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FINITE ELEMENT OPTIMISATION TECHNIQUES APPLIED TO HUMAN VERTEBRAL CANCELLOUS BONE

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Abstract

With an aging population lower back pain is a growing concern amongst many people. Recent developments in FE have made possible the simulation of complex geometries, such as trabecular bone. Most current techniques homogenise vertebrae into solids with averaged material properties. This is undesirable as analysis on the effects within trabecular tissue is impossible. As vertebral tissue is highly anisotropic this study investigates the effects on anisotropy when the mesh resolution and orientation are varied. Trabecular cubes were taken from a human donor at different orientations around the medial-lateral axis (0° , 45° , 90°) and tested in all three axes. Prior to testing they were CT scanned (X-Tek), reconstructed (CTPro) for and meshed (ScanIP). The full size scans were linearly downsampled to $32\mu\text{m}$, $50\mu\text{m}$, $64\mu\text{m}$, $128\mu\text{m}$ and $256\mu\text{m}$. Using a power-law based on material properties in the literature ($E=15\text{GPa}$, $\rho=1800\text{ g/cm}^3$ and $\nu=0.3$) each mesh was quasi-statically compressed in all three directions. Our finite-element analysis shows good agreement with the experimental results, showing that a pixel resolution of $64\mu\text{m}$ is good for preserving anisotropy in vertebral bone. This model was further validated against the other models at different orientations also showing a good agreement with the experimental results.

1. Introduction

Low back pain is common amongst the general public. While it has been linked to occupational and accidental damage, either from vibration or impact, the cause has not yet been clearly defined. It is general thought that low back pain is related to structural changes within the vertebrae. As the vertebral body is orthotropic, angle of loading and posture are of critical importance to explore the mechanics of damage (Hinz, Seidel, Hofmann, & Menzel, 2008). Past studies indicate that there is large variation in mechanical properties between the major loading axes of human bone (Uchiyama et al., 2016). It has been demonstrated that bones are mostly orthotropic or transversally isotropic in nature. In this field micro-finite element techniques are of great help (Chen et al., 2014) but in order to

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feasibly analyse a whole spine the spinal segments need simplifying. This paper will examine the effect that μ CT and FE resolution has on the anisotropic structure of vertebral cancellous bone and to develop a generic model to accurately estimate macroscopic stiffness, by selection of Young's Modulus, in cases where the structure (4 samples), the orientation (3 directions) and the axes (3 loading axes) are changing.

2. Methods

A human spine was obtained of the lumber-thoracic region from the NDRI (National disease research interchange, USA) in which all health issues relating to bone were excluded. The spines were stored at -20°C until thawed at room temperature for dissection. Vertebral testing cubes were obtained from the spine at varying angles (0° , 45° , 90°) rotated clockwise around the medial-lateral axis. After sample preparation the cubes were stored in ringer's solution until CT and mechanical testing. A CT scan was made of each cube, prior to mechanical compression testing, using an X-Tek μ CT. ScanIP software (Simpleware) was then used to downsample the CT data as a basis to create tetrahedral FE meshes. The voxel resolutions meshed were $32\mu\text{m}$, $50\mu\text{m}$, $64\mu\text{m}$, $128\mu\text{m}$ and $256\mu\text{m}$. For examining, two masks were created. One was a threshold of the bone tissue and the other was a filler material to preserve sample continuum and allow FEA. The material properties for the bone tissue were taken from the literature as follows; $E=15\text{GPa}$, $\rho=1800\text{ g/cm}^3$ and $\nu=0.3$. The second mask had material properties of; $E=1\text{KPa}$, $\rho=1\text{ mg/cm}^3$ and $\nu=0.3$. For the FE at different orientationssamples at a voxel size of $0.64\mu\text{m}$ at varying Young's modulus of 12, 15 and 18 GPa. Multiple models were made to find the point at which the model best fitted the experimental results.

3. Results

Structural direction has previously been shown to have an effect on mechanical properties (Rapillard, Charlebois, & Zysset, 2006). Our tests (Figure 1) demonstrate that high resolution small element size FE models express anisotropy in all 3-axis, whereas models with larger element sizes fail to capture anisotropy accurately, i.e. For an FE resolution above $256\mu\text{m}$. Results applying this method to the other samples (T10, T11, L4) have shown that it is possible to predict sample stiffness values in three orthogonal directions by tuning the assigned bone material modulus values within (Table 2 and Figure 2). Agreement in all three axes can be further improved by changing other material parameters, or refining the micro-finite element approach (mesh size, thresholds and boundary conditions).

Table 1: Mesh resolution comparison

T10		
Pixel size (μm)	Connectivity	BV/TV
32	4044.5	0.126
50	3536	0.125
64	3442.75	0.138
128	2595.75	0.16
256	1129.625	0.155

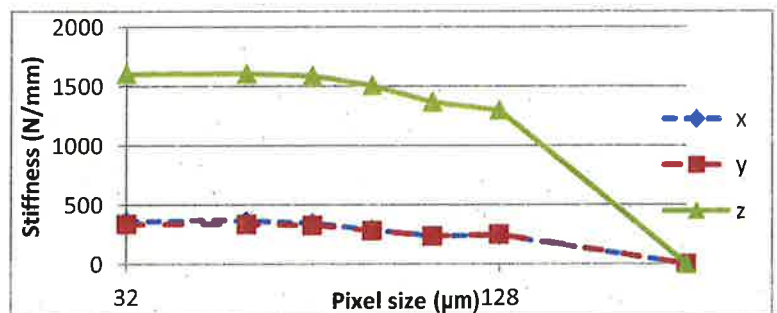


Figure 1: Stiffness against mesh resolution in 3 direction

Table 2: Stiffness comparison in relation to anisotropy

Sample	T10		T11		L4 Right		L4 Left	
Type of test	Exp	Fea	Exp	Fea	Exp	Fea	Exp	Fea
Z Direction	1250	1296	270	249	450	460	150	149
Y Direction	330	240	305	349	350	366	210	191
X Direction	370	249	1280	1350	650	526	165	170
Z difference	1.04		0.92		1.02		0.99	
Y difference	0.73		1.14		1.05		0.91	
X difference	0.67		1.05		0.81		1.03	

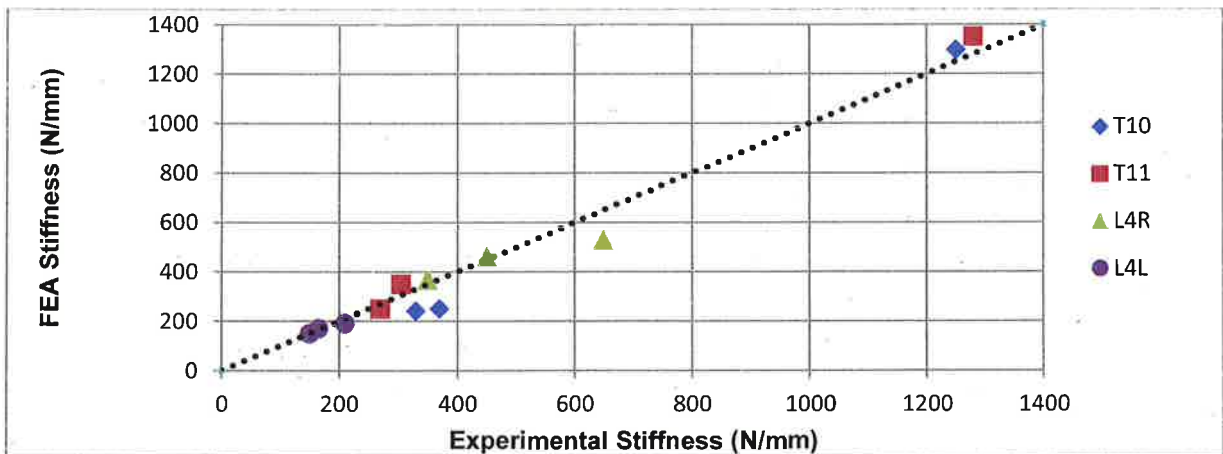


Figure 2: Experimental stiffness against Finite-Element Stiffness

4. Conclusion

Microfinite element models are powerful tools for predicting and modelling biological structures but suffer from complexity, namely they are resource intensive and time consuming. By comparison homogenised models of structures with uniform properties are simpler, faster and less expensive, however, they lack the fidelity and specificity that μ FE offers. This can be mitigated by assigning axial material properties on the mesh in order to preserve the multi-axial mechanical properties of cancellous bone. Vertebral cancellous bone is also orthotropic and computational predictions in all directions prove to be very challenging. Further work into material property assignment based upon CT data and non-linear material properties is needed to create unbiased and autonomous FE models for trabecular bone.

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