Investigating the Structure of Trabecular Bone

Isobel Sands, supervisor Prof. Chris Burgoyne

UNIVERSITY OF CAMBRIDGE

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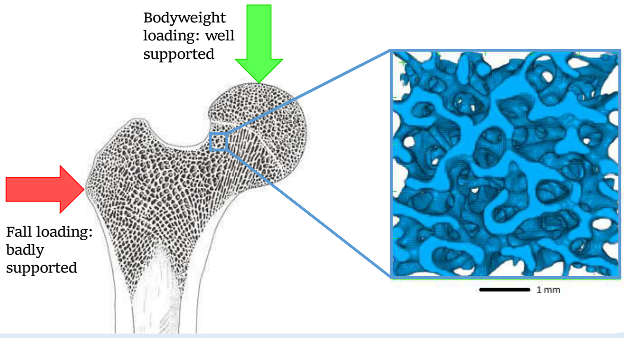
Hip Fractures are Common and Dangerous

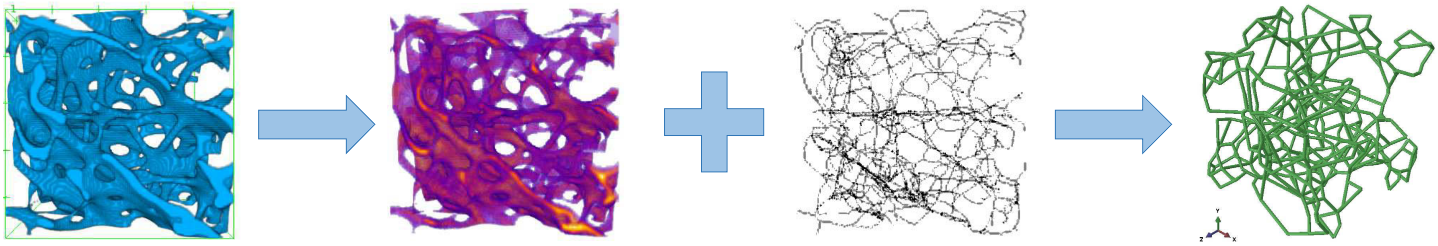
The femoral head is composed of dense cortical bone supported by spongy trabecular bone. Risk of hip fracture increases with age, as the trabecular bone models itself to support vertical loading but becomes worse at supporting horizontal loading. The effects of osteoporosis – severe age-related loss of bone mass – exacerbates this problem.

Clinical diagnosis of fracture risk is based on assessing the overall density of the trabecular bone, which may not account for localised bone loss or account for the structural significance of the lost bone.

Structural analysis of trabecular bone may be more useful.



Simplifying the Trabecular Structure



CT scan — Distance map — Skeleton — Simplified truss

CT scans of human trabecular bone from elderly hip fracture patients, sampled from directly underneath the cortex in an area known for localised osteoporosis, were used. Each scan was reduced to a distance map and a skeletal representation using ImageJ open source software. A line-following algorithm was written to convert this data into a set of distinct pathways.

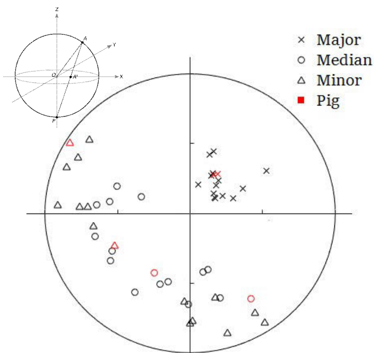
MATLAB scripts then simplified this set of pathways into a truss structure composed of straight cylindrical rods, retaining the structurally significant elements of the bone. This simplified truss structure can be analysed in the finite element program Abaqus, with a computational time on the order of minutes as opposed to hours for a mesh taken directly from the CT scan.

CT scans of trabecular bone were transformed into simplified models suitable for structural analysis.

Finite Element Analysis

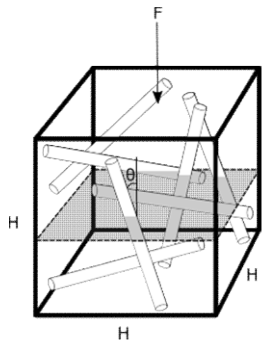
Linear elastic FE analysis was used to find the principal stiffness directions of each sample. Projection onto the unit circle x-y plane shows radial clustering of major axes and median and minor axes (right).

The sample z-axes were perpendicular to the bone surface. The projected radius of major axes (~0.36) corresponds to the vertical, and that of the median and minor axes (~0.47) to the horizontal.



Simplified truss models behaved as expected.

Dimensionless Number Analysis



$$\mu = \frac{1}{H^3}\sum_i \frac{A_i^2}{L_i}\cos^2(\theta_i)$$

$$\lambda = \frac{1}{H^2}\sum_i A_i \cos^2(\theta_i)$$

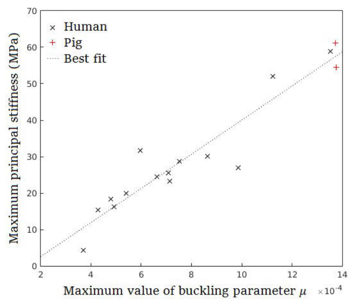
We describe the behaviour of the structure as a sum of the behaviour of its elements. μ represents the buckling resistance, i.e. ***strength***, dependent on element slenderness. λ represents the ***stiffness*** of the structure, dependent on element cross-sectional area.

Model orientation was described without FEA.

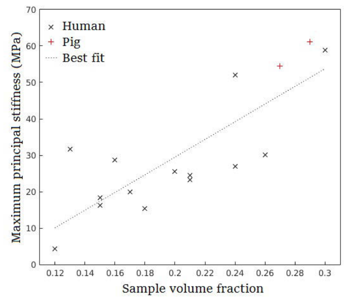
Comparing Structure & Density Correlations

The dimensionless measures μ and λ correlate more strongly with finite element performance of the samples than the local volume fraction of the bone. Not pictured: the correlation between λ and maximum principal stiffness has 95% of the data within 28% of the best fit parameters. This suggests that structural metrics may provide useful information in predicting fracture risk; an approach which could potentially be extended to the analysis of short-fibre composites.

Directions for future work include performing non-linear FEA to account for buckling in the structure, and working with a larger data set including healthy human controls to confirm these findings.



95% within 20% of best fit parameters



95% within 40% of best fit parameters

Orientation-based structural metrics show a stronger correlation with bone stiffness than density-based clinical metrics, and may be useful in predicting fracture risk.