BIOMECHANICAL KIDNEY MODEL FOR PREDICTING TUMOR DISPLACEMENT IN THE PRESENCE OF EXTERNAL PRESSURE LOAD

Ivan Figueroa-Garcia¹, Jean-Marc Peyrat², Ghassan Hamarneh³ and Rafeef Abugharbieh¹

¹Biomedical Signal and Image Computing Lab, University of British Columbia, Vancouver, BC, Canada
²Qatar Robotic Surgery Centre, Qatar Science & Technology Park, Doha, Qatar
³Medical Image Analysis Lab, Simon Fraser University, Vancouver, BC, Canada

ABSTRACT
Robot-assisted partial nephrectomy (RAPN) is a minimally invasive surgery for the treatment of renal cell carcinoma that consists of removing the portion of the kidney that contains the tumor. To plan the resection, surgeons rely on preoperative scans of the patient. However, at surgery time, the shape of abdominal organs differs from these images due to factors such as patient position, insufflation and manipulation with surgical instruments. In this work, we focus on the simulation of kidney deformation due to an external pressure load, e.g. during insufflation, to provide a better estimation of the tumor mass position that is particularly important to plan resection with proper margins. The CT scans of ex vivo lamb kidneys with artificial tumors and fiducials are acquired in absence of external pressure load. From these images, 3D tetrahedral meshes of kidney parenchyma and tumor, as well as a triangular mesh of the capsule, are extracted and then used along with a soft tissue biomechanical model to simulate deformations under additional external pressure load. A second CT scan of the same kidneys under real pressure load are acquired as a reference to evaluate the advantage of simulating deformations over using the first CT scan without external pressure load. Results show that the biomechanical simulation improves by 29% the tumor localization.

Index Terms— Partial nephrectomy, image-guided surgery, FEM organ model, biomechanical simulation.

1. INTRODUCTION
In order to plan surgical interventions in Minimally Invasive Surgery (MIS), the surgeon uses pre-operative scans, e.g. CT or MR, that are usually acquired weeks or months beforehand. During the procedure, endoscopic video is used intraoperatively to navigate inside the patient’s body and perform the surgical procedure as planned. An example of such minimally invasive intervention is the treatment of renal cell carcinoma with partial nephrectomy. In this surgery, a portion of the kidney containing the cancerous tumor is resected. Abdominal CT scans are acquired preoperatively to localize the tumor and plan a proper resection, however the kidneys and surrounding organs move from their locations in previously acquired CT images as well as deform at the time of the surgery affecting the surgical plan [1]. To prepare a more accurate surgical plan that follows the actual anatomy during surgery, a certain degree of deformation should be applied to the preoperative images. During surgery, organs undergo two main categories of deformation: surgeon and environment induced. Surgeon induced deformations are tissue retractions and resections, while examples of environment induced deformations are gravity, abdominal organ collision, insufflation pressure, patient breathing and blood flow. Biomechanical models of organs are particularly helpful when modeling organ deformations due to instrument motion [2], incision and loss of turgidity [3], abdominal cavity insufflation [4] and loss of perfusion [5]. Furthermore, biomechanical models of organs can improve the position estimation of internal structures such as vessels and tumors. Traditionally, a partial nephrectomy requires the removal of up to 1 cm margin of healthy tissue surrounding a resected tumor, though less than 1 mm can be accepted as long as the tumor is completely excised [6]. Localization of the tumor is still one of the main challenges identified in such procedures [7]. To address this problem, different formulations of finite element method (FEM) can be used to model the deformation [8]. By using a biomechanical model based simulation, Haouchine et al. achieved 4 mm position differences between a simulated and scanned tumor inside a liver phantom under known external loads [9]. Rucker et al. also achieved average phantom tumor registration errors of 4 mm using a combination of rigid transformations and model-based non-rigid transformations [10].

The objective of this work is to provide a pre-operative estimation of the organ shape and tumor position under external pressure load by using a biomechanical model to simulate the organ deformation. This would help surgical planning and further processing such as intra-operative image-guided augmented reality solutions for tumor identification [11]. The contributions of our work are: 1) A preliminary study on the effects of kidney surface external pressure on the tumor position and 2) the simulation of a biomechanical model of the kidney that includes the parenchyma, tumor and the capsule.
2. MATERIALS & METHODS

Materials. Five ex vivo lamb kidneys were positioned inside rigid plastic containers and scanned in a Siemens Somatom CT scanner with 512 \times 512 \times 684 voxels and an isotropic resolution of 0.4 \times 0.4 \times 0.6 \text{ mm}. The kidneys had artificial tumors previously inserted as well as fiducials attached to the surface.

3D Model construction. We constructed a 3D kidney model that includes these three structures: parenchyma, capsule and tumor, as shown in Fig. 1. The parenchyma is the bulk of the organ and is the tissue that changes volume the most under external pressure changes. The capsule is a thin layer of the kidney that holds the parenchyma and yields turgidity. The tumor is a stiff tissue that remains surrounded by the parenchyma in stage T1 (tumor < 7 cm).

Fig. 1. Intraoperatively, the kidney will experience different types of external loads that induce changes in the internal structures.

Using the CT images, we performed a two-label semi-automatic segmentation of the kidney parenchyma and tumor and a 3D volumetric mesh was extracted using Turtle-Seg\cite{12}. Next, we simplified and smoothed the mesh using a quadric edge collapse decimation and a 3-step Laplacian smoothing filter using MeshLab\cite{2}. A volumetric mesh was then constructed with tetrahedral elements using GMSH\cite{1} that will be further used in the biomechanical simulation to compute the deformation.

Biomechanical Simulation. During surgery, external pressure loads due to insufflation of the patient affect the shape of the kidney, causing a non-uniform deformation and changes to the tumor position from the estimation based on pre-operative images. To simulate this deformation, we used a FEM with linear elastic corotational kinematic description, because of its effectiveness when treating large-rotation, small-strain problems. The FEM system solves the second order differential equation shown in (1) over all the elements vertices.

\[ M \ddot{u} + C \dot{u} + Ku = F_{\text{external}} \]

\[ F_{\text{external}} = \text{Gravity} + \frac{\text{Pressure}}{\text{Kidney surface}} \]  

where \( M, C \) and \( K \) are the mass, damping and stiffness matrices for all vertices, \( F \) is the external load applied to the system accounting for gravity and pressure, and \( u \) is the vertices’ displacement. For the three structures of our model, different mechanical parameters are inputted as material properties. Parenchyma and tumor are given a Young’s modulus \( E \) and Poisson ratio \( v \) taken from literature: 7 kPa and 0.43 for parenchyma and 10 kPa and 0.42 for tumor \cite{13, 14}. Meanwhile, the capsule is modeled as a surface triangular spring with a stiffness parameter of 100 N/m \cite{15}. To add the external pressure, the kidneys were submerged into water. In the simulation, water pressure is computed by Tait’s equation. The volume mesh was loaded into SOFA framework\cite{4}. The corotational FEM description is solved with a conjugate gradient algorithm and an Euler implicit solver.

Error Analysis. Before the tumor resection stage of partial nephrectomy, the surgeon sees only a portion of the kidney’s surface. This is why providing localization information with respect to the kidney’s surface is relevant to the surgeon performing the procedure. Using the CT-extracted volumes, a distance \( d_{ij} \) is computed from a fiducial \( f_i \) on the surface of the kidney to each vertex \( t_j \) of the tumor surface. The volume deformation due to pressure and gravity is simulated and a second distance \( s_{ij} \) is computed in the same manner from the fiducial to the tumor. Then, a simulation localization error \( e_s \) is measured as the difference between \( d_{ij} \) and \( s_{ij} \) given by,

\[ e_r = |d_{ij} - r_{ij}| \quad e_s = |d_{ij} - s_{ij}|. \]

To measure the enhancement of tumor localization with the use of our model, we acquired a second set of five CT scans under water as an external pressure load conditions. We computed a third distance \( r_{ij} \) from the kidney surface to the tumor using the real deformed CT-extracted volume. Finally, we computed the difference of the distance \( d_{ij} \) from the undeformed CT to the real distance under deformation \( r_{ij} \) to measure the real localization error \( e_r \), (2).

3. RESULTS

First, we performed a comparison of the two CT-extracted volumes to measure the tumor displacement with respect of the surface of the kidney in the presence of an external pressure load. An example of this deformation is depicted in Fig. 2, where the presence of pressure due to water deforms the shape of the ex vivo kidney and changes the relative distance from the tumor centroid to the kidney surface by an average of 2.17 mm.

\[^1\text{http://www.turtleseg.org/}\]
\[^2\text{http://meshlab.sourceforge.net/}\]
\[^3\text{http://geuz.org/gmsh/}\]
\[^4\text{http://www.sofa-framework.org/}\]
Fig. 2. Kidney volumes extracted from CT images. (a) Shows the kidney volume under gravity and (b) the same volume submerged in water. A change in the distance of the tumor centroid to the kidney surface can be appreciated.

The model with its structures is in Fig. 3. Kidney parenchyma and tumor are constructed using tetrahedral elements with different material parameters. The parenchyma and tumor meshes constituted by 10,465 and 1,034 tetrahedra, respectively. The capsule is built by mapping the external faces of the tetrahedra to form a triangular surface mesh with uniform stiffness springs. The implemented model is placed in a virtual environment and simulations of gravity and water pressure run at 5 FPS.

Fig. 3. Model construction: (a) Shows a CT-scan slice with visible tumor, (b) generated model with surface capsule and inner tetrahedral meshes for parenchyma and tumor.

Fig. 4. Standard deviation, mean and maximum error of real error $e_r$ and simulation error $e_s$ for the five cases.

By analyzing the error for each fiducial in all the cases, another trend becomes noticeable. The fiducials that are close to the tumor present $e_s < e_r$, whereas the fiducials located at a further distance from tumor surface have less or negative improvement. An example is shown in Fig. 5.

Fig. 5. Two example cases with fiducial’s position depicted by circles if the simulation performs better, $e_s < e_r$, or crosses if on the contrary, $e_s \geq e_r$.

4. DISCUSSION

One of the main criticisms made to biomechanical models in image guided procedures is the choice of linear elastic models over non-linear, anisotropic, hyperelastic models. Al-Mayah et al. [16] presented a comparison of linear and non-linear finite element formulation for deformation modeling in image registration. Their results showed no significant differences between the models using combinations of materials (elastic, hyper-elastic) and formulation (linear, non-linear). In the present work, the average accuracy achieved by the model prediction is within 1 mm of the real displacement so it promises a sufficient accuracy in providing visual information to the surgeon about the position of the tumor.
5. CONCLUSION

This work presented the construction of a three structure biomechanical kidney model constructed from CT with parameters adopted from existing literature. The model was implemented in a virtual environment in which an external pressure load was simulated. Five different ex vivo phantom cases were analyzed comparing a position error measure of the tumor using a second reference CT scan. The results show a mean localization error improvement of 29%, thus proving the feasibility of the model for surgery planning to better localize a tumor position relative to the kidney surface. Future work will focus on a patient-specific selection of the Young’s modulus and Poisson ratio that could lead to more accurate simulation and therefore better tumor localization. However, work on the model sensitivity to parameters and their value extraction from imaging still needs to be done. Besides the pressure external load, other sources of deformation will also be analyzed.

ACKNOWLEDGMENT

This work was supported by NPRP Grant #4-161-2-056 from the Qatar National Research Fund (a member of the Qatar Foundation). The statements made herein are solely the responsibility of the authors. Grateful thanks to Dr. Abdulla Al-Ansari and Dr. Osama Al-Alao for data acquisition.

6. REFERENCES


