Deployment of architectured membranes for biomedical application.

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Elastic sheets with mesoscale architecture obtained by folding or cutting have recently drawn considerable interest in the mechanics and engineering community. The cuts and features can be tailored to allow the sheets to morph into complex three dimensional shapes with unusual mechanical characteristics such as auxeticity, deployability and programmable non-linear properties.

The main objective of the project is twofold: to identify and build a fundamental understanding of the **mechanical response of hyperelastic membranes with architected cut patterns** on the one hand and to transfer the resulting tunable mechanisms to prototypes for more reliable **compliant medical devices** on the other hand.

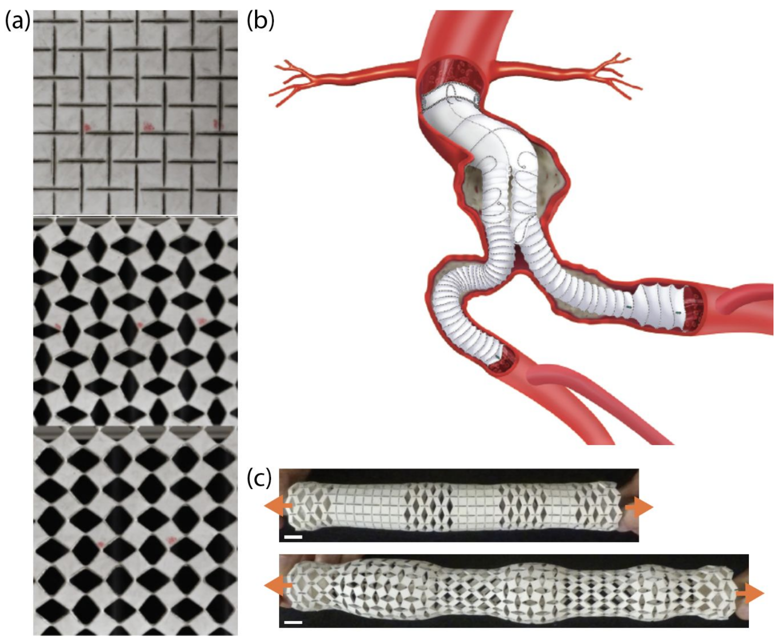

Figure 1: (a) Preliminary experiment of a tension test showing the deformation mode of an hyperelastic membrane with architected cut patterns. (b) Anaconda stent system composed of three piece modular track design in infrarenal abdominal aortic aneurysm (from [4]) (c) Architected tube with non-periodic network can expand and contract radially upon stretching (from [1]).

1. Mechanical response of hyperelastic membranes with architected cut patterns.

Recent studies have rationalized the deformation modes of sheets with architectured cut patterns by describing their kinematics [1] and have attempted to address the inverse problem of determining the number, size and orientation of the cuts that enable the deployment of the membrane into a three dimensional target shape [2,3]. These kinematic studies do not provide a predictive description of the mechanical response of the structure. This model is necessary to understand the deployment path and the stability of the deployed state. The first task of the project is to create a mechanical model of this type of structure. We will develop model experiments using digital fabrication and rapid prototyping techniques and characterize the kinematic and mechanical response of the structure. Hand in hand with experimental characterization, we will develop a numerical approach to build a nonlinear effective shell model based on homogenization of periodic network of cut patterns using Homtools toolbox on Abaqus to compute the relationship between the average generalized stresses and average generalized strains of the structure. We will extend this approach to non-periodic networks (with slow variation of the microstructure). To account for cases with abrupt variation of the microstructure, we will develop a parallel strategy based on global energy minimization of a reduced description of the structure (rigid panel connected by rotating hinges with bending and extensional stiffnesses). Both models will be benchmarked against mechanical response measured in experiments.

2. **Transfer to architectured tubes for compliant medical devices.**

Stents are routinely used in angioplasty procedures to open narrowed arteries (e.g. to treat coronary artery disease) or to tunnel blood flow away from aneurysms. The complexity of the anatomy of some arteries (Fig.1b) currently limits the use of endoprostheses. Practitioners use artisanal handicraft design rather than optimized tailor-made solutions. While conventional stents have cylindrical uniform diameters, more complex deployed forms are needed to better adapt to the anatomy of arteries that present a high sinuosity [4]. We will focus on cylindrical geometry to program the cut patterns on tubes. We will first focus on hyperelastic model materials (Fig.1c), extend the mechanical description developed for the sheets to cylindrical geometry and optimize the cut pattern to program the mechanical properties and deploy the tube into the specific anatomical target shape. Medium term research aim includes transfering the deployment process to prototypes made of nitinol, a shape memory alloy compatible with biomedical applications used in self-expanding stents, in collaboration with the *Cardiac and Vascular Disease unit* of the CHU Montpellier.

3. **Expected profile.**

Candidates with either a PhD in Mechanical/Civil/Aerospace Engineering and research achievement in the general area of soft/compliant mechanics or structures are welcomed to apply. The project will have an experimental component, so experience in laboratory settings is desired. The following areas of expertise are particularly welcomed: rapid prototyping, micro-fabrication, material science and mechanical testing. Familiarity in using finite element analysis and optimization methods is highly desirable. The successful candidate will join a team of researchers with interdisciplinary expertise in experimental, computational and theoretical mechanics. Experiments will be conducted in IUSTI with J.Marthelot, homogenisation with Homtools, reduced description of the structure and shape optimization under the supervision of S. Bourgeois and C. Bellis in LMA. Opportunities for involvement in the teaching of mechanics-related classes in the new Mechanical and Engineering Institute from Aix-Marseille University (for example through the supervision of M3S projects with S. Bourgeois and J. Marthelot in Centrale Marseille) will be provided.

Bibliography:

[1] Celli, P. et al. Shape-morphing architected sheets with non-periodic cut patterns. *Soft matter* **14** 9744-9749 (2018).

[2] Konaković, M. et al. Beyond developable: computational design and fabrication with auxetic materials. *ACM Transactions on Graphics* ***35***(4), 1-11 (2016).

[3] Choi G.P.T., et al. Programming shape using kirigami tessellations. *Nature Materials* **18**, 999-1004 (2019).

[4] Geelkerken R.H. et al., Anaconda™ AAA Stent Graft System for Challenging AAA Anatomy. *Endovascular Today* (Nov. 2016)