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A micro-poro-mechanical model of the lung parenchyma

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1. Introduction

To better understand the link between the macroscopic behavior of the lung parenchyma and its microscopic geometrical and mechanical features, we developed a micromechanical (alveolar scale) model and studied its global response (in terms of average stress/strain as well as pressure/porosity) to various loadings (average stress, strain or pressure). We also compared its global response to the one of a macroscopic (tissue scale) poromechanical model which we recently proposed for the lung parenchyma (Patte, Genet, et al. 2022). In fine, the microscopic model will help us derive a better macroscopic model, hence performing more physiological organ scale breathing simulations for clinical applications (Patte, Brillet, et al. 2022; Laville et al. 2023) while maintaining a link to the state of the tissue at alveolar scale, opening the door for explicitly modeling alveolar scale phenomena such as surface tensions, remodeling mechanisms, etc.

2. Methods

2.1 Microstructure & Micromechanics

We considered a 2D hexagonal periodic microstructure, as shown in Figure 1, whose walls obey a generic hyperelastic constitutive law with neohookean and Ogden-Ciarlet-Geymonat potentials.

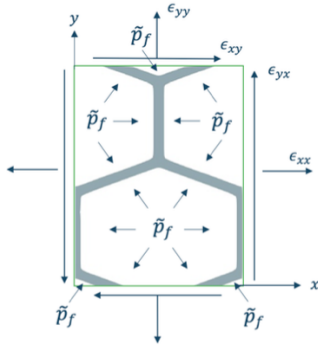


Figure 1. Generic porous microstructure.

2.1 Micro-poro-mechanics problem formulation

To formulate the problem, we start by decomposing the total displacement into an affine part and a periodic perturbation:

$$\underline{U}(\underline{X}) := \underline{\underline{\epsilon}} \cdot (\underline{X} - \underline{X}_0) + \widehat{U}(\underline{X}),$$

where $\underline{\underline{\epsilon}}$ is a symmetric second order tensor, i.e., the macroscopic strain, \underline{X}_0 an arbitrary reference point and \widehat{U} a periodic displacement field. Let us introduce another variable, namely the macroscopic stress:

$$\underline{\underline{\sigma}} := \frac{1}{|\omega|} \left(\int \underline{\underline{\sigma}} d\omega_s - |\omega_f| p_f \underline{1} \right),$$

where $\omega = \omega_s \cup \omega_f$ is the deformed domain, composed of solid and fluid parts, $\underline{\underline{\sigma}}$ is the Cauchy stress tensor, p_f is the fluid pressure. The strong form of the general micro-poro-mechanics problem is thus:

$$\text{Find } (\underline{\underline{\epsilon}}, \widehat{U}) \text{ such that } \begin{cases} \widehat{U} \text{ is periodic} \\ \text{div}(\underline{\underline{\sigma}}) = 0 \text{ in } \omega_s \\ {}^t \underline{\underline{\sigma}} = \underline{\underline{\sigma}} \text{ in } \omega_s \\ \underline{\underline{\sigma}} \cdot \underline{n} = -p_f \underline{n} \text{ on } \partial\omega_s \setminus \partial\omega \\ \llbracket \underline{\underline{\sigma}} \cdot \underline{n} \rrbracket = 0 \text{ on } \partial\omega_s \cap \partial\omega \\ \underline{\underline{\Sigma}} = \underline{\underline{\Sigma}}(\underline{U}) \text{ in } \Omega_s \\ \tilde{\epsilon}_{ij} = \tilde{\epsilon}'_{ij} \\ \tilde{\sigma}_{kl} = \tilde{\sigma}'_{kl} \end{cases},$$

Where $\underline{\underline{\Sigma}}$ is the second Piola-Kirchhoff stress tensor.

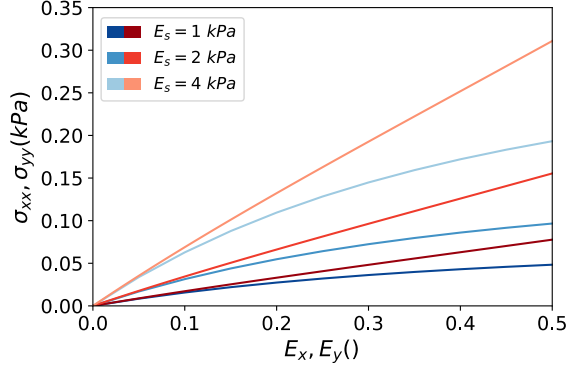
This system describes the balance of linear momentum, the balance of angular momentum, the applied pressure on the inner surface, the periodicity of the stress field, the constitutive relation, the constraint of some component of the macroscopic strain to a given value $\tilde{\epsilon}'_{ij}$, and the constraint of some component of the macroscopic stress to a given value $\tilde{\sigma}'_{kl}$. In practice we pull all equations back to the reference configuration, and formulate the problem in weak form. Compared to (Álvarez-Barrientos et al. 2021), we explicitly express the macroscopic stress, which make the formulation valid for any microstructure. This general formulation allows to impose various types of loading to the microstructure: fluid pressure and/or macroscopic strain and/or macroscopic stress.

3. Results and discussion

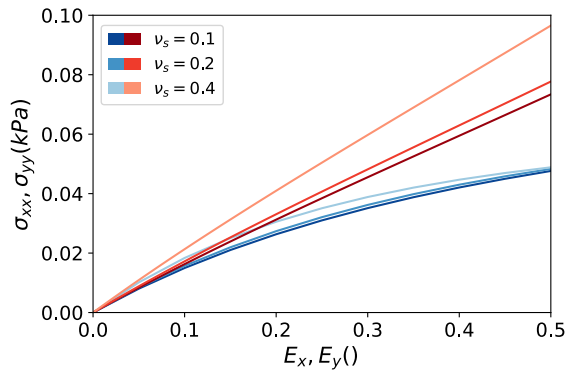
We systematically compared the global response of the microscopic model to the one of our poromechanical model. Some results are shown in Figure 2. Figures 2a & 2b show the stress-strain response to an imposed equi-biaxial strain for different values of the solid Young modulus and Poisson coefficient. The material parameters of both models are chosen such that the linearized response match, which is apparent on the plots. For larger levels of deformation, the responses of the micro- and macro-models differ. Also, as expected, the response is much more sensitive to the Young modulus than the Poisson coefficient. Figure 2c shows the Terzaghi stress as a function of strain, for different levels of fluid pressure. In the context of our micro-model, we define the Terzaghi stress as:

$$\underline{\underline{\sigma}}_T := \underline{\underline{\tilde{\sigma}}} + \frac{|\omega_f|}{|\omega|} p_f \underline{\underline{1}}.$$

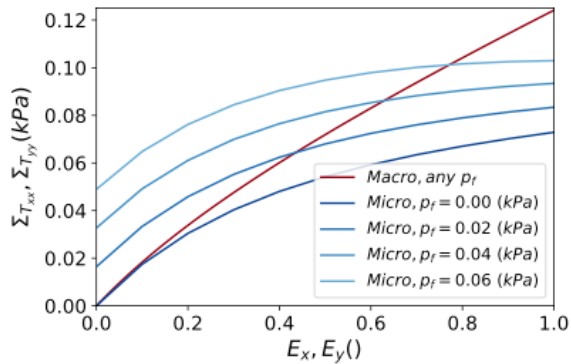
In the very construction of our poromechanical model, the Terzaghi stress is independent from the fluid pressure (Chapelle and Moireau 2014). On the contrary, our micromodel shows a strong coupling between the applied strain and fluid pressure.



(a) Cauchy stress-strain response to an imposed equi-biaxial strain for different values of the solid Young modulus.



(b) Cauchy stress-strain response to an imposed equi-biaxial strain for different values of the solid Poisson coefficient.



(c) Terzaghi stress-strain response to an imposed equi-biaxial strain for different fluid pressure values.

Figure 2. Global response of the micro-poro-mechanical model (blue) vs. a macro-poro-mechanical model (Patte, Genet, et al. 2022) (red)

4. Conclusions

We have developed a micro-poro-mechanical model of the lung parenchyma, based on a general formulation that allows to compute the response of the microstructure to fluid pressure, macroscopic strain and/or macroscopic stress. This model allows to investigate the fundamental hypothesis underlying macroscopic poromechanical models. We now plan to introduce additional mechanisms (e.g., surface tension, fibrosis, etc.) within our micromodel, as well as develop a model reduction approach to be able to perform organ scale simulations directly based on this micro-model.

Acknowledgements

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