Mesh convergence is affected by poroelasticity in multi-tissue intervertebral disc models

Carlos Ruiz[1], Jérôme Noailly[1] and Damien Lacroix[1,2]

[1] *Institute for Bioengineering of Catalonia,*[2]*University of Sheffield, UK*

Correspondence: jnoailly@ibecbarcelona.eu; +34 934020266; Baldiri Reixac 4, 08028 Barcelona, Spain

Introduction

Soft tissues of the Virtual Physiological Human are mostly considered as biphasic consisting in a solid and fluid phases that create an overall viscoelastic behavior of the tissues. Therefore, many studies describe the mechanical behavior of soft tissues as poroelastic o porohyperelastic. However, it has been reported recently by Stokes et al. [1] that instabilities may be present for such formulation under rapid loading. Since poroelastic models are often used for intervertebral disc (IVD) simulations, it is hypothesized that numerical instabilities are also present in the disc for rapid loading. This study aims to evaluate whether the numerical convergence of an IVD poroelastic model is reached under physiological loading rates.

Materials and Methods

An anatomical IVD model including the annulus fibrosus (AF), the nucleus pulposus (NP), and the endplates was used with four different mesh sizes: Δh= 3.04 mm (model 1), Δh= 2.76 mm (model 2), Δh= 1.72 mm (model 3) and Δh= 0.83 mm (model 4). Material properties were taken from the literature (Table 1) [2]. The stress-strain relation follows the expression:

$$\sigma_{ij} = \frac{G}{J}\left(\bar{B}_{ij} - \frac{1}{3}\delta_{ij}\bar{B}_{kk}\right) + K(J-1)\delta_{ij} \quad , \quad \bar{B}_{ij} = B_{ij}/J^{-2/3}$$

A strain-dependent permeability was implemented [3]:

$$k = k_0\left[\frac{e(1-e_0)}{e_0(1+e)}\right]^2 exp\left[M\left(\frac{1+e}{1+e_0} - 1\right)\right]$$

Physiological extension and axial rotation motions were simulated, corresponding to 7.5 Nm moments [4] applied in 1s. External pore pressure was nil. Strain energy density (SED) and fluid velocity (FV) were calculated along (1) mid-sagittal plane (Fig. 1), (2) disc circumference, and (3) posterior and (4) anterior disc height node paths. The presence of possible numerical instabilities related to the poromechanical predictions was explored, and different strategies were tested to stabilize the predictions, i.e. local mesh and material refinements. The numerical stability of the poromechanical results was additionally explored along a stress relaxation period of 1h, with and without swelling. Swelling application consisted in a previous step of free swelling due to a NP osmotic pressure of 0.15 MPa until pore pressure stabilization in the IVD center.

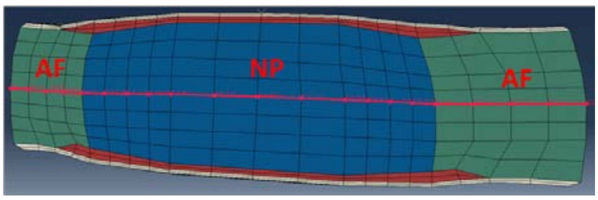

Figure 1: Path 1, mid-sagittal plane

Material	G (MPa)	K (MPa)	Initial Void Ratio	Permeability (mm^4/Ns)
Annulus Fibrous	0.28	0.37	3.08	Variable
Nucleus Pulposus	0.17	0.22	4.88	Variable
Cartilage endplate	7.14	15.2	4	Variable
Bony endplate	4274	5051	0.05	26,800

Table 1: Material properties

Results and Discussion

Under extension, models 2, 3 and 4 led to similar SED predictions, whereas in axial rotation, neither model 2 nor model 3 converged to model 4 results. For all models, FV oscillations occurred along the mid-sagittal plane. Although the calculations related to solid matrix elasticity indicated that model 3 had not an optimal mesh size under axial rotation, this model was chosen to explore the FV instabilities because of the low computation time (1h) compared to model 4 (16h). Accordingly, oscillations were investigated only under sagittal extension.

Since there was no discontinuity for a model with one continuous material, it was concluded that oscillations were caused by material discontinuities. Different local mesh refinements were performed based on Vermeer and Verruijt criterion [1]. However the fulfillment of this criterion was inefficient to cope with FV oscillations at material discontinuities (Fig. 2b). Indeed, comparing fluid velocity instabilities to the spatial variations of the different terms of Darcy's equation and of the pore pressure revealed that the spatial derivative of the pore pressure was mostly responsible for these oscillations. The creation of a material transition area with a local consolidation-adapted mesh refinements (Δh= 1.44 mm) and interpolated properties showed significant improvements, i.e. oscillations were reduced by 91% (Fig. 2b). An additional tangential refinement (Δh= 0.96 mm) was required to made the model 3 results converged to model 4 results.

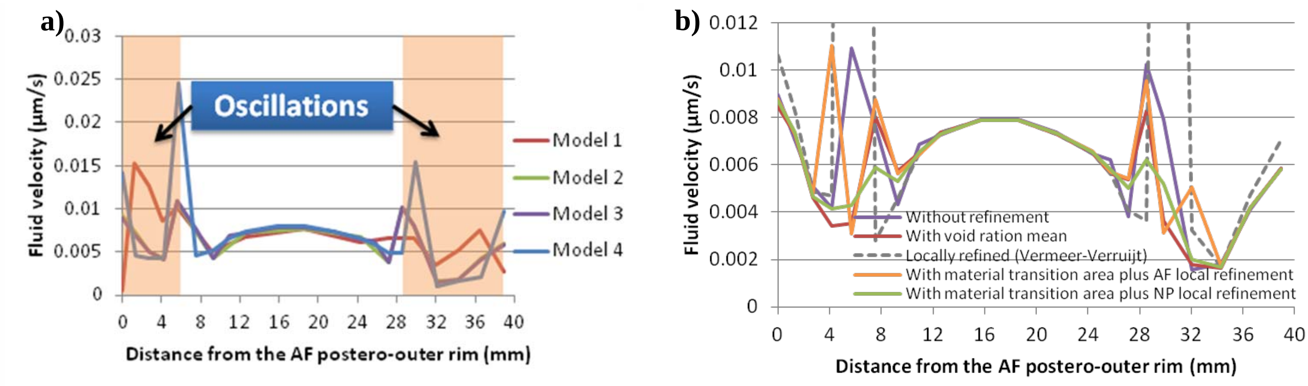

Figure 2: FV oscillations, a) in the different models studied and b) in model 3 with and without material transition area.

By using the locally refined model that included the interpolated transition material properties, instabilities disappeared after 30 minutes of load relaxation suggesting that FV decreased below a material-dependent critical value (Fig. 3a). The incorporation of the osmotic pressure at the nucleus also improved the FV results eliminating the oscillation in the posterior part of the disc. However, in the anterior part the oscillation remained, suggesting that simulating swelling effects selectively attenuates the oscillation of pore pressure gradient in the compressed areas of the disc (Fig. 3b).

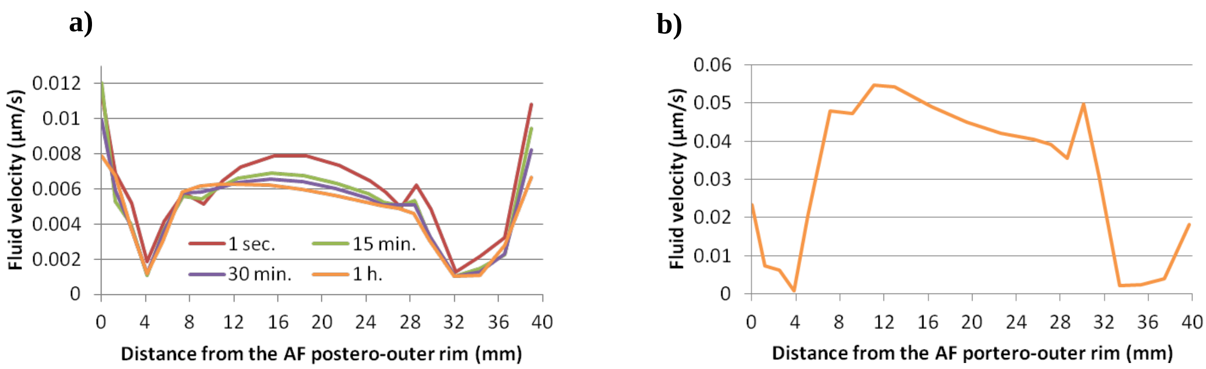

Figure 3: FV behavior, a) after 1h of load relaxation, and b) incorporating of the osmotic pressure at the nucleus

Conclusions

This study showed that material discontinuities create oscillations in poroelastic models when physiological loads rates are applied in the intervertebral disc. The creation of an AF-NP transition zone, with a gradient of material properties and local refinement, removed the oscillations partially and is indeed more representative of the true configuration of the transition between the two IVD sub-tissues.

Acknowledgements

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References

1. Stokes, I., Chegini, G., Ferguson, S., Gardner-Morse, M., Iatridis, J. & Laible, J. 2010 Limitation of Finite Element Analysis of Poroelastic Behavior of Biological Tissues Undergoing Rapid Loading. Annals of Biomedical Engineering 38, 1780-1788. (DOI: 10.1007/s10439-010-9938-0)

2. Malandrino, A., Noailly, J. & Lacroix, D. 2011 The Effect of Sustained Compression on Oxygen Metabolic Transport in the Intervertebral Disc Decreases with Degenerative Changes. PLoS Comput Biol 7(8): e1002112. (DOI:10.1371/journal.pcbi.1002112)

3. Argoubi, M. & Shirazi-Adl, A. 1996 Poroelastic creep response analysis of a lumbar motion segment in compression. Journal of Biomechanics 29, 1331–1339.

4. Noailly, J., Wilke, HJ., Planell, JA. & Lacroix, D. 2007 How does the geometry affect the internal biomechanics of a lumbar spine bi-segment finite element model? Consequences on the validation process. Journal of Biomechanics 40, 2414-2425. (DOI:10.1016/j.jbiomech.2006.11.021)