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Innovative and efficient stent flexibility simulations based on isogeometric analysis

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Abstract

One of the main properties of cardiovascular stents is to properly bend in order to accommodate the tortuous vascular structure and Finite Element Analyses (FEA) are currently the preferred computational tool to properly evaluate the stent response under bending. Isogeometric Analysis (IgA) has recently emerged as a cost-effective alternative to classical FEA, based on the use of typical CAD basis functions for both geometric description and variable approximation. This implies the capability to describe accurately the computational domain geometry and, typically, a better approximation of the solution with many fewer degrees of freedom with respect to FEA.

Accordingly, this work aims at describing a computational framework based on IgA to evaluate the mechanical performance of endovascular stents. In particular, stent bending analyses involving large deformations are performed using both IgA and classical FEA for two carotid artery stent designs. The results discussed here suggest that for a given level of accuracy IgA attains a better performance with at least one order of magnitude fewer degrees of freedom than classical FEA. Moreover IgA shows an improved capability to reproduce local geometrical instabilities due to buckling.

Keywords: Isogeometric analysis; Shape memory alloys; Carotid artery stents; Stent flexibility; Buckling

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1. Introduction

In the last decade the use of carotid artery stents (CAS) for stroke prevention has rapidly evolved as a reliable alternative to the traditional approach of carotid endarterectomy. As an example, in the United States CAS expanded from less than 3% of the total number of carotid artery revascularization procedures in 1998 to 13% in 2008 [1]. The key device of CAS is the so-called *stent*, a metallic frame that is driven to the target lesion to restore the carotid artery patency by enlarging the narrowed lumen.

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A proper delivery and placement of endovascular stent devices is of utmost importance to ensure the safety and performance of the implant. For this reason, an adequate stent flexibility, typically evaluated by means of bending tests, plays an important role in the stent delivery process as well as in the reduction of the stress generated by the interaction between the device and the surrounding biological tissue.

In this aspect, the quantitative evaluation of mechanical and geometrical properties is of critical relevance for a reliable characterization of flexibility for stents already available on the market or during the design process of new devices. This topic has been widely investigated in the literature, both from the experimental and the numerical point of view. In particular, different experimental benchmarks were proposed with particular emphasis on coronary artery stents [2–4]. However, only the works of Müller-Hülsbeck et al. [5] and Carnelli et al. [6] implemented an experimental benchmark for carotid artery stents. On the other side, many virtual benchmark tests, typically based on structural Finite Element Analysis (FEA), have been developed as a complementary tool to the experimental studies [7–11].

Within this context, FEA is widely employed when experimental tests are difficult to implement or when a large number of materials, geometries, and loading conditions need to be investigated before prototype fabrication. In particular, Mori and Saito [4] studied the flexibility of four coronary artery stents by means of a two-dimensional (2D) FEA model resembling a small portion of the complete device. Petrini et al. [7] and Grogan et al. [11] proposed a there-dimensional (3D) FEA model for stainless steel and adsorbable metallic coronary stents, respectively. Both models reproduce only a portion of the complete device. Eventually, Wu et al. [8] proposed a virtual flexibility test for coronary artery stents based on a multipoint constraint. They implemented a 3D FEA model of a full elasto plastic device. We believe our work is the first numerical study approaching the flexibility evaluation for shape memory alloy carotid artery stents within a computational framework applied to a 3D model of the whole device, considering also geometrical instability phenomena.

In our view, FEA presents some drawbacks that can limit the description of the domain under investigation and the accuracy of the approximated solution. In particular, the low-order and low-regularity polynomials used to discretize the continuum domain do not allow, in general, to accurately represent complex geometries unless extremely fine meshes are adopted. At the same time, FEA basis functions do not allow one to properly approximate the solution without resorting to a high number of degrees of freedom.

Isogeometric analysis (IgA) has recently been developed as an exact-geometry, cost-effective alternative to classical FEA [12,13]. Roughly speaking, IgA proposes to replace the low-order, low-regularity FEA basis functions with the high-order, high-regularity basis functions employed in computer-aided design (CAD) while retaining an isoparametric framework. In particular, non-uniform rational B-splines (NURBS) were initially chosen as the basic environment for IgA due to their widespread use in the CAD community, but nowadays other more flexible options also are available (see, e.g., [13–15]).

An initial motivation for IgA was a desire to reduce the engineering time for model generation by using a single mathematical representation for both design and analysis. However, the higher regularity of IgA shape functions with respect to FEA extended the range of applications to all the fields in which high continuity plays a preeminent role, e.g., the study of structural vibrations [16–19], the analysis of nearly incompressible solids [20–22], novel structural elements [23–27], novel contact formulations [28], turbulent flows and fluid–structure interaction [29,30].

Only a few works have investigated the features of IgA applied to vascular biomechanics. In particular, Zhang et al. [31] focused on the geometrical representation of complex vascular branches to get accurate, IgA-suitable models for the analysis of blood flow. Bazilevs et al. [32] and Bazilevs et al. [14] developed an IgA-based fluid–structure interaction model, developed within an Arbitrary Lagrangian Eulerian framework, to investigate the interaction of the arterial wall and the blood flow. Morganti et al. [33] developed a computational framework to compare the performance of IgA and FEA applied to the structural closure of a patient-specific aortic valve model. The work of Morganti et al. [33] is the first structural investigation addressing the benefits of IgA with respect to benchmark FEA shell elements applied to vascular biomechanics.

Within this context, the present paper represents the first study investigating the impact of structural IgA for the evaluation of the mechanical properties of endovascular devices. In this work we consider the behavior of two carotid artery stent designs that resemble two commercially available devices. NURBS-based IgA and classical FEA are adopted to model the 3D bending problem in a large deformation regime corresponding to the cantilever beam bending experiment proposed by Müller-Hülsbeck et al. [5]. In our work we develop a computational framework able to automatically obtain an IgA-suitable stent discretization from a CAD model. Moreover, our framework is also extended to automatically obtain an equivalent highly structured finite element mesh.