DESCRIBING FIBER BUNDLE MESOSTRUCTURE OF THE AORTIC HEART VALVE

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INTRODUCTION

Collagenous soft tissues, such as skin, ligaments, and heart valves, have complex branching mesostructures that are directly related to their function. In the heart valve, distinct fiber bundles extend from the commissures to the belly of the valve (Fig. 1). These fiber bundles are connected to one another along their length by thin sheets of collagen. Many of the fiber bundles also transition into sheets towards the belly of the valve.

Because of the complexity of the branching patterns and the irregular shape of the fiber bundles, developing descriptive and realistic geometric models of heart valves is technically challenging. To create a FEA mesh of a heart valve cusp, one could recreate some of the branching fiber patterns by hand. While certainly possible, manual tracing is time consuming and subject to human error and bias. Three dimensional reconstruction from serial section tracings is also possible, but posses similar (or greater) technical challenges.

Fractal descriptions have been used successfully to describe tissues and organic structures such as lung [1] and ferns [2]. Fractal methods work best for self-similar structures, where the macroscopic branching patterns are topographically similar to the microscopic patterns. Most load bearing connective tissues, however, do not appear to conform to the self-similarity assumption. In heart valves, fiber bundles rarely branch more than two or three times, and often transition abruptly into different structures, such as sheets or the aortic root.

Because connective tissues bear loads, it is likely that their morphology is dependent on some combination of genetic programming and Wolff's Law (form follows function). Adaptive optimization methods have proven useful in previous studies of strain energy-based structural remodeling in bone [3] and may be applicable to soft tissues as well. Our overall objective is to develop an adaptive optimization approach to heart valve computational modeling. The specific aims of this study were to develop general kinematic and geometric descriptions of fiber bundles, sheets, and their connectivity. Realistic descriptions of these mesostructures may be useful for building models of valves and other connective tissues.

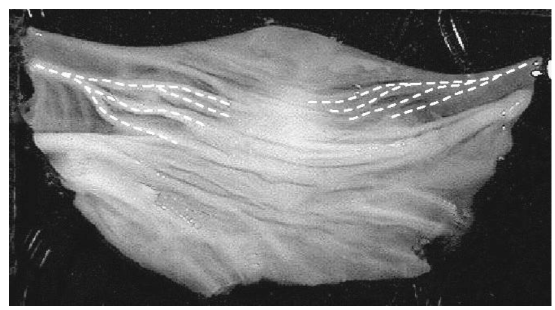

Figure 1. The aortic heart valve cusp with dashed lines emphasizing some of the branching fiber bundles.

METHODS

In order to represent the fiber bundle mesostructure in the heart valve cusp, we developed a set of simple elements defined in local coordinate systems. Each element had its own equation and parameters that controlled its shape, as follows:

- Line $y = a x$
- Parabola $y = a x^2 + b$
- General power function $y = a x^n + b$

A kinematic approach was then used to transform the predefined elementary objects in different coordinate frames using Matlab™ (The Mathworks Inc., Natick, MA). The elementary objects were transformed and scaled to form more complex one-ended structures by operating a (4 x 4) homogenous transformation matrix, T_H, on these objects.

Considering bundle bifurcation, which is the common pattern of bundle branching in the native heart valve cusp, fiber bundle mesostructures were built in a generational heirarchy by various combinations of primary elements, with scaling factors (S_x, S_y, S_z)

introduced to control the final sizes of each element, given as

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \\ 0 \end{bmatrix} = T_H \cdot \begin{bmatrix} [S_x \cdot x_0] \\ [S_y \cdot y_0] \\ [S_z \cdot z_0] \\ 0 \end{bmatrix}.$$

To characterize the combinatorial architecture in the heart valve cusp, two different models were developed. In the first model, a one-ended branching structure was constructed starting from opposing boundaries of the global coordinate system and then the last objects of each form were matched and connected, resulting in a single double-ended structure. In a second model, sheet-like mesostructures observed in the native valve were created by adding families of parametrically varying elementary objects.

RESULTS

A combination of lines and the general power function appeared to provide the most flexibility for generating fiber bundle structures. Plots of three-generation, single-ended fiber bundle structures looked remarkably similar to those of the native cusp (Figure 2). For this example, elements using the general power function with n = 0.7 were used (Figure 2, inset).

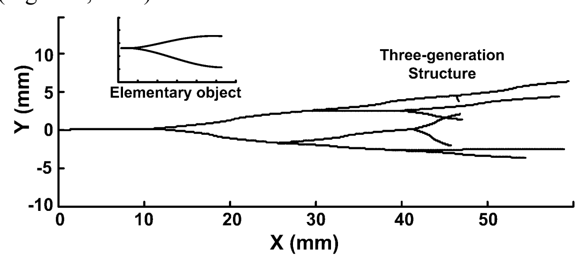

Figure 2. Hierarchical fiber bundle structure generated from a combination of simple primary elements (inset).

Combining multiple primary elements with different semi-random parameter variations produced fiber bundle mesostructures such as fan-like sheets (Figure 3) that were similar to the sheets observed in the native valve.

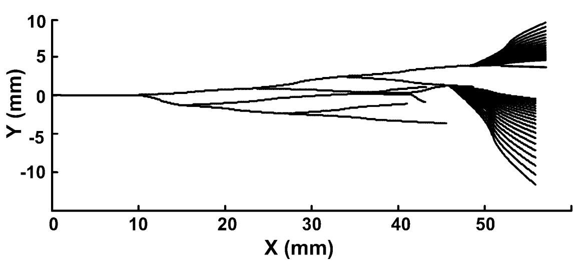

Figure 3. Single ended fiber bundle structure with fan-like mesostructural elements.

Two single-ended fiber bundle structures, beginning from opposite boundaries of the global coordinate system and connected at their third generation, were representative of the native double-ended fiber bundles that run from commisure to commissure (Figure 4). Finally, the elementary objects were combined into 3D structures using 3D transformations (Figure 5).

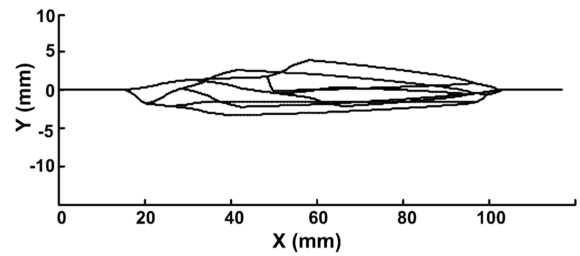

Figure 4. Double-ended fiber bundle structure.

DISCUSSION

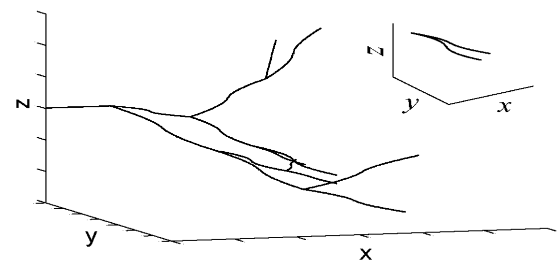

Figure 5. 3D Fiber bundle structure constructed from a combination of simple elements (inset).

The continuity and structural architecture of the heart valve cusp is still not well understood. Polarized light microscopy images of heart valve cusps show both continuous and non-continuous collagen bundles in the complex cusp matrix. These observations ultimately lead to the concept of valve cusp mesostructure.

The realistic fiber geometries shown in the plots demonstrate the feasibility of representing the mesostructural geometry of the heart valve cusps using a kinematic approach. By using simple geometric elements as building blocks, remarkably complex hierarchical structures were generated through a combination of kinematic transformations and scaling. Double-connected branching patterns, similar to observed morphologies were also generated using this relatively simple approach.

Some of the current limitations of this method are that fibers are represented by relatively simple functions, and that they are drawn as lines in 3D space, not as cylinders or tubes. Present work is focused on converting the line structures to cylinders with variable cross-section, establishing physiologically relevant rules for self-assembly and fiber bundle creation or removal, and developing layered structures.

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