HAVERSIAN CANAL STRUCTURES CAN BE ASSOCIATED WITH SIZE EFFECTS IN CORTICAL BONE

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ABSTRACT: Prediction of periprosthetic failure may be improved by an improved model of bone elasticity which includes microstructural information. Micropolar theory facilitates such information to be included in a continuum model. We assessed the extent of bone's micropolar behaviour in bending both numerically and experimentally. The numerical model was consistent with micropolar behaviour, and experimental results exhibited size effects that may have been confounded by surface roughness effects, as predicted numerically.

1. INTRODUCTION

Cortical bone is a heterogeneous material consisting of a hierarchical microstructure characterised by fibrous, porous and particulate features. This microstructure determines the macroscopic material properties. Bone and prostheses are typically modelled using classical continuum elasticity, however, the lack of microstructural characterisation of bone may not adequately describe periprosthetic stress concentrations, with associated with periprosthetic fractures [1]. A material model which incorporates microstructural features may more accurately describe the material response in these critical loci [2].

Micropolar materials exhibit a size effect in bending or torsion tests, in which smaller specimens are relatively stiffer and, importantly, cortical bone has previously been shown to follow trends associated with micropolar behaviour [3]. We aim to include idealised Haversian canal structures into a FE model of bone to numerically assess potential size effects in three point bending and to compare it with experiments on bone.

2. METHODS

Finite Element (FE) modelling (ANSYS 12.1) was used to create an array of regularly repeating voids in beams with and without surface perforations, crudely mimicking cortical bone's Haversian canal microstructure (Figure 1a). Surface semi-cylindrical voids were reduced in diameter with respect to the internal void size whilst maintaining a constant surface void volume. This was done to assess the effect of surface roughness, as a result of sanding and polishing and inherent Haversian canal structures, on the mechanical behaviour of the model. By applying three-point-bending loading constraints the stiffness of the beam was determined over a range of depths, evaluating the size effect of the material.

The fundamental behaviour of the FE model was compared to experimental data. Three specimens were excised, under irrigation, from each of five bovine femur mid-diaphyses and sanded and finally polished using 800 grit SiC paper to approximately 50mm in length and 5mm in depth and breadth aligned with the length along the long axis of the diaphysis. Each sample was subjected to three three point bend tests (Bose Electroforce 3200) to 1% surface strain under displacement control at 0.005 s^{-1}. Load was measured using a 450N load cell. Subsequently, each specimen was reduced in size by further sanding and polishing to a depth of 4mm and the three point bend test repeated. The length:depth ratio was maintained at 10:1 for all tests. This was repeated for approximate depths of 3, 2, 1.5, 1.2 and 0.9 mm. In accordance with micropolar theory, the variation in bending stiffness was determined with respect to 1/depth^2. Specimens from four bones were tested in a saline bath, whilst specimens from one bone were tested after drying for 24 hours at 100°C.

3. RESULTS

Numerically, the idealised porous heterogeneous material demonstrated micropolar behaviour in 3-point-bending with a size stiffening effect with decreasing depth. The micropolar characteristic length in bending was found to be dependent on the void arrangement and size. In models with voids perforating the surface, an anti-micropolar size softening effect was observed. Models with reduced surface perforation size initially displayed size stiffening with decreasing size and then size softening with a further reduction in specimen size.

Experimentally, the wet and dry specimens behaved differently: dry specimens showed initially increased in stiffness with decreasing size with subsequent softening on continued size reduction, whilst wet specimens showed an anti-micropolar trend followed by subsequent stiffening on further specimen reduction.

4. DISCUSSIONS

Size effects consistent with micropolar theory have been observed numerically: with a perfectly flat surface longitudinally aligned “canals” are associated with a stiffening of the tissue with a reduction in sample size. Furthermore, the characteristic length (one of the four additional micropolar parameters) was found to be of the order of the canal diameter. Numerical results further suggest that, as specimens decrease in size, the effect of surface imperfections due to Haversian canal structures or polishing marks will increase, reducing the stiffness of the material.

The experimental protocol, which repeatedly using the same specimen at low strains to investigate size effects, reduced the variation associated with intra and inter bone variation. Also, the strain rates applied to the bone specimens were fast in order to avoid viscoelastic effects. The experimental data from the dry bone, at least, in comparison with the numerical data, demonstrate initial micropolar behaviour but also suggest that the degree of surface roughness in the direction of the length of the specimen may be of particular importance to the overall stiffness. The initial anti-micropolar behaviour of the wet bones may have been due to a greater surface roughness. Alternatively, and speculatively, recent work has suggested that initial anti-micropolar behaviour with a reduction in size with subsequent stiffening, may be indicative of surface grooves perpendicular to the long axis of the specimen.

To include microstructural information in models of bone one either needs to specifically model the microstructure and use classical elasticity theory, or determine the additional parameters that would define a continuum non-local material such as a micropolar material. This latter geometrically simpler, but constitutively more complex model would offer computational savings if an appropriate solver was utilised, and may provide a clearer understanding of periprosthetic stress concentrations and stress shielding. However, extracting the necessary parameters experimentally using standard testing regimens may prove problematic due to experimental issues such as controlling surface effects.

5. CONCLUSIONS

Size effects have been observed both numerically and experimentally and both have been potentially affected by surface roughness effects. The major microstructural unit, the Haversian canal and surrounding osteon, may be responsible for these size effects. However, surface roughness due to preparatory techniques may produce experimental artefacts that are of the same order of magnitude as the micropolar effects thereby obscuring and confounding experimental interpretation.

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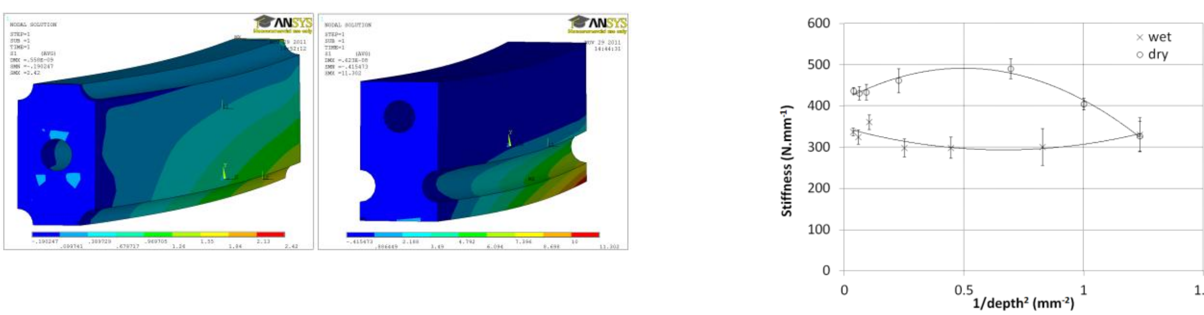

(a) (b)

Figure 1 – (a) Numerical repeating unit with and without surface perforations
(b) Experimental variation in stiffness with 1/depth^2 for experimental data (wet n=12, dry n=3)

7. REFERENCES

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