LARGE-SCALE FINITE ELEMENT MODELING OF PRE-STRESS IN ARTICULAR CARTILAGE

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Introduction

Background:

- Analysis of articular cartilage (AC) through *in silico* methods is crucial due to the prevalence of osteoarthritis [1].
- Multiphysics models can achieve high-fidelity AC simulation by computing osmotic pressure.
- Osmotic pressure leads to pre-stressing in the model, which can be handled using a pre-stressing algorithm (PSA).

Motivations:

- Our previous research [2] presented a PSA with separate geometrical and material optimizations, which might be too expensive for a large-scale simulation.
- Biomechanical data recorded with respect to the known pre-stressed state may still lead to theoretical inconsistencies.

Aims:

- To develop an automatic pipeline for large-scale pre-stressing using a unified optimizer.
- To perform a pre-stressing analysis on a knee model.

Methodology

Modeling:

- AC components contribute to the load resistance by [2-5]:

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}^{COL} - \boldsymbol{\sigma}^{MAT} + \boldsymbol{\sigma}^{GAG} - p\mathbf{I}$$

total stress, fibrillar stress, non-fibrillar stress, osmotic pressure, fluid pressure

$$\boldsymbol{\sigma}^{COL} = \frac{1}{J}\phi_0^S \sum_{I=1}^{9} \left(\rho_C^I\left(E_0 + E_\varepsilon \varepsilon^I\right)\varepsilon^I \lambda^I \mathbf{n}^I \otimes \mathbf{n}^I\right) \quad (\text{if } \varepsilon^I > 0)$$

volumetric part of the deformation gradient $\mathbf{F}$; material parameters; elongation; I^{th} fibrillar direction; strain

$$\boldsymbol{\sigma}^{MAT} = G_m\left(1 - \rho_0^{COL}\right)\frac{\phi_0^S}{J}\left[-\frac{\ln J}{6}\left(3\phi_0^S \frac{J \ln J}{\left(J - \phi_0^S\right)^2} - 1 - 3\frac{J + \phi_0^S}{J - \phi_0^S}\right)\mathbf{I} + \left(\mathbf{F}\cdot\mathbf{F}^T - J^{2/3}\mathbf{I}\right)\right]$$

material parameters

$$\boldsymbol{\sigma}^{GAG} = \alpha_1\left(\frac{1}{J}\right)^{\alpha_2}\mathbf{I} \quad \Rightarrow \quad \boldsymbol{\sigma}_0 = -\alpha_1 \mathbf{I}$$

material parameters; pre-stressing

- Material parameters are determined using the experimentally observed microstructure of the pre-stressed knee, as indicated by the normalized depth (ND) and split lines on the AC surfaces.
- ND values are calculated by an algorithm of the nearest neighbor searching [6] to then approximate the pointwise values of the reference state $\mathbf{V}^{\text{REF}}$, set as the PSA target.
- The optimizer updates the geometrical and material state $\mathbf{v}$ (including the nodal coordinate $\mathbf{x}$) to reach the target state:

$$\mathbf{v}_{t-1} \xrightarrow[\text{analysis}]{\text{forward}} \mathbf{x}_t \xrightarrow[\text{analysis}]{\text{backward}} \mathbf{v}_t$$

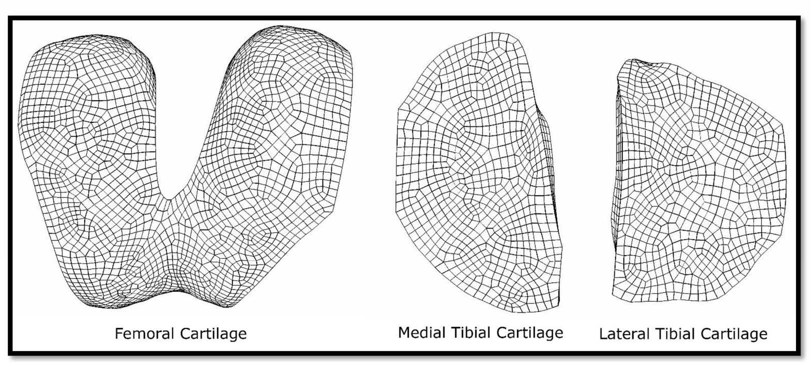
With $\mathbf{v}_0 \coloneqq \mathbf{V}^{\text{REF}}$ and the residual function $r = \|\mathbf{v}_t - \mathbf{v}_{t-1}\|_\infty$, updating finite element (FE) mesh with the zeta parameter ζ using the forward analysis:

$$\mathbf{x}_t \coloneqq \zeta(\mathbf{x}_{t-1} - \mathbf{x}_t)$$

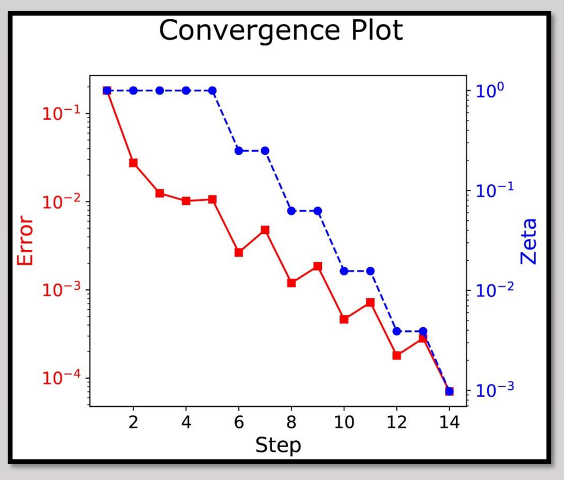
And the backward analysis starts with $\mathbf{V}^{\text{REF}}$ to reach $\mathbf{x}_t$

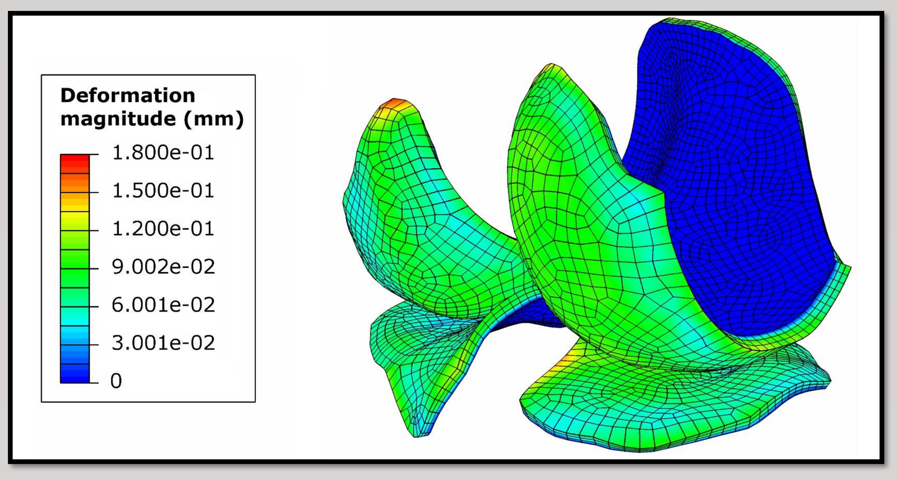
Simulation:

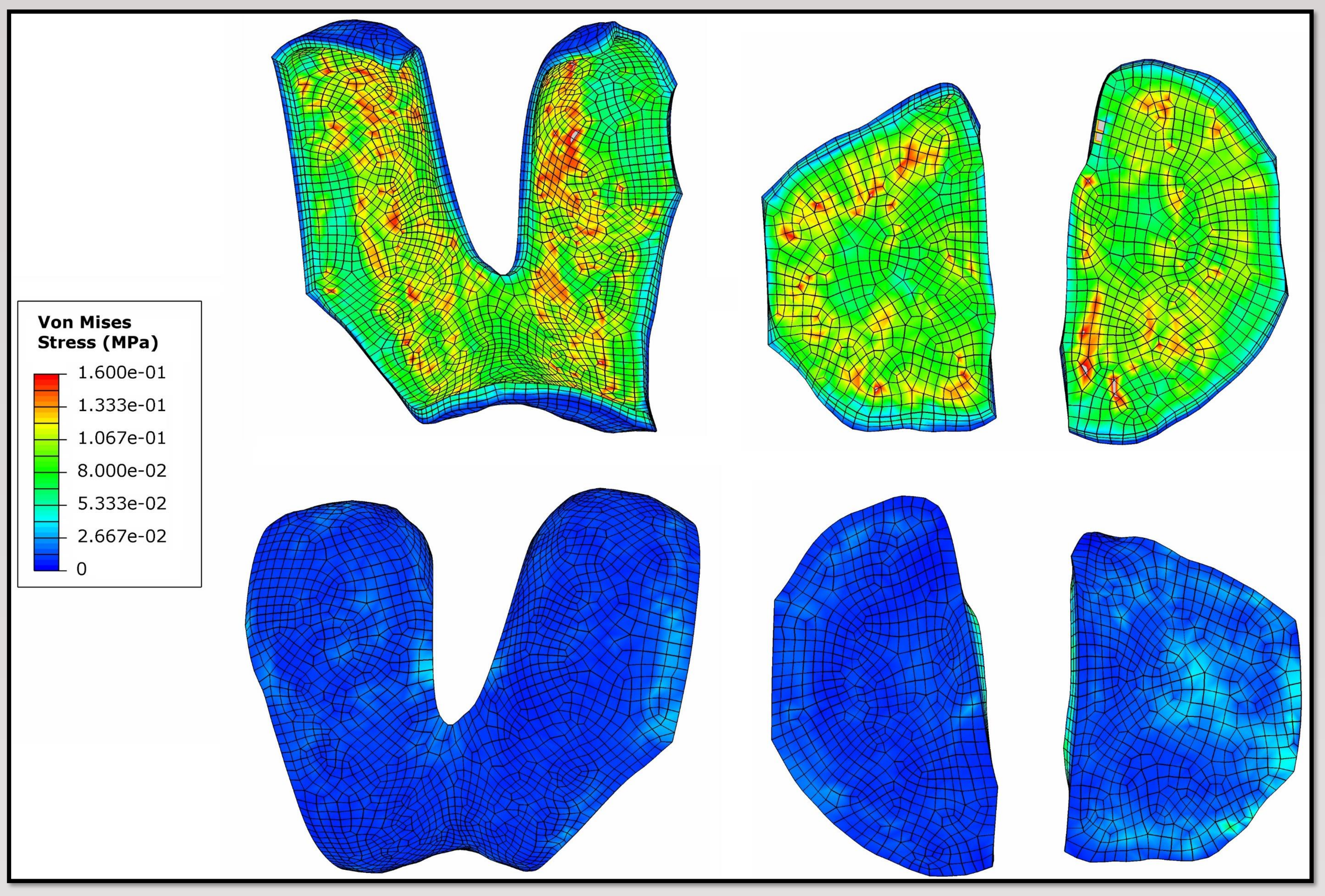
- The FE model is extracted from the Open Knee project [7].
- The pre-stressing effects are recorded with an emphasis on the deep and contacting layers of the tibiofemoral joint, as shown on the right.

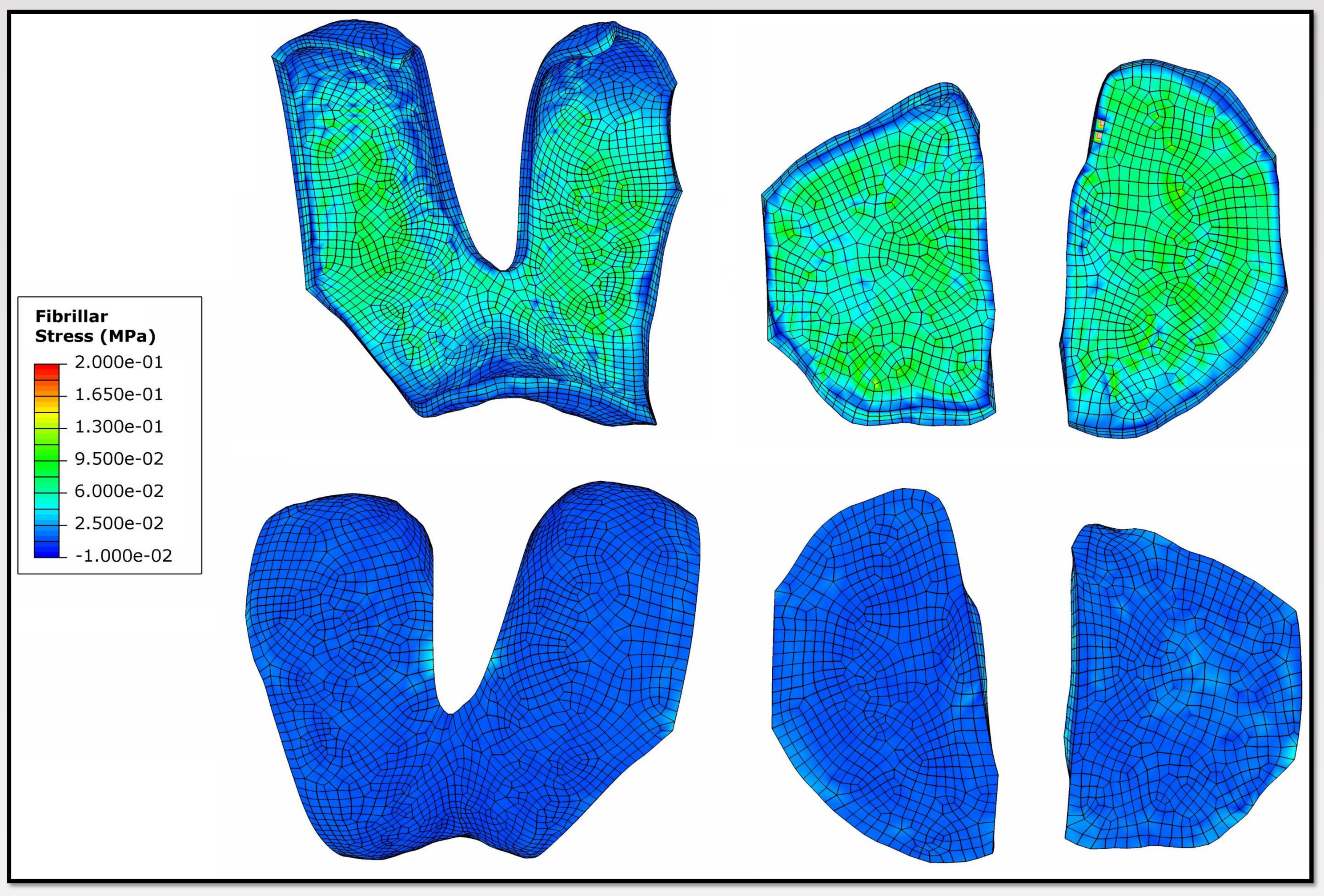


Results









Discussion and conclusions

- The PSA algorithm was found to be highly efficient, taking around 3 hours to complete, but this could be reduced to an hour with a rough error of 0.001 mm.
- The deformation results were consistent with expectations, with the maximum effect observed on the contacting surfaces.
- Our findings indicate that total and fibrillar stresses on the contacting surfaces are negligible and may not be affected by pre-stressing. However, the deeper zones may not follow the same pattern.
- The PSA algorithm needed minimal human intervention, only for adjusting the value of zeta.
- The results can be indirectly validated by comparing them to the previous study [8].

References

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