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Multiscale fluid-structure homogenization for the characterization of vascular distribution on liver mechanical behavior

D. George [(1)], M. Baniassadi [(2)], Y. Hoarau [(1)], M. Kugler [(1)], Y. Rémond [(1)]

[(1)] Laboratoire ICube, Université de Strasbourg, CNRS UMR 7357, Strasbourg
[(2)] School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran 11155-4563, Iran

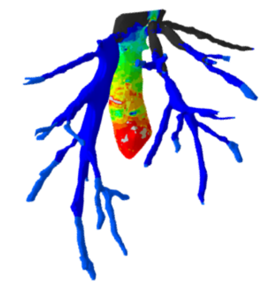
Context

In the context of mechanobiology of soft tissue, numerical models have the advantages of providing information that will help all people in need of predictive tools to bridge the physiological biology and solid physics. More specifically, in the context of mini-invasive tumor surgery of the liver, real time augmented reality provide the surgeon with a lot of information in 3D that can help him in making the right surgical decisions. To provide pre and per-operation 3D real time data, a numerical model requires to be computed quickly while providing a high level of precision. The current study focuses on mini-invasive liver surgery where a multilevel homogenization is used based on the results obtained on a full model on a real patient liver and blood vessels geometry. The homogenised results are integrate on a macroscopic level to provide a complete model with a rigidity variation over the full geometry to allow internal deformation computation.

Mechanical impact of the vascularisation distribution and blood flow study

In order to determine the exact mechanical impact of the vascularisation geometry and the blood flow on the macroscopic level of the liver, a fluid-structure interaction study is carried out. Indentations are done on a liver for which the blood vessels walls correspond to the movable boundary conditions of a flow study. The pressure on the blood walls are reported at each step in the structure simulation.

First results show an important difference between sub-hepatic vein pressure which is considerably lower than the vein cave main trunk wall pressure. In addition the liver internal vein pressure remain constant independently of the total blood quantity going through the liver. This allows to consider the internal pressure as constant, and to homogenise in a second stage the blood impact.

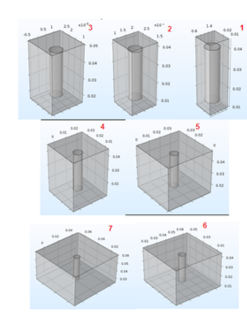


Homogenization

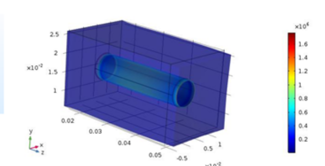
Assuming a homogeneous host tissue, the vascularizations interaction with host tissue are homogenized. The first step uses the Generalized Explicit Eshelby-type Estimator (GEEE) approach by Ghazavizadeh at al. (2017). GEEE is not only accurate and general enough to cover any ellipsoidal configuration or limit cases thereof, but fast to implement.

For the host tissue, a Mori-Tanaka scheme was used for the second level of homogenization. The first step and the host medium are plugged into Mori-Tanaka relationships to estimate the effective properties of the biological tissue.

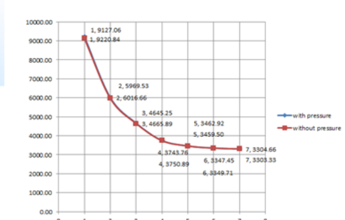
Simulations have been performed to estimate the equivalent Young's modulus. The liver material is considered with a Young modulus of 3 KPa and Poisson ratio 0.3 with the density 1000 kg/m^3. The vascularization is considered with a Young modulus of 620 KPa and Poisson ratio 0.3 with the density 1000 kg/m^3. Seven prototypes with different sizes were simulated. In order to account for the influence of blood vessel's pressure on the equivalent Young modulus, all simulations were performed twice ; once with an applied pressure of 15998.5 Pa and once without pressure. The calculated Young modulus away from the vascularization was found to be 3305 Pa.



Seven prototypes with different size



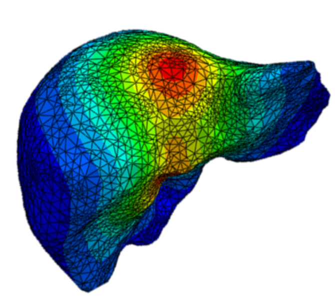
Von Mises stresses of inclusion (N/mm²)



Effective Young modulus

Full Model constitution

In addition to the homogenization scheme, the fluid study results highlighted the mechanical importance of the blood system entrance and allowed to identify an impact coefficient of those structure on their neighbourhood and depending on the distance and vein radius.



Integrated as a sum of normal law decreasing from the homogenised vein mechanical property to the liver one it leads to a function which provides a patient specific rigidity 3D map integrating the liver vasculature system.

$$E(d) = E_f + \left(E_v - E_f\right) * e^{\left(-\alpha \frac{d^2}{R^2}\right)}$$

$$E_{eq}(X) = \left(E_f + \left(E_v - E_f\right) * \sum_{i=1}^{n}\left(\frac{\prod_{j\neq i} d_{Xj}}{\prod_{j\neq i} d_{ij}} e^{\left(-\alpha \frac{d_{Xi}^2}{R_i^2}\right)}\right)\right)$$

Conclusion

With homogenised mechanical properties accounting for vascularizations, the constituted model allow a quick computation with a parametric dimension reduction approach. Once integrated in the surgery room, it provides the underlying physics real-time deformations through augmented reality to help the surgeon's gestures.

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