

Fabric-Elasticity Property Relationships of the Human Cortical Femur

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ABSTRACT

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1. Introduction

Bone is a hierarchical material...

1.1. Bone structure

- Bone composition
- Mineralised collagen fibrils
- Lamellar bone
- Osteon
- Cortical bone

1.2. Mechanical testing

- Nanoindentation
- Resonant ultrasound spectroscopy

1.3. Imaging

- Micro-computed tomography

1.4. Bone Properties Estimation

- Micro finite element analysis
- Density and fabric
- Homogenised finite element analysis

The aim of the present study is to investigate the influence of the bone matrix properties and microstructure on the mechanical properties of human bone. The relationships between density, fabric and mechanics are presented from the bone matrix (bone of full density) down to the low density of trabecular bone with a strong focus on the cortical bone. Additionally to relationships description, the objective is to provide material constants for bone properties estimation.

Abbreviations: ROI, region of interest; μ CT, micro-computed tomography;

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2. Material and Methods

2.1. Bone Experimental Properties

Lamellar bone

- Nanoindentation data
- Virtual fabric

Cortical bone

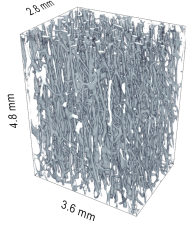
- Samples
- Micro-CT
- RUS data

In the present study:

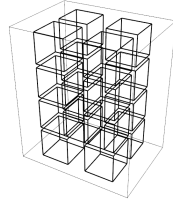
- Downsampling factor 2
- 16x 1mm³ Relationships
- Isotropic vs transverse isotropic material
- Average \mathbb{S} per sample

$$\mathbf{S}_{transverse} = \begin{pmatrix} S'_{11} & S'_{12} & S'_{13} & 0 & 0 & 0 \\ S'_{12} & S'_{22} & S'_{23} & 0 & 0 & 0 \\ S'_{13} & S'_{23} & S'_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S'_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S'_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S'_{66} \end{pmatrix} \quad (3)$$

$$\begin{pmatrix} S_{11} \\ S_{12} \\ S_{13} \\ S_{21} \\ S_{22} \\ S_{23} \\ S_{31} \\ S_{32} \\ S_{33} \\ S_{44} \\ S_{55} \\ S_{66} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 1 & -1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} S'_{11} \\ S'_{12} \\ S'_{13} \\ S'_{33} \\ S'_{44} \end{pmatrix} \quad (4)$$



(a) Typical sample with its porosities



(b) ROIs analysed

2.2. Theoretical Model

- Density-elasticity relationships
- Fabric-elasticity relationships

Proposed Model Hypotheses:

- Cortical bone: $\rho > 0.5$
- Transverse isotropic: $m1 = m2$
- Homogeneous samples: $CV < 0.263$

$$\mathbf{S} = \sum_{i=1}^6 \Lambda_i \mathbf{N}_i \otimes \mathbf{N}_i \quad (1)$$

Project to transverse isotropy

$$\mathbf{S} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{21} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{31} & S_{32} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{pmatrix} \quad (2)$$

Table 1
Nanoindentation - cortical bone matrix properties

Study	E1	E2	E3	Nu12	Nu13	Nu23	Mu12	M13	Mu23
Dall'Ara									
Fanzoso									
Present	14796.9	14796.9	21175.8	0.34	0.284214	0.284214	5521.23	6604.96	6604.96

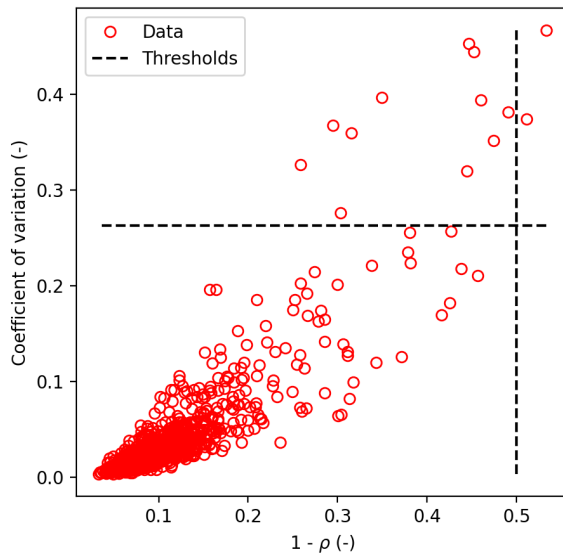


Figure 2: Coefficient of variation as function of porosity

3. Results

3.1. Nanoindentation

3.2. Cortical Bone Morphology

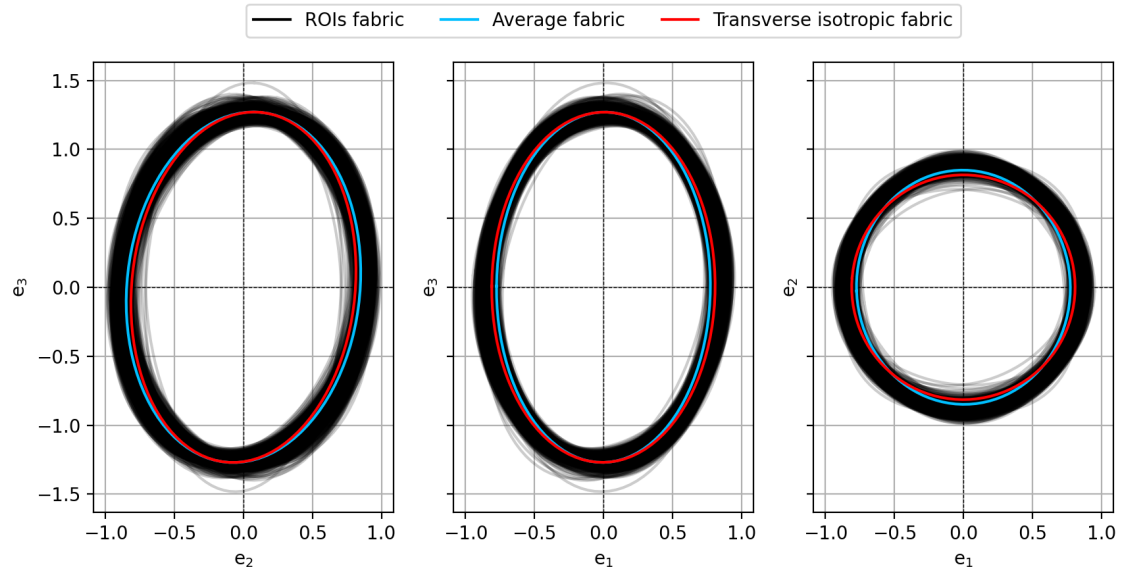


Figure 3: ROIs fabric projected on principal planes

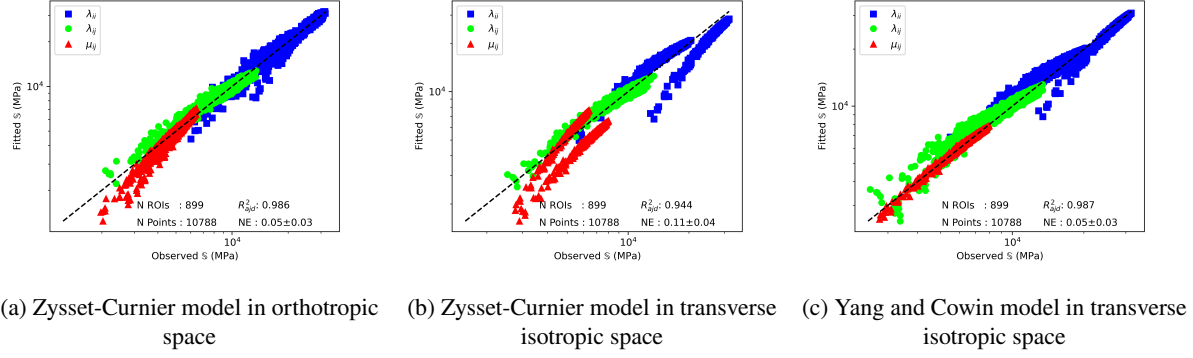


Figure 4: Models fitting results

Table 2

Parameters and fit quality coefficient obtained with the standard Zysset-Curnier model in orthotropic and transverse isotropic space.

Model	λ_0	λ'_0	μ_0	k	l	R^2_{adj}	NE
Orthotropic	19831	12618	3527	2.48	0.57	0.99	0.05
Transverse	17505	13117	4016	2.49	0.39	0.94	0.11

3.3. Fit to model

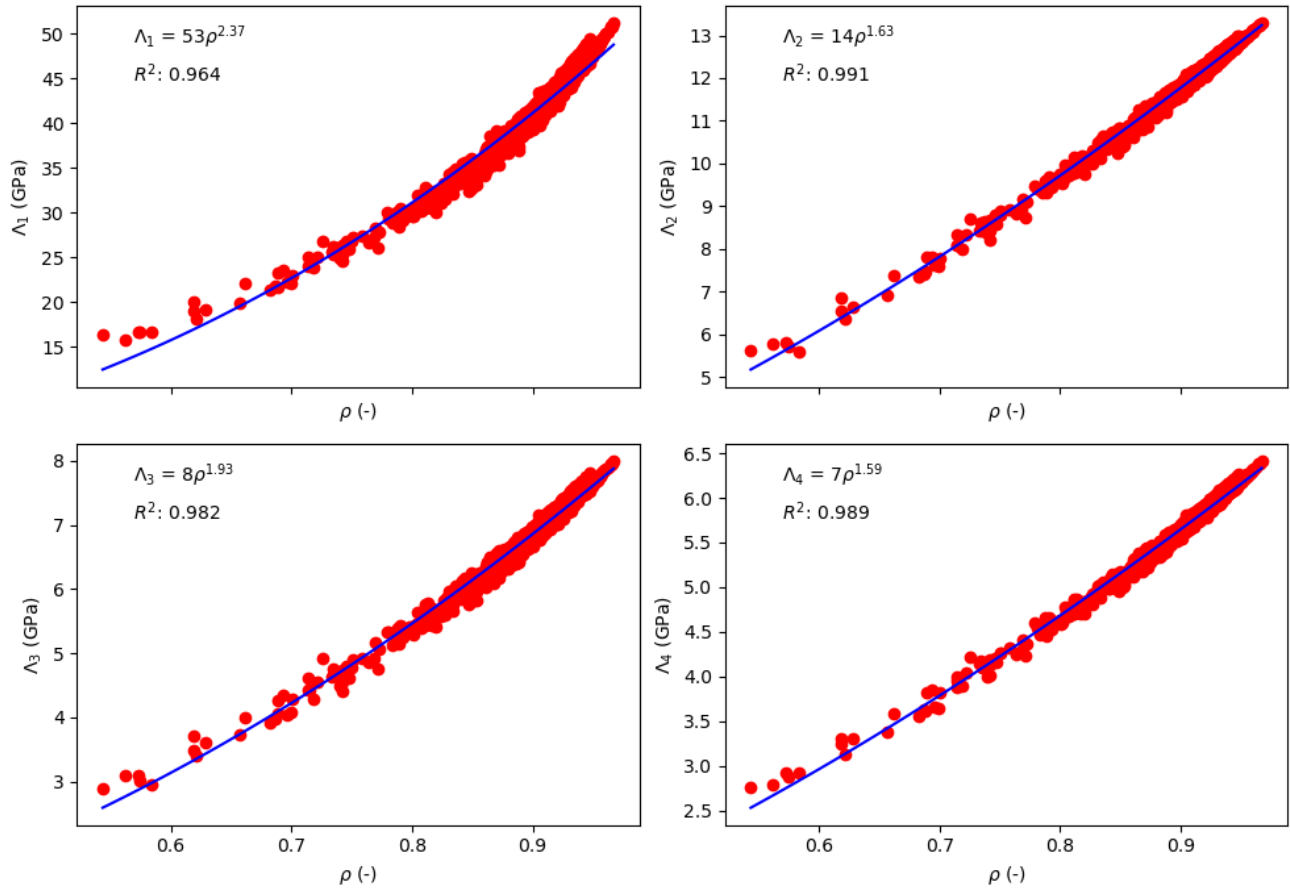


Figure 5: Eigenvalues of the stiffness tensor as function of porosity

3.4. Comparison to RUS

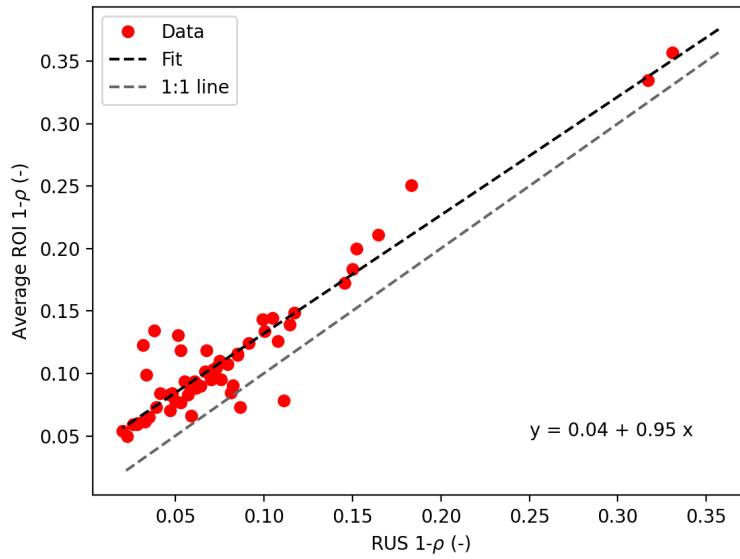


Figure 6: Average ROI porosity vs porosity from Cai et al.

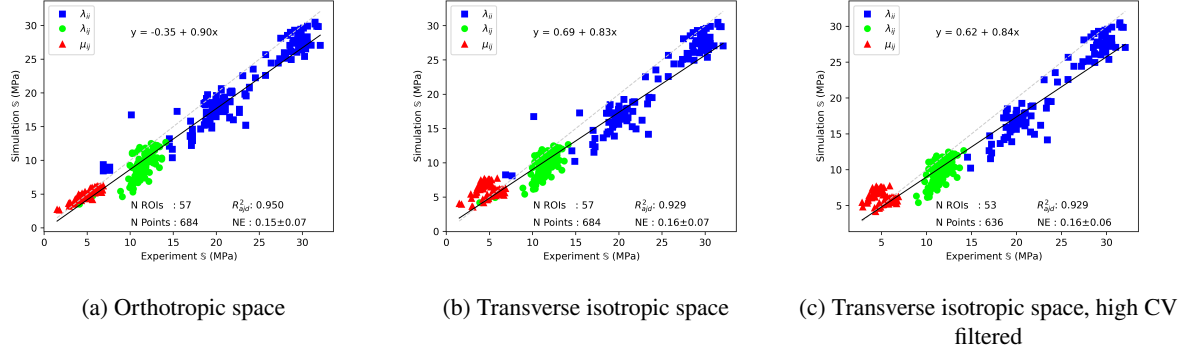


Figure 7: Simulation vs experimental stiffness tensor components

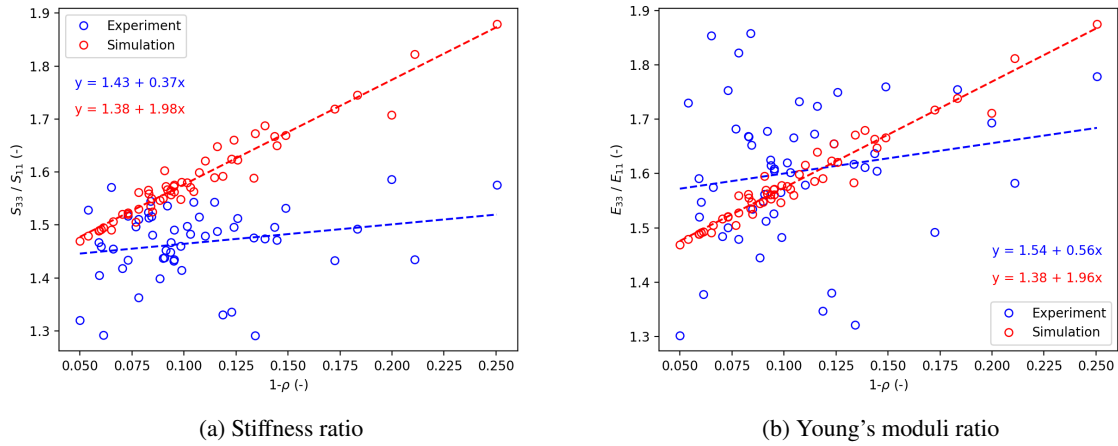


Figure 8: Degree of anisotropy

4. Discussion and Conclusion

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Data availability statement

The data that support the findings of this study are available on request. The data are not publicly available due to privacy/ethical restrictions. The scripts used for the analyses performed in the present study are available on Github: <https://github.com/artorg-unibe-ch/FABTIB>

Research ethics

We further confirm that any aspect of the work covered in this manuscript that has involved human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

CRedit author statement

Mathieu Simon: Data Curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft. **Philippe Zysset:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing - review and editing.

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