

Modeling Liver with Glisson's Capsule in Real-Time Medical Simulations

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Abstract

Accurate biomechanical modeling of liver is of a paramount interest for pre-operative planning or computer-aided per-operative guidance. However, such simulations remain a challenging task, since the organ is composed of three constituents: parenchyma, vascularization and Glisson's capsule, each having different mechanical properties. In this paper we propose a complete liver model, where the parenchyma is modeled as a finite element volume, the vessels are modeled as series of beam elements, and the corotational membrane elements based on constant-strain formulation, which are coupled mechanically to the underlying tetrahedra. We show that using this model we are able to reproduce accurately biomechanical tests, while maintaining the real-time aspect of the simulation.

Keywords: Simulation, modeling, liver, biomechanics

1. Introduction

According to the statistics, nearly 100,000 European citizens die of cirrhosis or liver cancer each year. Although new methods such as radio-frequency- and cryo-ablation known in the interventional radiology seem to be promising, surgery remains the option that offers the foremost success rate against these pathologies. Nevertheless, surgery is not always performed due to several limitations, in particular the determination of accurate eligibility criteria for the patient. In this context, the pre-operational planning becomes a crucial task having a significant impact on the treatment.

Computer-aided physics-based medical simulation has proven to be an extremely useful technique in the area of medical training. Nevertheless, whereas generic models are usually required in training simulators, accurate patient-specific modeling becomes necessary as soon as computer simulation is to be employed in the pre-operative planning. At the same time, interactivity of such models remains an important aspect, requiring real-time simulation which is often difficult to achieve given the complexity of soft tissues. When simulating the behavior of human liver, the task of real-time accurate modeling is challenging, mainly because of the complex structure of this organ composed of three main constituents: *parenchyma*, *vascular networks* and *Glisson's capsule*. The parenchyma has certainly been the most studied component of the liver; actually re-

searchers agree on hyperelastic properties of the tissue, for which the mechanical parameters have been reported for example in [7, 5]. Moreover, several methods have been proposed to model the hyperelastic behaviour at real-time rates, such as multiplicative Jacobian decomposition introduced in [8]. The mechanical importance of the vascular structures in liver is studied in [11]. It shows that the influence of vessels on the mechanical behaviour of the organ is significant. Since a detailed modeling of the vessels would be extremely costly (mainly because of the small thickness of the vessel wall), the authors propose a composite model allowing for real-time simulation.

Rather a small number of studies have been conducted dealing with the third liver constituent, the Glisson's capsule. Quantitative results of experiments on a porcine liver have been published in [12]; the measurements indicate that although being very thin (10–20 μ m), the capsule shows to be stiff in tensile tests: the Young's modulus of the capsule reported to be 8.22 ± 3.42 MPa exceeds the values for the parenchyma by three orders of magnitude. This suggests that the mechanical influence of the membrane on the liver behaviour is not negligible. In [6], a local influence of the capsule has been measured using a special aspiration device. The study was then repeated in vivo on human patients during the operation, confirming the mechanical importance of the membrane [1, 9].

In this paper we present preliminary results of our work on the complete liver model. We present a real-time composite model accounting for parenchyma and Glisson's capsule. The model is based on two different finite element representations for each constituent coupled together. We show that the model mimics the *local* experiments described in [6].

2. Methods & Materials

In this section we describe the construction of a composite model based on two components: tetrahedral FE model of the parenchyma and triangular membrane elements used for the capsule.

2.1. Parenchyma

It is known that the parenchyma exhibits non-linear viscoelastic behaviour [8]. However, as we are mainly interested in the static equilibrium, we do not model the time-dependent phenomena related to viscosity. The parenchyma is modeled using corotational finite elements [3]. Although it relies on linear stress-strain relationship, large displacements including rotations are modeled correctly. While in the full non-linear formulation the stiffness matrix relates the forces \mathbf{f} and displacements \mathbf{u} as $\mathbf{f} = \mathbf{K}(\mathbf{u})$, the corotational model requires the stiffness matrix \mathbf{K}_0 of the system to be computed only once before the simulation begins. Then, in each step, the motion of each element e is decomposed into rigid rotation \mathbf{R}^e and local deformation. The rotations are then used to update each local element stiffness matrix as $\mathbf{R}^e \mathbf{K}_0 \mathbf{R}^{e\top}$ whereas the deformations are used to compute the linear strain in the local corotational frame. There are several ways of computing the corotational frame for elements; we rely on the geometrical method proposed in [10].

2.2. Glisson's Capsule

The thickness of the Glisson's capsule is relatively small: the values in range of 10-20 μm have been reported in [12]. It is not possible to model such thin structure with classical tetrahedral elements, if the real-time aspect of the simulation is to be preserved. Furthermore, modeling both the tissue and the capsule would require an extremely dense mesh to avoid numerical instabilities and thus would significantly violate the speed requirements imposed for medical simulators. Instead, modeling the capsule with two-dimensional elements that abstract from the thickness in the third dimension seems to be a natural choice. In the elasticity theory, this functionality is usually provided by membrane and shell elements. Based on the observation of its behaviour,

we also assume negligible bending forces and propose a model based on membrane elements. To maintain simplicity of the composite model we choose simple triangular elements with constant strain (CST).

The computation of elastic stiffness matrix follows the common derivation

$$\mathbf{K}^m = \int_V \mathbf{B}^T \mathbf{E} \mathbf{B} dV \quad (1)$$

$$= h \int_A \mathbf{B}^T \mathbf{E} \mathbf{B} dA \quad (2)$$

$$= h \mathbf{A} \mathbf{B}^T \mathbf{E} \mathbf{B} \quad (3)$$

where \mathbf{B} is the strain-displacement matrix, \mathbf{E} the material matrix, h is the thickness and A area of the element. In the previous (2) follows from the fact that we assume constant thickness of the element and (3) follows from the fact that the strain-displacement matrix is constant in our case. The strain-displacement matrix for the CST element can be expressed as:

$$\mathbf{B} = \frac{1}{2A} \begin{bmatrix} y_{23} & 0 & y_{31} & 0 & y_{12} & 0 \\ 0 & x_{32} & 0 & x_{13} & 0 & x_{21} \\ x_{32} & y_{23} & x_{13} & y_{31} & x_{21} & y_{12} \end{bmatrix} \quad (4)$$

The values $x_{ij} = x_i - x_j$ and $y_{ij} = y_i - y_j$ are computed from the x or y coordinates of the nodes i, j of the triangular element. The reader can refer to the respective literature [4] for more thorough description.

Similarly as with model of parenchyma we use linear elastic material and employ the corotational formulation for the CST elements.

2.3. Coupling Between Capsule and Parenchyma

The literature reports high cohesion between capsule and parenchyma. Based on this property we assume there is no relative motion of the capsule w.r.t. the parenchyma. Although an arbitrary surface mesh could be used to model the capsule, we exploit the fact that the parenchyma is modeled by tetrahedral elements having triangular faces. Thus, as the boundary of the volumetric mesh is already triangulated, we simply employ the triangles on the mesh surface to model the capsule.

Using directly the boundary of the tetrahedral mesh does not only solve the problem of building the surface mesh, but has one more advantage: the nodes of the triangular mesh coincide with the nodes of the tetrahedral mesh, so no projection of one mesh onto the other is needed. Moreover, the stiffness matrices for capsule and parenchyma are then easily assembled together. Without the loss of generality we can assume the tetrahedron

consists of nodes p_1, p_2, p_3 and p_4 and the boundary triangle has nodes p_1, p_2 and p_3 . We can reorder the degrees of freedom so that the stiffness matrix \mathbf{K}^t for the tetrahedron can be written as:

$$\mathbf{K}^t = \left[\begin{array}{c|c} \mathbf{K}_{1-3,1-3}^t & \mathbf{K}_{1-3,4}^t \\ \hline \mathbf{K}_{4,1-3}^t & \mathbf{K}_{4,4}^t \end{array} \right] \quad (5)$$

Hence, the assembled stiffness matrix for the element is

$$\mathbf{K} = \left[\begin{array}{c|c} \mathbf{K}_{1-3,1-3}^t & \mathbf{K}_{1-3,4}^t \\ \hline \mathbf{K}_{4,1-3}^t & \mathbf{K}_{4,4}^t \end{array} \right] + \left[\begin{array}{c|c} \mathbf{K}^m & 0 \\ \hline 0 & 0 \end{array} \right] \quad (6)$$

where \mathbf{K}^m is the stiffness matrix of the triangular membrane.

The resulting system of linear equations is solved by direct solver based on Cholesky decomposition.

3. Methods

The model presented in the previous section was implemented in SOFA¹ and a set of numerical simulations was performed. In this section we provide comparison of local deformations with the results reported in literature to validate the method.

During the contact with an instrument such as probe, needle, scalpel and others, specific deformations take place in the vicinity of the instrument. This type of deformation may not necessarily induce the deformation of the object as a whole and therefore can be considered as local. Correct material properties are not only important to quantify the displacement, but also play an important role in capturing the correct area of the deformation or its profile near the instrument.

A good example of such a local deformation is the aspiration test where the response of liver exposed locally to a negative pressure is measured. The aspiration device consists of a tube having 1 cm in diameter and allows to control the pressure inside the tube. The test is performed by attaching the tube to the tissue and measuring the tissue response. We set up a simulation in SOFA to reproduce the experiment (see Fig. 1): we meshed a $15 \times 15 \times 15 \text{ mm}^3$ cube representing the tissue resulting in 2648 tetrahedra. Then we attached a 1 cm tube and applied a pressure of 3 kPa inside the tube.

Since the tube is in direct contact with the tissue, unilateral constraints with friction were chosen to model this interaction properly. We opted for a method based on *non-linear complementarity problem* (NLCP) where

the non-linearity is introduced due to the friction. The NLCP allows for solution of the Signorini's problem to avoid any interpenetration between the colliding objects (see [2] for details). Since NLCP requires explicitly the computation of compliance matrix which is homogeneous to the inverse of the stiffness matrix, we employed a direct solver based on LDL decomposition to solve the system and compute the inverse matrices.

4. Results and Discussion

As the first step, we evaluate the influence of the Glisson's capsule on the mechanical response of the tissue during the aspiration test. In [6] it is reported that the influence of the capsule is significant, as modeling only the parenchyma without considering the membrane results in overestimation of the deformation by a factor of 2 to 3. In order to verify this observation, we performed a simulation using capsule parameters measured experimentally on ex-vivo pig liver [12]: Young's modulus of the membrane was set to $E_c = 8.22 \text{ MPa}$ and thickness was $t_c = 20 \mu\text{m}$. Since the values for parenchyma elasticity reported in the literature vary significantly being usually reported between 2 kPa to 5 kPa, we employed a value $E_p = 3.5 \text{ kPa}$ for the Young's modulus of the parenchyma.

In Fig. 2 the profiles of cuts in the middle of the test cube are presented showing significantly larger deformation in the model without capsule assuming that the same negative pressure was applied on the tissue surface inside the tube. Moreover, it can be observed that the deformation without capsule is overestimated by a factor close to 2, which is in perfect agreement with the results reported in [6]. Fig. 3 presents the evolution of displacement in time at central node on the cube surface. The effect of increased combined stiffness is clearly visible.

In the second step, we employed the simulation to reproduce the displacements values obtained via simulation in [6, 9]. Whereas the simulation in the referenced work was done on a mesh composed of tetrahedral elements for both the parenchyma and the capsule, we modeled the capsule using the triangular elements as shown in section 2.2.

Since the Young's moduli of neither parenchyma (E_p) nor capsule (E_c) were specified exactly, we obtained both as follows: first, we performed a set of simulations without the capsule for different values of E_p : the value that provided a good match with reported displacements was $E_p = 30 \text{ kPa}$. Then, we fixed the thickness of the capsule to be $t = 93 \mu\text{m}$ (reported as the average value in the paper) and using $E_p = 30 \text{ kPa}$, we ran

¹www.sofa-framework.org

the simulation repeatedly using the model with the capsule. In each simulation we used different value E_c of the Young's modulus for the capsule in order to minimize the displacement error w.r.t. the reported values. The minimal value of error (not exceeding 1%) was obtained for $E_c=3$ MPa. This value lies in the range of capsule elasticity coefficients reported by experimental measurements.

In the scenario presented in this paper, we focus on local influence of the capsule. Nevertheless, it is possible to employ the actual model to demonstrate the global impact of the capsule and to further validate the accuracy of such a complete model w.r.t. experimental measures. Detailed description of such validation is however beyond the scope of this paper. In spite of this we would like to emphasize that we have already integrated the capsule model with vascularized liver model described in [11]. Adding the capsule did not affect the performance significantly: a visual refresh rate exceeding 25 FPS was achieved on a PC with CPU Intel i7 running at 3.00 GHz. This suggests that the proposed technique is compatible with real-time simulation of whole organ while modeling the local properties accurately.

5. Conclusion

In this paper we presented a composite liver model based on volume and membrane elements. When compared to experimental data provided in the literature we found similar results, but with faster computation times than standard computationally expensive model based entirely on volume elements.

6. References

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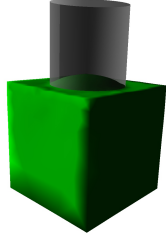


Figure 1: The SOFA simulation scene of the aspiration test.

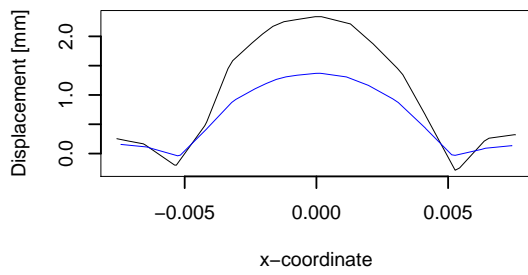


Figure 2: Displacement profile of the cube in the aspiration test with (blue) and without (black) the capsule.

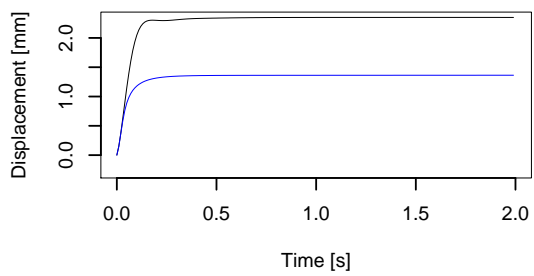


Figure 3: Evolution of the displacement at the center in time for test with (blue) and without (black) the capsule.