION OF VERTEBRAL BONE

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INTRODUCTION

Biomechanical studies of vertebral compression fractures and cement augmentation typically rely on cadaver vertebrae, which exhibit highly variable structural and material characteristics depending on the age and degeneration of the samples. Moreover, cadaveric specimens are increasingly difficult to obtain in sufficient numbers for statistically valid studies. The goal of this project was to create and mechanically test a synthetic vertebral body using commercially available open-cell foam, which is marketed as a structural analog to human cancellous bone. The open-cell structure allows for cement injection making it a desirable testing material for vertebral cement augmentation studies.

METHODS

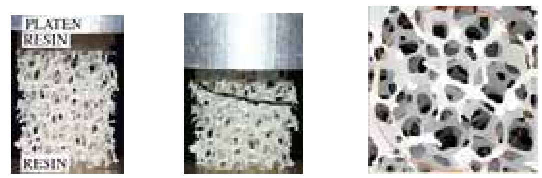
Blocks of open cell foam (apparent density, ρ_a= 0.12 g/cm^3) were obtained from Pacific Research Laboratories, Inc. (Vashon Island, WA). A 9mm foam cube was digitized using a µCT scanner (36 micron voxels). Volume fraction (BV/TV), three-dimensional (3-D) material anisotropy, and standard morphology (Tb.N, Tb.Th, Tb.Sp) were characterized using a proprietary program based on the parallel plate model method [1]. Ten samples of open cell foam were cut into cylindrical cores (12.8 mm diameter by 19.8 mm height) using a brass-coring tool. Using a servo-hydraulic test machine, the cylindrical foam samples were initially subjected to non-destructive uniaxial compression tests under displacement control. Foam specimens were preloaded to 0.5N, preconditioned for 5 cycles to 0.4% strain using a 1Hz sinusoid, and ramp loaded at 0.016 mm/s to 0.8% strain. 1.5 mm thick fiberglass resin end-plates were molded to the top and bottom surfaces of the foam samples (Fig. 1a). The fiberglass resin end-plate was representative of the cortical bone endplate present in vertebral centrum, and served to reinforce the damaged (cut), load-bearing surface of the foam cylinders. Foam+endplate samples were non-destructively tested as described previously, followed by a failure ramp at a rate of 0.016 mm/s.

Stress-strain data were used to obtain the apparent modulus (E_a), 0.2% offset yield stress (σ_y), 0.2% offset yield strain (ε_y), ultimate stress (σ_{ult}), and ultimate strain (ε_{ult}). The apparent elastic modulus was determined over a 0.5% strain range for the non-destructive tests. A paired-observations t-test (POTT) was used to compare the apparent modulus of foam vs. foam+endplate samples.

Table 1: Apparent modulus (mean ± standard deviation) of foam vs. foam+endplate test specimens.

	Open Cell Foam	Foam + Endplates
Modulus E_a (MPa)	4.97 ± 2.13	6.62 ± 3.04*

*no significant difference (POTT, $p > 0.05$)



a) b) c)

Figure 1: a) Foam sample with fiberglass endplates prior to compression; b) Post-yield crush zone (highlighted) is visible ($\varepsilon \sim$ 15%); c) µCT 3-D rendering (9 mm x 9 mm).

RESULTS AND DISCUSSION

The foam specimens consisted of an interconnected network of rods similar in morphology to vertebral trabecular bone (Fig. 1c). Foam samples were characterized as transverse isotropic with a BV/TV, Tb.N, Tb.Th, Tb.Sp of 0.106, 0.280mm^{-1}, 0.378 mm, and 3.20 mm, respectively. Human vertebral cancellous bone is transverse isotropic with similar morphology and has an apparent density ranging from 0.05–0.30 g/cm^3 [2]. The latter corresponds to a volume fraction ranging from 0.03 – 0.156 (assuming a bone tissue density ρ_t = 1.9 g/cm^3). The foam+endplate specimens exhibited a crush or fracture consolidation typical of open-celled materials (Fig. 1b). Addition of the endplate increased the stiffness of the foam cores 33%, but this was not statistically significant (Table 1). Mean ± standard deviation for σ_y, ε_y, σ_{ult} and ε_{ult} were 0.231 ± 0.033 MPa, 3.44 ± 0.72 %, 0.241 ± 0.029 MPa and 3.78 ± 0.74 %, respectively. The ultimate apparent strength and stiffness of similar density vertebral cancellous bone is 0.745 MPa and 12.4 MPa, respectively [2]. The lower values obtained for the foam samples (most likely) reflect the 40% lower tissue density of the foam compared to bone tissue (ρ_t= 0.12 g/cm^3 / 0.106 = 1.13 g/cm^3). Strain values, ε_y and ε_{ult} were also lower than lumbar trabecular bone, which are reported as 6.0% and 7.4%, respectively [3].

CONCLUSIONS

Our results indicate that the synthetic open-cell foam exhibits morphology similar to human vertebral cancellous bone, but has a lower density and concomitant lower strength and stiffness in comparison to human bone. Future work will focus on creation of a synthetic foam wedge fracture and cement augmentation model to study vertebral kyphoplasty.

REFERENCES

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