Patient-specific isogeometric analysis for vascular biomechanics

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YIC2013
Second ECCOMAS Young Investigators Conference
2–6 September 2013, Bordeaux, France

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Abstract. *Isogeometric Analysis (IGA) has recently emerged as a cost-effective alternative to classic isoparametric Finite Element Analysis. In this work a novel computational framework is proposed in order to get IGA-suitable geometries to simulate different vascular minimally-invasive procedures. The preliminary results show the capability of the framework to import in a straightforward way patient-specific vascular geometries and set an analysis enviroment suitable for the solver FEAP.*

Keywords: Isogeometric Analysis; Vascular Biomechanics; Mapping; FEAP.

1 INTRODUCTION

Cardiovascular disease (CVD) is the main cause of death in western countries and it is responsible for hundreds of thousands of early deaths all over the world. CVD is not only a major threat to individuals' lives and their quality of life but it is also a major economic cost to all European countries [1]. Several treatment options are nowadays available for managing many CVD but, thanks also to the encouraging outcomes achieved in the coronary district, the application of percutaneous minimally-invasive techniques, such as stenting, grafting and angioplasty procedure, are also applied to other peripheral districts. Device design, development and performance assessment of these minimally-invasive procedures are the natural application field of computational biomechanics, which applies the principle of mechanics to investigate biological systems and their interaction with artificial implants. In particular, patient-specific modeling has been proposed in recent years as a new paradigm in surgical planning support based on computational tools [2, 3, 4, 5].
Moreover, Isogeometric Analysis (IGA) has recently emerged as a cost-effective alternative to classic isoparametric Finite Element Analysis (FEA) [6]. The main feature of the method consists of using typical CAD basis functions for both geometric description and variable approximation. This implies the ability to describe exactly the computational domain geometry throughout the analysis process, including, at the same time, the chance to control the basis functions continuity. These features led to a wide variety of approaches able to treat efficiently many critical aspects of FEA (e.g., analysis of nearly incompressibile solids and novel contact formulations [7, 8]). Starting from these results, the aim of this work is to create a computational workflow able to convert the information coming from vascular patient-specific DICOM images into a IGA-suitable geometric structure and to perform a preliminary analysis resembling a minimal-invasive procedure i.e., carotid angioplasty, using an an extension of FEAP, a numerical solver widely adopted for research in FEA, to IGA [9].

2 MATERIALS AND METHODS

The main objective of this work is to provide, given the vascular medical images, a geometrical structure IGA-suitable. This task can be achieved through the following steps:

- Image processing: the set of DICOM medical images need to be processed in order to get a finite number of point able to describe the vascular surface;
- Mapping: starting from a given NURBS parametrization (primitive surface) and the set of points previously extracted (reference surface), a least-square based mapping procedure was implemented in order to obtain two patient-specific NURBS surfaces, resembling the inner and outer vascular wall, respectively;
- FEAP-suitable block structure: the two NURBS surface need to be integrated in order to obtain a 3D IGA solid structure suitable for the solver FEAP;

The proposed framework includes all the other ingredients needed by IGA (boundary conditions, material definition) and, as a preliminary analysis, a displacement-control simulation of angioplasty procedure has been performed.

2.1 Image processing

The vessel model considered in this study reflects the geometry of a patient-specific carotid artery, derived from DICOM images of a neck-head Computed Tomography Angiography (see fig.1-a). After a segmentation step (fig 1-b), the vascular surface was splitted into its main branches (fig 1-c) using the vascular model toolkit VMTK [10]. The final pre-processing step consist on the skeletonization of the surfaces and the subsequent points extraction (fig 1-d). These points represent the reference surface for the subsequent mapping procedure.

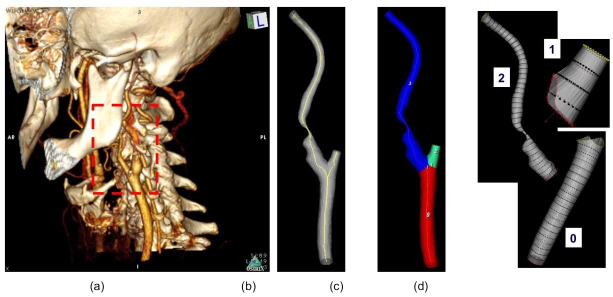

Figure 1: Image processing step: 3D volumetric reconstruction from CTA images (a); vascular STL surface and centerline (b); vascular surfaces after branch splitting (c); sampled sections after skeletonization process (d).

2.2 Mapping procedure

In order to obtain a IGA-suitable NURBS structure starting from a set of points representing the vascular geometry, we implemented the mapping procedure proposed by Morganti [11], that has been successfully applied to aortic root geometries. A generic NURBS surface defined in $\mathbb{R}^3$ can be described with the following relation:

$$\mathbf{S}(\psi,\eta) = \frac{\sum_i \sum_j N_{i,p}(\psi) M_{j,q}(\eta) \mathbf{B}_{ij} w_{ij}}{\sum_i \sum_j N_{i,p}(\psi) M_{j,q}(\eta) w_{ij}} \tag{1}$$

where $\mathbf{B}_{ij}$ and w_{ij} represent the i,j-th control point coordinates and weight, respectively, and $N_{j,q}$ and $M_{i,p}$ are the i-th j-th shape functions of order p and q respectively, related to each parametric direction.

Assuming constant weights, after some simple algebraic manipulations, eq.1 can be rearranged in order to get the following matricial form

$$\mathbf{S_T}^{\mathbf{r}} = \mathbf{C} * \mathbf{B}^{\mathbf{r}}{}_{vec} \tag{2}$$

where $\mathbf{S_T}^{\mathbf{r}}$ represents the r-th cartesian nodal component of the sampling points belonging to the reference surface, $\mathbf{B}^{\mathbf{r}}{}_{vec}$ is the r-th cartesian component of the control points ordere in vectorial form and $\mathbf{C}$ roughly contains the products between shape functions values in both parametric directions. It is immediate to observe that eq.2 represents a linear system which can be solved (in the least-square sense) in order to obtain the r-th component of the mapped control points.
The proposed approach can be used to map a primitive cylinder with a predefined parametrization onto each of the carotid artery branch.

2.3 IGA structure and preliminary analysis

After the mapping procedure, the three NURBS patches, one for each vessel branch, need to be refined and integrated in a single vessel geometry, defined by 3D solid elements. This task is achieved by means of an in-house Matlab code (The Mathworks Inc., Natick, MA, USA) that includes a refinement step, both *h* and *p*, and several routines for the management of some critical geometrical aspects, as the interpach continuity at the bifurcation level. In the last part of the code the NURBS structure is exported in a format compatible with the isogeometric package for FEAP. The Matlab code takes advantage of the routines given by the NURBS toolbox and by some customed routines from the software tool GeoPDEs [12]. As preliminary analysis, a simulated angioplasty (AP) procedure for the carotid artery has been performed. From the clinical perspective AP is defined as the technique of mechanically widening narrowed or obstructed arteries, typically being a result of atherosclerosis. This task is achieved by mean of a ballon catheter that is passed into the narrowed location and then inflated to a fixed size and subsequently deflated and withdrawn. From the computational viewpoint AP can be roughly simplified as a displacement-controlled analysis with a finite-strain regime and (non)linear elastic constitutive behavior associated with the vessel model. The mechanical response of the vessel is reproduced assuming a Neohookean hyperelastic material model, defined by the two parameters E=2 MPa and ν=0.45. The ballon expansion was simulated by mean of a displacement field applied to the vessel's inner wall control points. The displacement values were structured as the difference between the expected configuration and the reference configuration

3 RESULTS AND DISCUSSION

The von Mises stress distribution after the AP simulation is depicted in figure 2. The results show, in a simplified way, the interaction between the expanded balloon and the vessel wall, exhibiting higher stress values in the stenotic region. This information, after a necessary refinement of the model features, can be associated with different clinical issues, such as vessel damage after AP and restenosis risk. It is important to note that this simulation was performed using only 3600 degrees of freedom, at least one order of magnitude less than typical FEA meshes for similar purposes [2, 3] . However, in order to ensure a fair comparison between FEA and IGA and to get a valuable tool for different cardiovascular applications, i.e., stenting and endografting, some more sophisticated tools, such as stable contact driver and complex constitutive models, need to be developed.

4 CONCLUSIONS

In the present study we present a novel computational framework able to integrate medical information and computational tools in order to perform IGA for vascular biomechanics. The results suggest that it is possible to obtain an IGA-suitable structure in a reasonable number of steps. Moreover, a preliminary analysis has been performed in order to make the point about the capability of the workflow to reproduce, in a simplified way, a minimally-invasive procedure present in the clinical practice. In order to obtain a valuable tool for a wider range of clinical procedures, such as stenting and grafting, some more sophisticated components (such as stable contact driver,pressure elements, biologic materials constitutive models etc.) need to be developed. We think that IGA for vascular biomechanics represents a big challenge both from computational and model design viewpoint and can give, in the next future, a crucial contribution to the integration of medicine and numerical analysis.

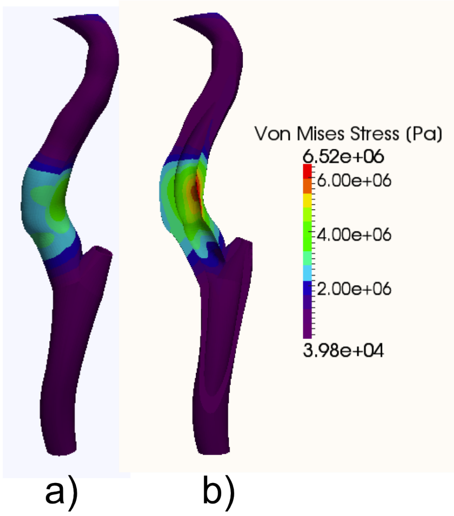

Figure 2: von Mises stress distribution of the ballon expansion simulation: complete vessel structure (a); clipped structure in order to visualize the stress at the lumen level (b).

5 ACKNOWLEDGEMENTS

This work is supported by the European Research Council through the FP7 Ideas Starting Grant project no. 259229 and by the Cariplo Foundation through the Project no. 2009.2822. The authors would also like to acknowledge Eng. Chiara Trentin for her support on medical imaging aspects related to the present work;

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