Design of Personalized Shape-Morphing Stents Using Auxetic – Non-Auxetic Metastructures

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Introduction: Mechanical metamaterials are engineered structures whose elastic properties originate primarily from the geometry and connectivity of their unit cells. Metamaterials have been considered in biomedical applications, especially in designing next-generation stents. The previous studies reported origami [1], kirigami [2] or lattice-based [3] stents to improve deployability and compliance. The common point of these studies is that the patterns of the structures are monophasic in terms of auxeticity, in other words, they are either fully auxetic, or fully non-auxetic. However, hybridizing auxetic and non-auxetic patterns through a computationally-driven design process may provide multiple shape-morphing characteristics which may enable design of stents to match complex curviplanar morphologies, such as the gastrointestinal tract. In this study we propose a design procedure for personalized-stents consisting of auxetic (anti-tetrachiral) and non-auxetic (nodal honeycomb) phases. The developed algorithm analyzes the geometrical configuration of the presumed canal, discretize the surface based on local shape formation, and generates the required pattern type and Poisson's ratio for each section.

Methods: Our design methodology uses the anatomical geometry as the deployed shape of the stent based on personalized imaging as a starting point. The approach then generates the uniform undeformed tubular structure. Sample input canal geometries with expanding, contracting and bending sections were designed as surfaces (Figure 1A) and they were meshed with 4-node rectangular elements (Figure 1B). The coordinate data of nodes were analyzed in Matlab. The developed algorithm calculates the distance of each node from the central axis of the stent and compares with the undeformed diameter. Depending on this comparison the sections with expansion and contraction (blue and red in Figure 1C respectively) are color mapped and the maximum and minimum node distances from the central axis are used to calculate the Poisson's ratio of each section. The nodes of which distance from the central axis is equal to the radius of the undeformed geometry are used to determine auxetic and non-auxetic phase boundaries (green in Figure 1C). The undeformed diameter of the tube was set as equal to the bottom end of the input geometry and the length is determined by reducing the length of the deformed geometry by assumed applied longitudinal strain for deployment (10%) (Figure 1D). Transferring the color map from deformed to undeformed body functions as a guide to build the stent in the next steps.

In order to combine different patterns, their unit structures must be relatable and have mutual geometrical features. Nodal honeycomb pattern was developed with the addition of square node to conventional honeycomb. This addition enabled auxetic anti-tetrachiral pattern to be combined with a non-auxetic pattern. For the geometrical integration the unit sizes were set as the same. The geometrical parameters of patterns with required Poisson's ratios were created by using the analytical models defining in plane mechanical characteristics [4,5]. Since we program the metastructure by tuning the Poisson's ratio ($x\nu_1 = y\nu_2 = z\nu_3 = \ldots$), Young's modulus of each section was set to the same value ($E_i = E_j$, i,j=1,2,3,..).

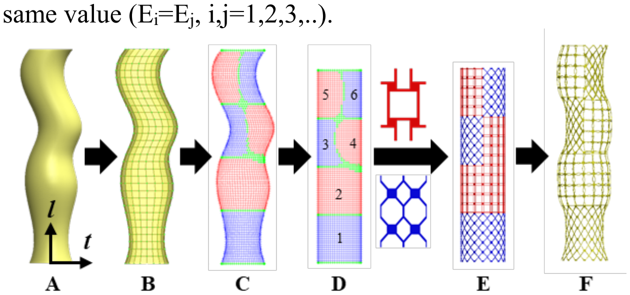

Figure 1: The design process

According to the output of the geometrical analysis algorithm and results of the mathematical models providing mechanical integration, the unit geometries were designed. The stent is built by assembling designed pattern pieces according to the color map on the undeformed body (Figure 1E). Resulting stent model was then tested via finite element analysis (SolidWorks 2019) by loading the model with the same pre-defined longitudinal strain value (10%) to compare with initial canal geometry (Figure 1F).

Results and conclusions: Data collected from edges of the deformed geometries (canal and stent) in *lt*-plane were plotted (Figure 2). The result shows a successful coherency with a maximum of 11% error. The error may be eliminated by creating a Poisson's ratio gradient within each section.

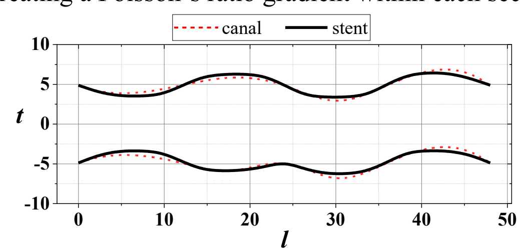

Figure 2: Comparison of pre-defined canal and deformed shape of the designed stent.

This study proposes a novel perspective for the stent technology by creating different shape-morphing characteristics in different regions of the structure which takes the geometric form of the targeted environment. This concept may be enriched with addition on other patterns. The next stage of the process will involve fabrication of patterns emerging for this design process using 3D printing and assessing their conformation to anatomical features that are derived from MR images.

References:

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