A finite-element Julia platform for solid-to-beam contact modelling in vascular biomechanics

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Abstract

Stent-based devices have become pivotal in the treatment of various peripheral and cerebrovascular diseases, including the use of stents for vessel support and stent retrievers for thrombectomy procedures. These devices, typically small cylindrical structures made of metal or polymer, are delivered into the vasculature via a catheter. Upon deployment, stents expand to prop open diseased vessels and restore blood flow, while stent retrievers are designed to capture and extract clots. However, the interaction between these devices and the vascular wall during deployment or retrieval can induce non-physiological stresses. Additionally, the significant displacements and geometric nonlinearities inherent to these processes make it difficult to predict the final device configuration or the treatment outcome. This unpredictability can lead to prolonged intervention times and potential complications. Therefore, there is a critical need for advanced computational algorithms that enable virtual planning of stent deployment and retrieval, delivering accurate simulations within clinically relevant timeframes.
Finite element models have been widely employed to simulate the intricate interactions between stent-based devices, arterial walls, and clots (1-3). These models offer valuable mechanical insights into the behaviour of these medical devices, facilitating the optimization of their designs to improve performance and durability (4). Additionally, patient-specific simulations, which incorporate individual anatomical geometries, are playing an increasingly prominent role in clinical decision-making by predicting both short- and long-term treatment outcomes (5).

In finite element simulations, 3D beam elements are commonly used to model stents due to their computational efficiency, while solid elements (e.g., tetrahedral or hexahedral) are typically reserved for detailed structural analyses (6,7). Arterial walls are represented using either shell (5) or solid (1) elements, depending on the level of complexity and the need to capture their multilayered architecture. Clots are typically modelled using solid tetrahedral elements (2), with material properties tailored to account for variations in their composition and mechanical behaviour.

Many prior studies on the subject rely on commercial software like Abaqus to perform these

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simulations. While commercial software offers reliability and ease of use, it comes with notable limitations. These include high licensing costs, thus typical restrictions on the number of licenses available, and limited flexibility for modifying the underlying computational formulations. Such constraints can limit the customization required for specialized applications and restrict the ability to run multiple simulations in parallel-an essential capability in machine learning.

In this context, this work proposes an efficient, open-source finite element framework for vascular biomechanics written completely in the Julia programming language. Julia was deemed a good candidate for the implementation because it provides an optimal balance between performance and usability, combining the computational speed of compiled languages with the interactivity of MATLAB and Python. This framework was developed leveraging existing formulation for solid mechanics (8) and our previous work on beam-to-surface contact mechanics (9). Specifically, we have recently reported an efficient 3D corotational formulation to simulate a beam-to-rigid surface contact. In contrast to total Lagrangian beam formulations, the motion of each element in this formulation is separated into a rigid body component and a small local deformation. Consequently, this approach yields a computationally efficient formulation by allowing us to model beam deformation via linear constitutive models while incorporating nonlinearities into the rigid body component. Specifically, this beam formulation was implemented within the Julia-package EndoBeams.jl, which has proved very fast, with computational times comparable with Abaqus, thanks to its specific finite element formulation and the very efficient implementation with parallel computing capabilities (10). For the vascular model, we relied on a 3D total Lagrangian implicit finite element formulation of solid elements, which allows the simulation of hyperelastic solids.

In the current work, we built upon these advances to develop a fully implicit algorithm to couple the contact between solid elements and corotational beam elements. The contact was modelled using the master-slave approach described in (11). The framework was used to simulate stent deployment in deformable vessels and clot retrieval using stent retrievers. After detailing the formulation and implementation, we will present several examples to demonstrate the efficacy and robustness of the proposed algorithm.

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