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
- Trabecula
- Trabecular bone
- Full bone

1.2. Mechanical testing

- Nanoindentation
- Resonant ultrasound spectroscopy
- Full section compression

1.3. Imaging

- Micro-computed tomography
- High-resolution peripheral quantitative computed tomography
- 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. Theorical Model

- Density-elasticity relationships
- Fabric-elasticity relationships

2.2. 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

Trabecular bone

3. Results

3.1. Sample Fabric

3.2. Fit to model

3.3. Comparison to RUS

3.4. Effect of Porosity

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

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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

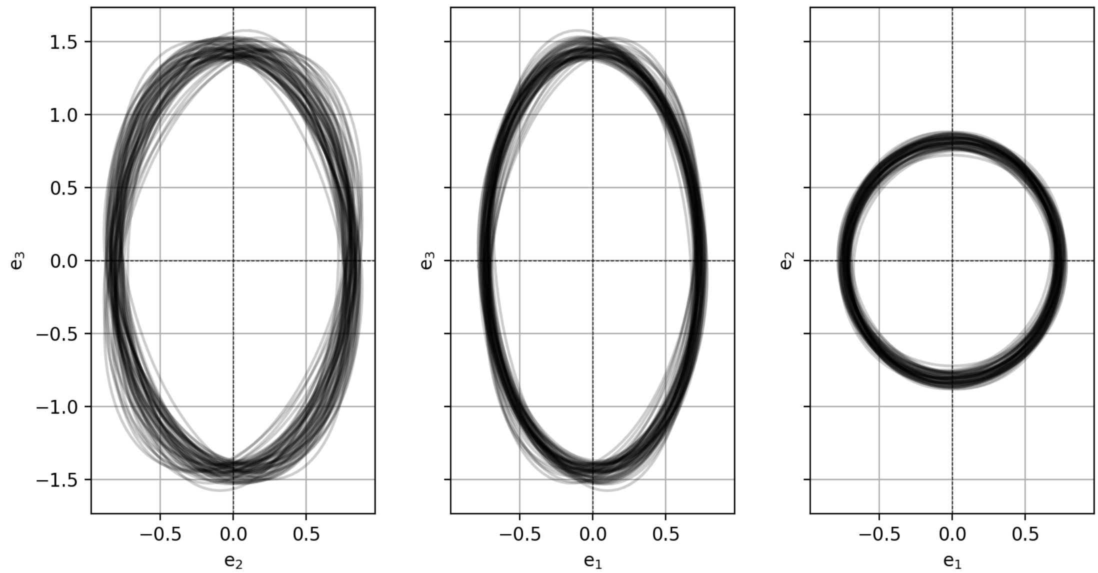
We further confirm that any aspect of the work covered in this manuscript that has involved human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

CRediT author statement

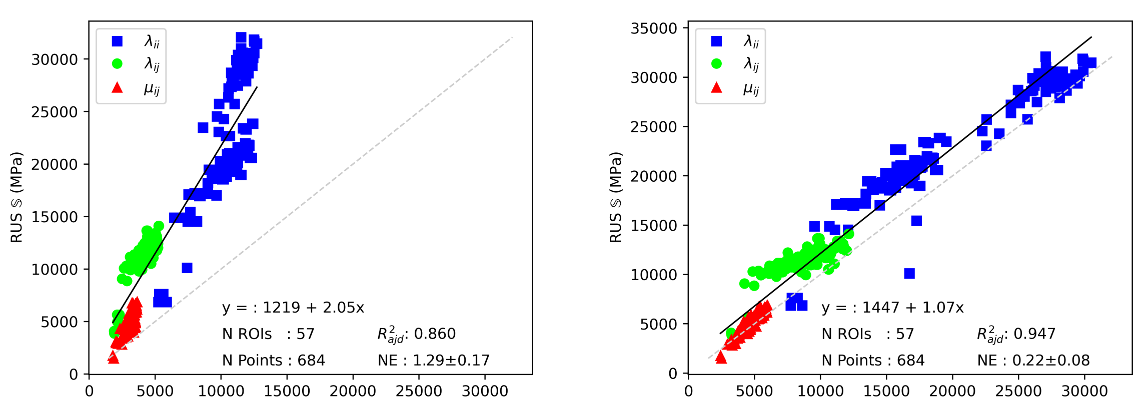
Mathieu Simon: Data Curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft. **Philippe Zysset:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing - review and editing.

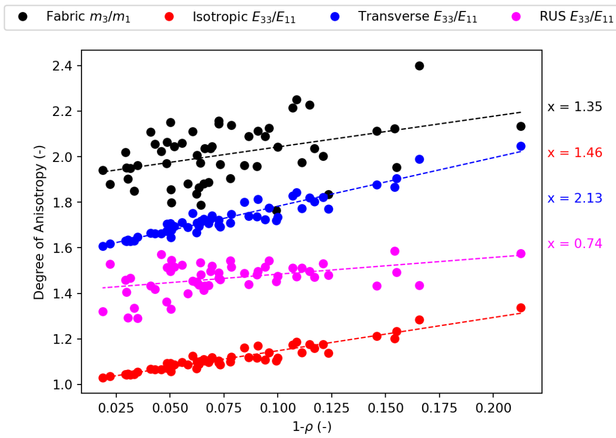
References

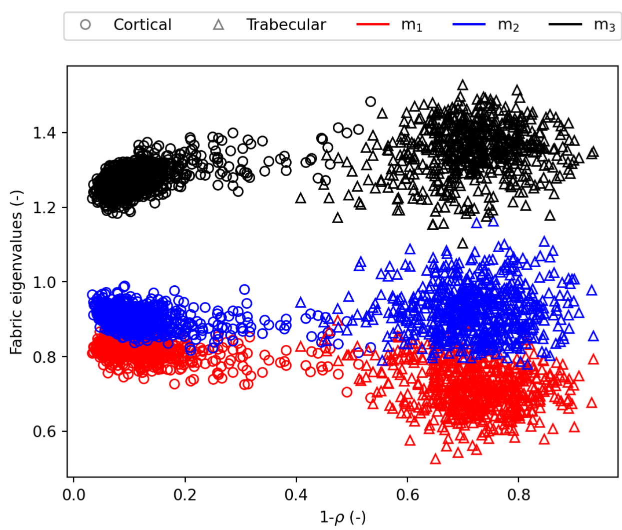
[1] Simon, M., Indermaur, M., Schenk, D., Hosseinitabatabaei, S., Willie, B.M., Zysset, P., 2022. Fabric-elasticity relationships of tibial trabecular bone are similar in osteogenesis imperfecta and healthy individuals. Bone 155, 116282. URL: https://www.sciencedirect.com/science/article/pii/S8756328221004488, doi:https://doi.org/10.1016/j.bone.2021.116282.

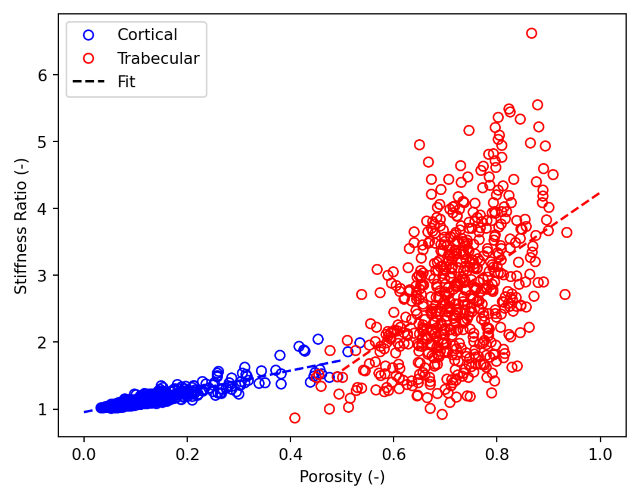


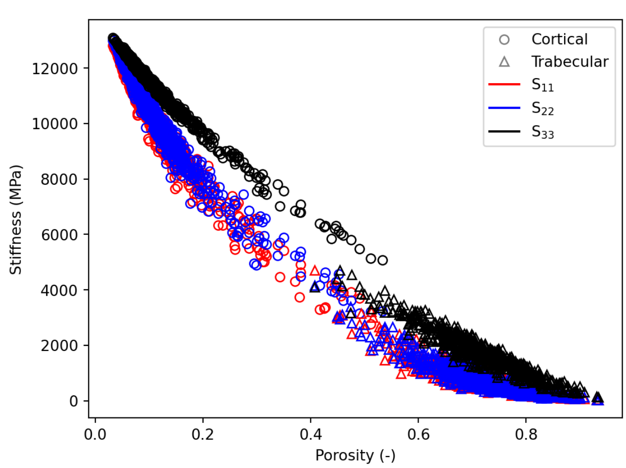
Material	$\lambda 0$	λ'_0	μ_0	k	l	R^2	NE
Isotropic	5170 [4982 - 5359]	5092 [5055 - 5129]	3860 [3825 - 3895]	2.13 [2.07 - 2.18]	0.08 [0.07 - 0.09]	0.99	0.04
Transverse isotropic	11150 [10761 - 11540]	11017 [10921 - 11114]	6158 [6091 - 6225]	2.20 [2.14 - 2.27]	0.42 [0.41 - 0.43]	0.99	0.05
Isotropic	4660 [4385 - 4936]	4590 [4541 - 4638]	3479 [3428 - 3531]	1.0	0.09 [0.07 - 0.11]	0.96	0.07
Transverse isotropic	9978 [9456 - 10504]	9860 [9745 - 9975]	5511 [5422 - 5602]	1.0	0.42 [0.40 - 0.44]	0.95	0.08
Isotropic	5601 [4111 - 7116]	5516 [5227 - 5821]	4181 [3909 - 4472]	2.0 [1.61 - 2.38]	1.0	0.61	0.40
Transverse isotropic	11649 [10266 - 13048]	11511 [11173 - 11858]	6434 [6199 - 6678]	2.26 [2.05 - 2.48]	1.0	0.85	0.25




Fabric m_3/m_1
Isotropic E_{33}/E_{11}
Transverse E_{33}/E_{11}
RUS E_{33}/E_{11}
x = 1.35
x = 1.46
x = 2.13
x = 0.74
Degree of Anisotropy (-)
1-ρ (-)


Cortical
Trabecular
m_1
m_2
m_3
Fabric eigenvalues (-)
1-ρ (-)


Cortical
Trabecular
Fit
Stiffness Ratio (-)
Porosity (-)


Cortical
Trabecular
S_{11}
S_{22}
S_{33}
Stiffness (MPa)
Porosity (-)