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FEM-based confidence assessment of non-rigid registration

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Non-rigid registration is often used for 3D representations during surgical procedures. It needs to provide good precision in order to guide the surgeon properly. We propose here a method that allows the computation of a local upper bound of the registration confidence over the whole organ volume. Using a biomechanical model, we apply tearing forces over the whole organ to compute the upper bound of the degrees of freedom left by the registrations constraints. Confrontation of our method with experimental data shows promising results to estimate the registration confidence. Indeed, the computed maximum error appears to be a real upper bound.

1 Introduction

While performing a surgery, the surgeon's goal is to minimize the risk for the patient. For this purpose, minimally invasive surgery has been favored over traditional open surgery, especially in abdominal surgery. Such procedures can be very challenging for the practitioner to perform. It is mainly due to the fact that they don't see what they are doing through their own eyes. Views are often showed through a screen and captured either with an endoscope, Ultrasound probe or other devices. This is challenging because it forces the surgeon to mentally map what he sees to what he is doing. A way to help surgeons during the surgery is to add virtual information on the screen, for instance the 3D volume of a tumor into a liver. This should provide information allowing him to resect a minimum of healthy tissues.

To reach this objective, one first needs to make a registration of the organ that the surgeon is seeing through the measurement device. Combining a biomechanical model to data extracted from intraoperative images have yielded good results. This can be done either by using some points extracted from the surface [1, 2], the whole surface [3] or information on the organ volume extracted from ultrasounds [4]. Yet all the above methods are subject to errors. Through this method, we propose a tool providing an estimation of the confidence of a model-based registration method.

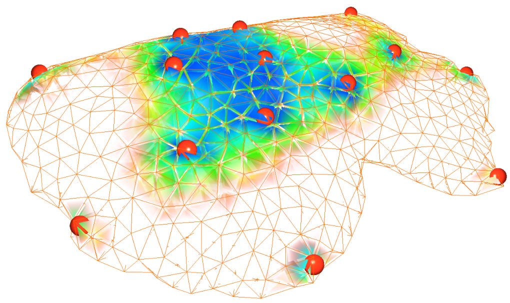

Figure 1: *High confidence (low mobility) areas are colored with shorter wavelength (blue). If the degree of confidence is lower than a threshold, the elements become transparent.*

2 Method

Our method takes as input the Finite Element mesh of the organ in the registered state. The registration can be performed by one of the method cited above or any method combining a biomechanical model with measured data. The method consists on evaluating the maximum mobility of the model at each point of its mesh, the confidence being high when the mobility of the point is low. The main assumption of the paper is that the deformation generated by the surgeon during the procedure does not damage tissues. Therefore, the maximum mobility is computed by applying an upper bound stress taken from the literature, known to cause irreversible deformations to the organ while satisfying the registration constraints into the simulation. This stress is successively applied along multiple directions on the model, in order to test each degree of freedom of the organ. Those directions are given by $\mathcal{D} = (\mathbf{x}, -\mathbf{x}, \mathbf{y}, -\mathbf{y}, \mathbf{z}, -\mathbf{z})$. The computation of the mobility $\mathbf{c}$ at each point i is formalized in the following equation :

$$\mathbf{c}_i = \max_f(||\mathbf{q}_i - C(\mathbf{d} \times f \times k)||) \quad \text{with} \quad \mathbf{d} \in \mathcal{D} \qquad (1)$$

Where C is a non linear function providing the positions of the model at static equilibrium after the application the volume force f multiplied by the surrounding volume k. The rest positions of the model are considered to be the positions provided by the registration method. This may lead to more mobility of the model because of the lack of internal stress which usually rigidify the tissue. This way, the computed displacement remains an upper bound. The confidence map can be represented as shown on the figure 1.

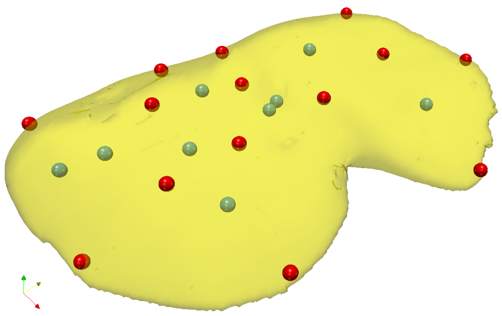

Figure 2: *Volume of a lamb liver with the outer markers in red and the inner ones in green.*

3 Confrontation to real data

Our method was tested on a data set of an ex-vivo liver of a lamb. External markers were put on the surface, which were then used to perform the registration along with internal markers that were used to evaluate the accuracy of the registration method. Then the volumes of the liver and the markers were segmented from CT-Scans in five different positions of the lamb liver.

Cross-registrations were performed between the different positions of the liver using external markers. We used a linear elastic model of the deformation along with a corotational finite element formulation [5] of the problem on tetrahedron elements. This formulation shows good results and gives good approximations of the non-linearity of the deformation while keeping low time complexity. The liver finite element model parameters are given by a Young modulus of $6kPa$ and a Poisson ration of 0.499 as found in the literature for healthy livers [8]. After the registrations, the distance between internal markers segmented from the CT images and the one provided by the model were considered as *ground truth* values of the registrations' accuracy. Our method was then applied on each configuration of the liver, in order to compute the theoretical upper bound of mobility. Given the material properties of the model described above, the force f used in the equation 1 is parameterized to reach 30% of strain. Indeed, despite the stress leading to tissue tearing vary amongst patients, this value is, according to the literature [6, 7], identified as an upper-bound value leading to irreversible deformations of the tissue.

4 Results

The mechanical study performed by our method takes into account the complex coupling between constraints provided by image data. Indeed, as shown in figure 1, the resulting confidence map provided by our method is not directly related to the distance with external markers. Instead, it provides complex shapes that cannot be generated with simple geometric primitives. Figure 3 shows that our method predicted 96.6% of the time a real upper bound of the registration accuracy.

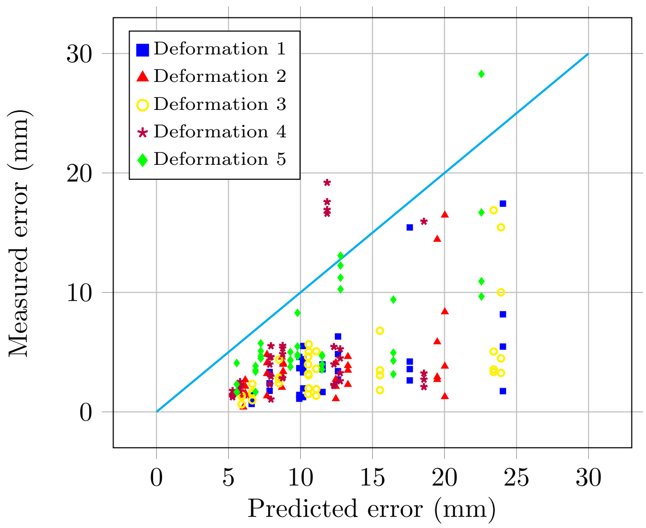

Figure 3: *Predicted error given by our method with respect to the measured error (given by the cross registrations) at each inner marker. Each label stands for a different target configuration.*

5 Conclusion

We proposed a method allowing to evaluate the registration accuracy of internal structures. The method provides an upper bound uncertainty of positions of a biomechanical model, that can be used to discriminate and display only the reliable parts of the model in the augmented view. Future works concern additional validation study with more data and registration methods.

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