DO STIFFNESS GRADIENTS PLAY A ROLE IN THE PROTECTION OF THE TENDON-TO-BONE INTERFACE? A COMPUTATIONAL STUDY

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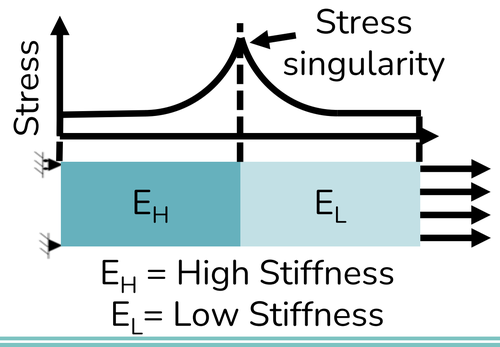
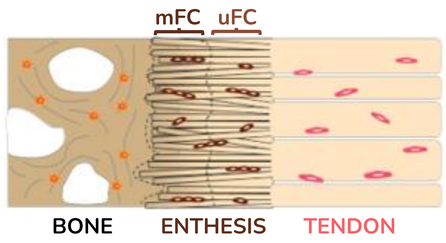
SCAN ME

Introduction

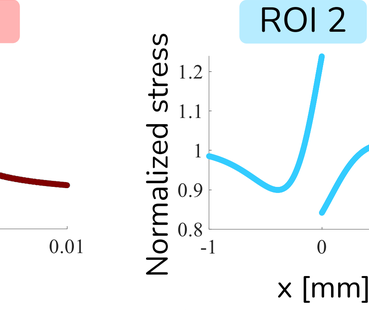
Understanding the biomechanics of the Achilles tendon-calcaneal bone interface is complex due to the interaction of tendon, bone, and the transitional fibrocartilaginous layer, divided in mineralized (mFC) and unmineralized (uFC), called the enthesis. Mechanical loads at this bi-material interface can cause stress concentrations, leading to structural weakness and failure, described by the singularity order (λ). Common strategies to reduce these stresses involve using intermediate layers with constant stiffness ratios. This study uses computational methods to explore how mechanical gradients affect stress concentration at the tendon-to-bone interface.





Previous Results [2,3]

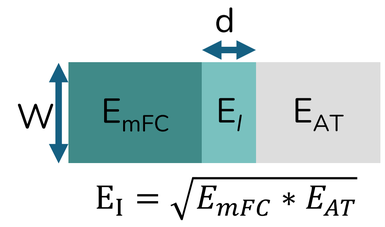
µ-CT
Microarchitecture



From µ-CT and SHG

Very **anisotropic** microstructure in all the layers of enthesis

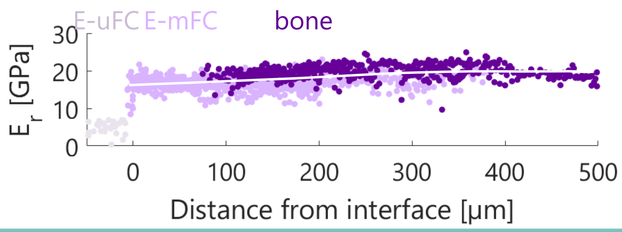
SHG
Fibers orientation

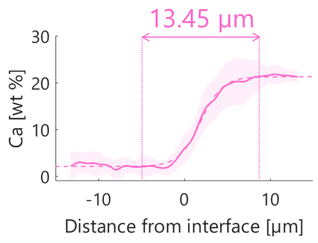


From qBEI and nIND

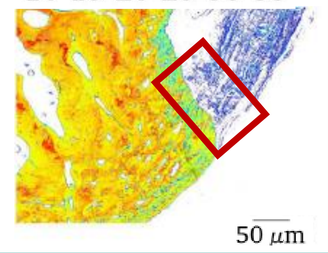
Very **steep gradient** both in indentation modulus and in calcium content across the interface

nIND
Mechanical properties



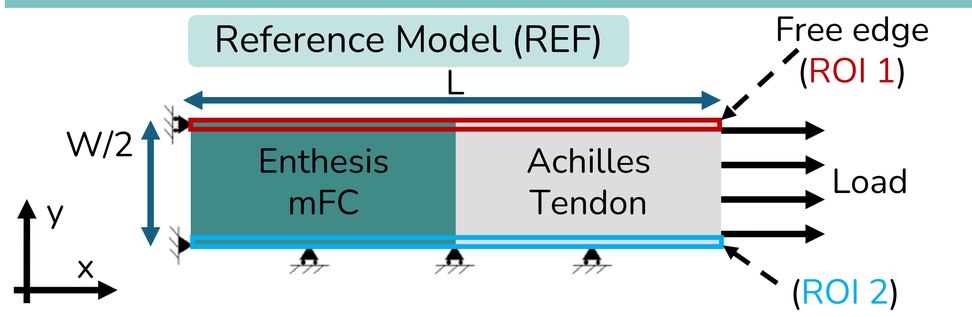


qBEI
Calcium content



Methods

Reference Model (REF)



Assumptions:
- 2D model
- Bimaterial model
- Isotropic elastic materials
- Stiffness ratio ($R_e = E_{mFC} / E_{AT} = 40$)
- Aspect ratio (L/W=10)
- Y-Symmetric model
- Isostatic boundary conditions on mFC
- Loaded with uniformly increasing tension

Mesh parameters:
- Quadrilateral
- Plane stress
- Single biases at the extremities
- Max bias factor = 50
- Total number of elements (REF) ~ 14M

Mesh analysis

Slow convergence

Total convergence

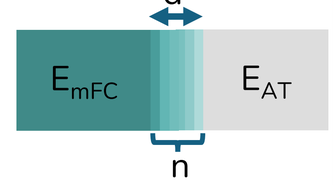
Configurations analyzed

1 Bridging layer thickness

Parameter:
Aspect ratio → **d/W**

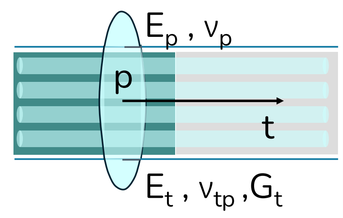
2 Multi-layer bridging

Parameter:
Number of Layers → **n**



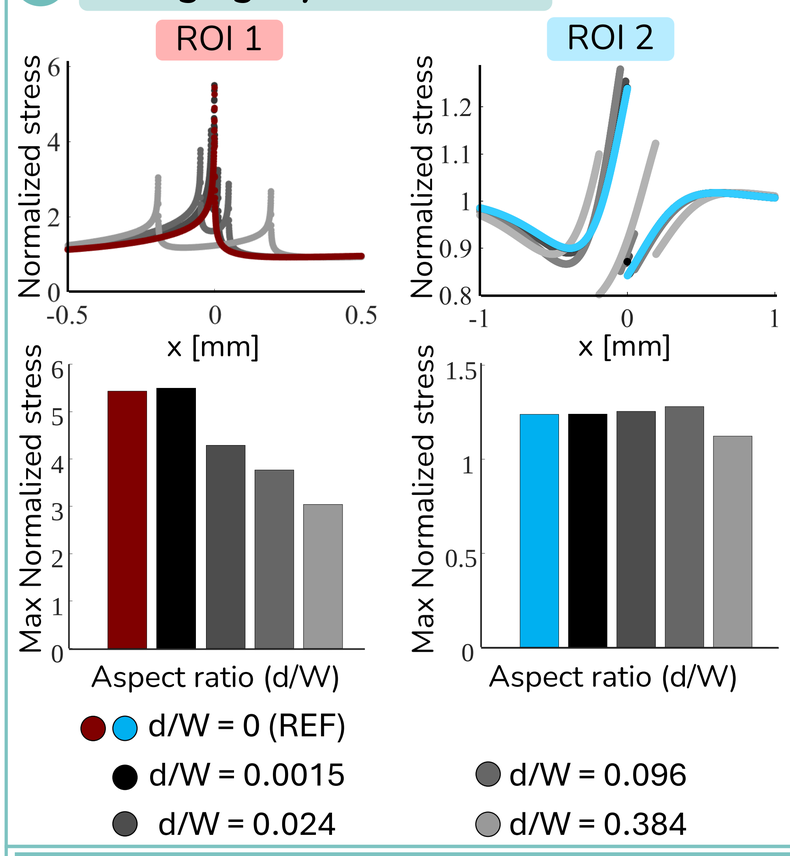
3 Transverse isotropic (TI) model

Parameter:
TI Poisson's ratio → **ν_{tp}**

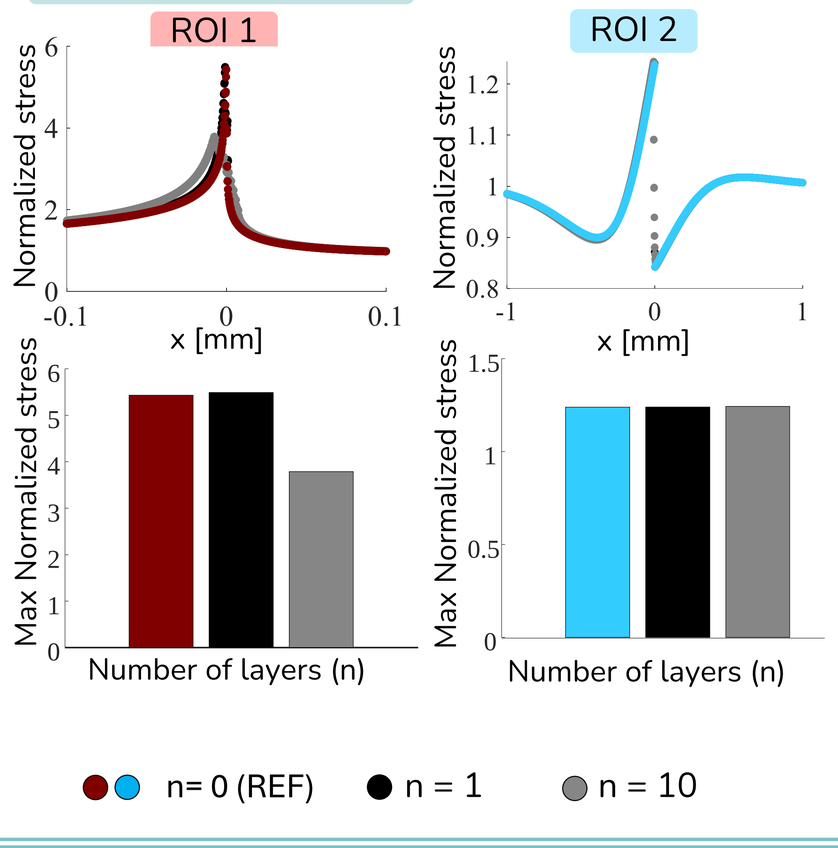


Results

1 Bridging layer thickness



2 Multi-layer bridging



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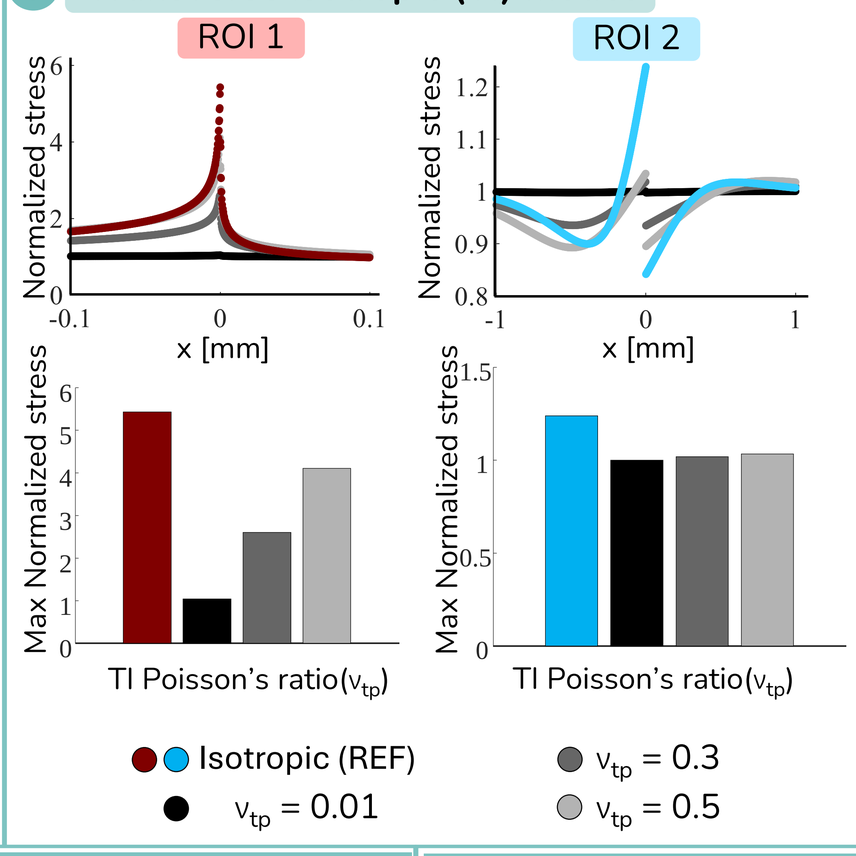

Conclusions & Perspectives

In conclusion, this study challenges previous assumptions by demonstrating that gradients are not always a solution to reduce the singularity effect. Indeed, it's evident that when there is not enough transition space (as observed experimentally at the Achilles tendon-to-bone interface [2,3]), the attenuation and dissipation effect of gradients is almost negligible. This implies that relying solely on compositional and mechanical gradients is insufficient for effective stress dissipation in bones, and it does not justify the efficient load response and transmission capability of the enthesis. Our models also highlighted that considering tissue anisotropy, such as the aligned collagen fibers in fibrocartilage (FC), significantly reduces interface stresses. These findings offer important insights for new research in both biomechanical field and bioinspired materials.

References

1. Uzan et al., Acta Biomater, 153:320-330, 2022.
2. Tits et al., Acta Biomater, 166: 409–418, 2023.
3. Tits et al., Sci rep, 11:1–17, 2021.

Social Networks

Albano Malerba

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