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Comparison and calibration of a real-time virtual stenting algorithm using Finite Element Analysis and Genetic Algorithms

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Abstract

In this paper, we perform a comparative analysis between two computational methods for virtual stent deployment: a novel fast virtual stenting method, which is based on a spring–mass model, is compared with detailed finite element analysis in a sequence of *in silico* experiments. Given the results of the initial comparison, we present a way to optimise the fast method by calibrating a set of parameters with the help of a genetic algorithm, which utilises the outcomes of the finite element analysis as a learning reference. As a result of the calibration phase, we were able to substantially reduce the force measure discrepancy between the two methods and validate the fast stenting method by assessing the differences in the final device configurations.

Keywords: Virtual stenting; FEA; Stent deployment; Genetic algorithm; Modelling; Spring–mass

1. Introduction

Endovascular devices (stents, stent grafts, flow diverters) are widely adopted for restoring the patency of arteries and veins. Over the last decade, the development in stent technology has been rapid and has revolutionised the treatment of many cardiovascular diseases by offering a minimally invasive alternative to complex open heart surgical interventions [1]. Progress on different designs, materials and surface processing allowed the use of stents for treating a wide variety of conditions, including stenosis and aneurysms of coronary [2], carotid [3], cerebral [4], thoracic [5] and peripheral arteries [6] and, more recently, cardiac valve dysfunction [7,8]. As a consequence, interventional cardiologists currently have an extensive range of products at their disposal that enable them to reach complex cardiovascular districts from different access sites. This variety of available devices also aims at targeting diverse patient populations

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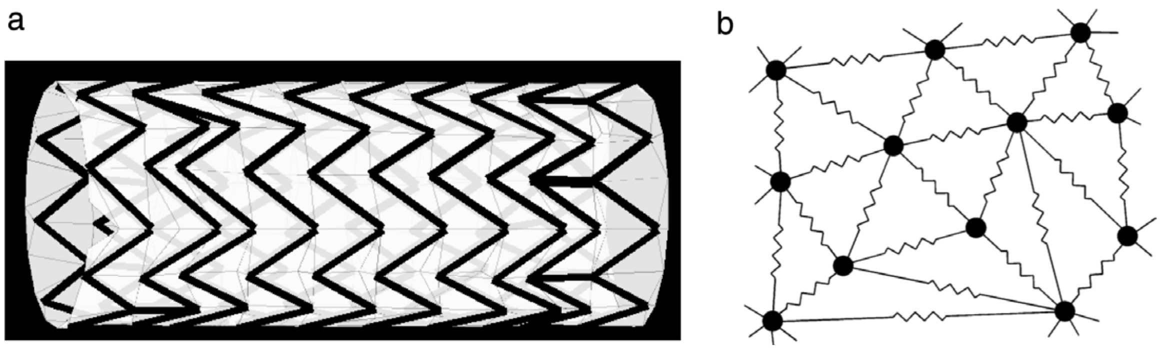

Fig. 1. Stent graft model. (a) Reconstruction of the stent graft. (b) Schematic representation of a spring–mass mesh: the mesh consists of discrete mass points connected by lineal springs.
Source: Image (b) adapted from Meier et al. [23].

who might suffer from acquired or congenital heart diseases. In addition, every stent is associated with its own mechanical implantation performance, characterised by different foreshortening, dog-boning, deliverability and elastic recoil [9]. Such increasing availability can make the choice of the most suitable device more complicated and, therefore, makes it desirable to accurately predict optimal stent placement, especially under patient-specific conditions [10–12].

Computational models, like finite element (FE), have been widely employed in the past to study stent implantation. FE simulations supported the inexpensive testing of novel designs, materials, etc., and contributed towards better understanding of the mechanisms of stent expansion [13,14]. More recently, thanks to the advances in cardiovascular imaging and computational power, it has also been possible to include patient-specific anatomical models in the simulations, to study the interactions with complex geometries [15–17] and the risk of structural failure in these environments [18]. However, the complexity of such simulations still requires relatively high computational times, which limit the use of FE simulations to support daily clinical activities.

In this context, there have been a number of attempts to develop different computational methods to simulate stent deployment in "real-time". These methods feature fast computational times, necessary for their usefulness in clinical settings; however, they still display considerable simplifications, especially in stent modelling, which is often based on fitting a generic cylinder inside the vessel, on the surface of which stent struts are subsequently drawn [19,20]. Even the approach proposed by Larrabide et al. [21] that models the stent design explicitly is challenged by complex vascular geometries. Therefore, to the best of our knowledge, no virtual stent deployment method has yet been proposed, that is able to combine fast turnover times with sufficient accuracy.

Against this background, we developed a novel fast computational method to simulate stent deployment under patient-specific conditions, specifically designed to be subsequently used in clinical practice [22]. This fast method is based on a spring–mass model and can potentially take into account different device designs as well as emulate deformable vasculature. Although the spring-mass method offers a convenient way to model mechanical behaviour in real-time due to its simplicity, the search for the appropriate springs constants is not straightforward. Moreover, the fast computational speed inevitably comes with a cost of reduced accuracy; therefore, the error has to be thoroughly estimated. Hence, the goal of this study is to perform a rigorous comparison of our fast method against FE analysis and to use FE outcomes as a learning base for fitting the required parameters. For that purpose, we conducted a series of experiments of increasing complexity, in order to evaluate the discrepancy in final device configurations and residual force estimation. Thereafter, we performed an optimisation step, in which the parameters of the fast method were calibrated with the help of a genetic algorithm which was guided by the FE results. We conclude the paper by presenting the post-calibration results and the outlook on further improvements.

2. Methods

This study focuses on the analysis of a novel numerical fast method (FM) to simulate the process of stent expansion, as compared to detailed Finite Element (FE) analysis. The device employed in this comparison resembled a self-expanding stent graft that is widely used for the treatment of aortic aneurysms and dissections (Fig. 1(a)). The device consists of an external self-expanding nitinol wire structure (i.e., stent struts) that is helically attached along the