Fabric-Elasticity Property Relationships of the Human Cortical Femur

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ARTICLE INFO

Keywords:
Bone
Fabric
Elasticity

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 ojective is to provide material constants for bone properties estimation.

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

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2. Material and Methods

2.1. Bone Experimental Properties

Lamellar bone

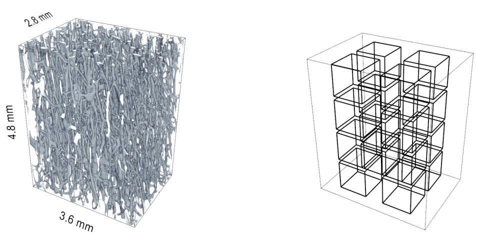
- Nanoindentation data
- Virtual fabric

Cortical bone

- Samples
- Micro-CT
- RUS data

In the present study:

- Downsampling factor 2
- 16x 1mm^3 Relationships
- Isotropic vs transverse isotropic material
- Average $\mathbb{S}$ per sample



(a) Typical sample with its porosities

(b) ROIs analysed

2.2. Theorical Model

- Density-elasticity relationships
- Fabric-elasticity relationships

Proposed Model Hypotheses:

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

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

Project to transverse isotropy

$$\mathbf{S}^T = \begin{pmatrix} S_{11}^T & S_{12}^T & S_{13}^T & 0 & 0 & 0 \\ S_{12}^T & S_{22}^T & S_{23}^T & 0 & 0 & 0 \\ S_{13}^T & S_{23}^T & S_{33}^T & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44}^T & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55}^T & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66}^T \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} S_{11} \\ S_{22} \\ S_{12} \\ S_{21} \\ S_{66} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} S_{11}^T \\ S_{12}^T \end{pmatrix} \tag{3}$$

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

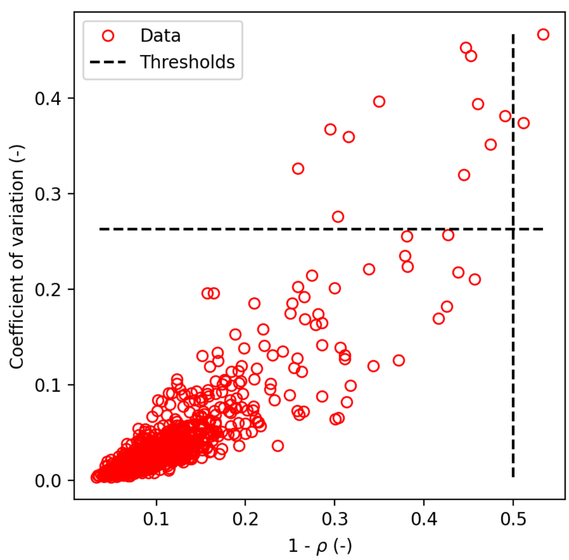


Figure 2: Coefficient of variation as function of porosity

3. Results

3.1. Nanoindentation

3.2. Cortical Bone Morphology

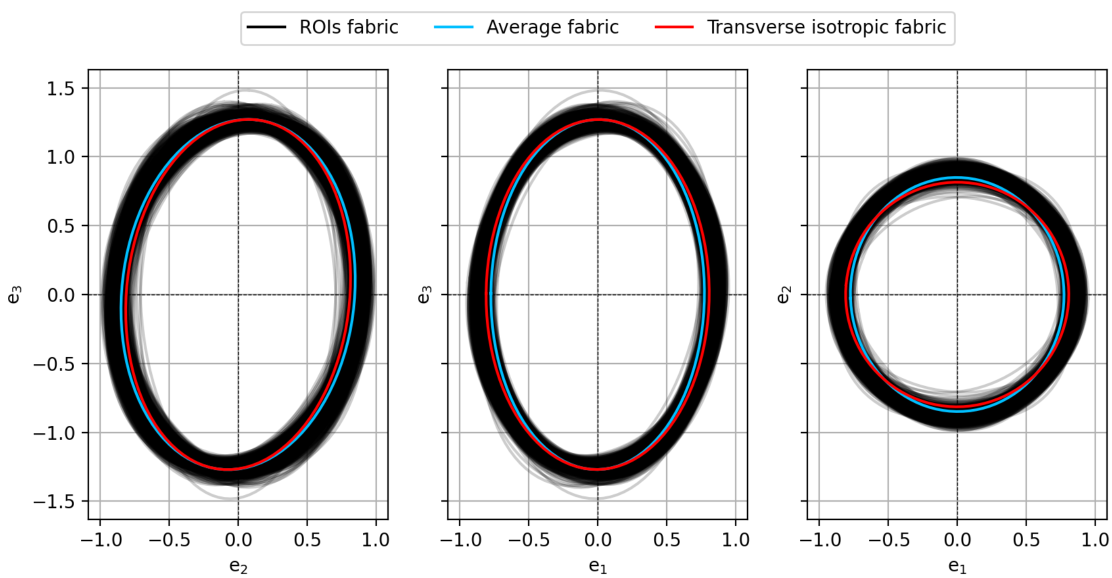


Figure 3: ROIs fabric projected on principal planes

Model	λ_0	λ_0'	μ_0	k_λ	k_μ	l	R^2_{adj}	NE
Standard	19917	12673	3542	2.52	2.52	0.59	0.988	0.04

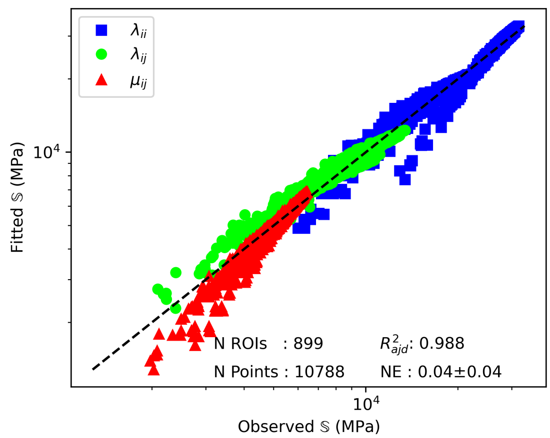


Figure 4: Fit to standard model

3.3. Fit to model

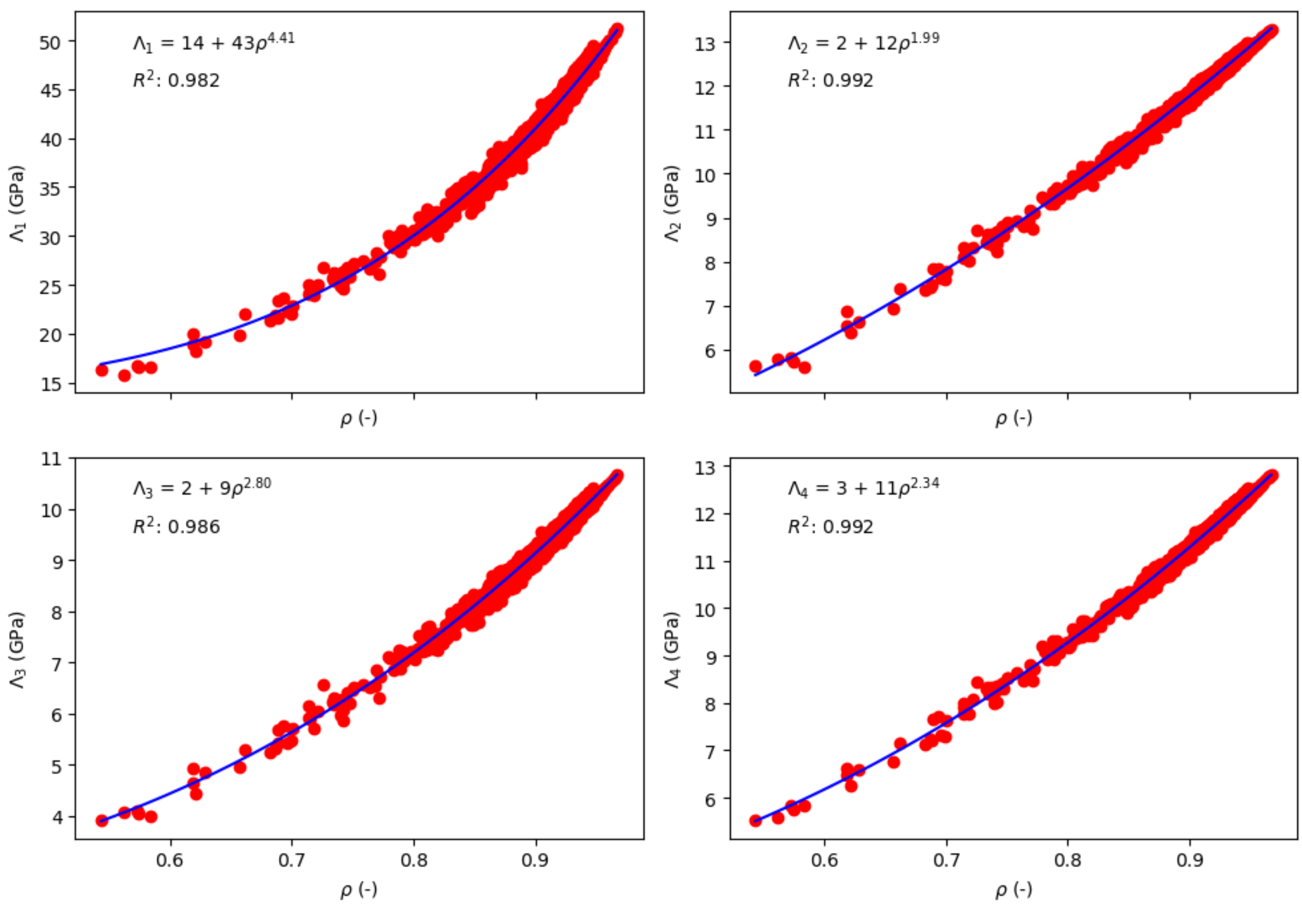


Figure 5: Fit to proposed model

3.4. Comparison to RUS

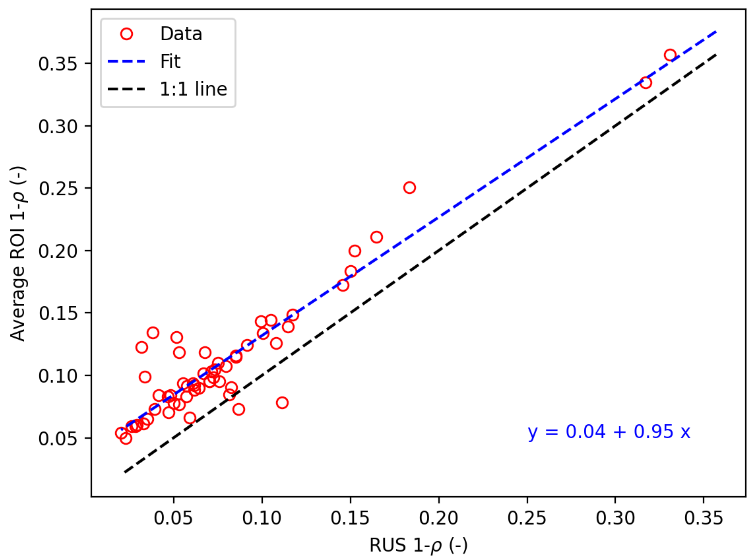


Figure 6: Average ROI porosity vs porosity from Cai et al.

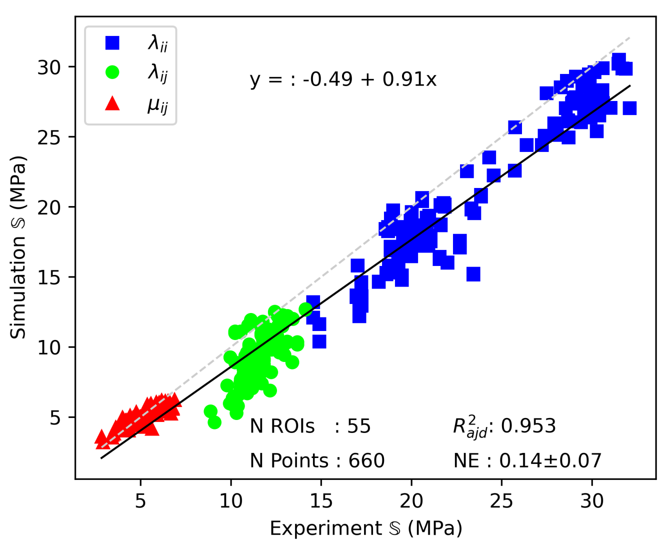
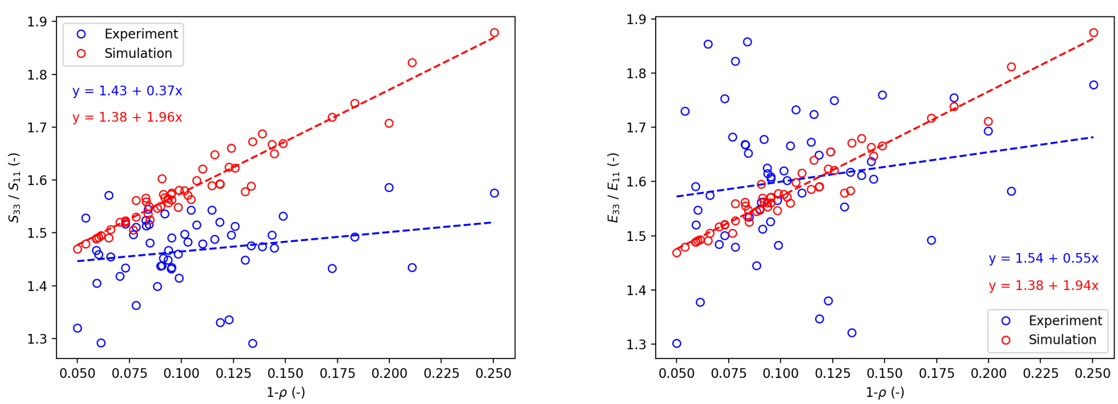


Figure 7: Simulation vs experimental stiffness tensor components



(a) Stiffness ratio

(b) Young's moduli ratio

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.

Funding

This work was funded by the Swiss National Science Foundation (SNSF), grant number 200365.

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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