Predictive Surgical Simulation of Aorta Reconstruction in Cardiac Surgery

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Abstract. This paper proposes a method for performing predictive simulation of complex cardiac surgery. It computes complex surgical results given a small amount of user inputs. In this way, the surgeon can easily explore various surgical options without having to go through all the detailed steps of the surgical procedure. Test results, using aorta reconstruction as an application example, show that the proposed method can generate realistic simulation results given different kinds of user inputs, thus demonstrating the feasibility of the approach.

Keywords. Predictive surgical simulation, cardiac surgery, aorta reconstruction, differential geometry method

Introduction

Many surgical simulation systems have been developed over the last decade. Among them, *reactive* systems [1,2] attempt to simulate real-time displacement and deformation of body tissues in response to user inputs that emulate surgical operations such as incision and suturing. They are useful for surgical training and preoperative planning of surgical operations. However, to use a reactive system to predict the results of a complex surgical procedure, one would need to go through all the surgical steps, which is tedious and time-consuming. In contrast, our research goal is to develop a *predictive* system for the simulation and planning of complex cardiac surgeries. This approach allows the surgeon to easily and efficiently explore various surgical options to determine the best ones without going through all the detailed surgical steps.

This paper illustrates our work on predictive surgical simulation using aorta reconstruction in arterial switch operation (ASO) as an application example. ASO is a surgery of choice for correcting transposition of the great arteries (TGA), in which the two great arteries, aorta and pulmonary trunk, are connected to the wrong ventricles at birth. To correct TGA, ASO performs transections of the two great arteries and reconnects them to the arterial roots attached to the correct ventricles. If the aorta is narrower than the neo-aortic root, the aorta needs to be cut longitudinally, opened, and patched with an additional tissue to expand it (Fig. 1). In predictive simulation of this operation, the arteries should deform according to their physical properties and additional requirements expected by the surgeon, e.g., minimum stretching and smooth joining of blood vessels.

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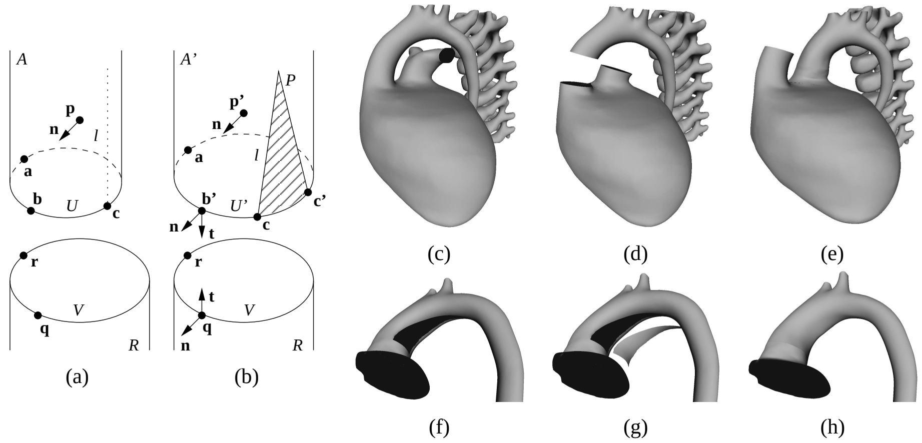

Figure 1. Aorta reconstruction. (a) Aorta A is cut at **c** longitudinally (dotted line), (b) opened and patched with a tissue P (shaded surface) to fit neo-aortic root R. (c) Input model of heart with TGA. (d) Arterial transection. Aortic root and pulmonary trunk are removed for visual clarity. (e) Reconstructed aorta. (f) Cut and expanded aorta is joined to the neo-aortic root. (g, h) Reconstruction result. The patch is displaced in (g) for visual clarity.

1. Predictive Surgical Simulation of Aorta Reconstruction

Given surface mesh models of the heart and the great arteries (Fig. 1(c)), predictive simulation of aorta reconstruction requires three basic operations to simulate surgical operations: cutting, joining, and deformation. Mesh cutting and joining are relatively straightforward, whereas mesh deformation is complex.

There are two main approaches for simulating soft tissue deformation. Finite Element Method (FEM) offers accurate model behavior but is computationally expensive. Mass spring model (MSM) is efficient and has been applied to reactive simulation of cardiac surgery [1,2]. However, its simulation accuracy highly depends on careful placements of springs between mass points, which do not necessarily have physical correlates.

Instead of using FEM and MSM, we apply differential geometry (DG) method [3,4], which offers more accurate and stable simulation results than MSM and is computationally more efficient than FEM. Unlike FEM and MSM, DG does not model physical forces acting on the object. Therefore, it has not been used in reactive simulation. However, DG turns out to be very useful for predictive simulation because the surgeons are interested in the expected surgical results instead of continuous shape change due to human interaction. Also, it provides intuitive ways to correlate physical properties and surgical requirements using different geometrical constraints [3]. With appropriate parameters of the constraints, it can produce realistic simulation of blood vessel's behavior.

Our predictive simulation system works as follows. First, it measures the diameters of the aorta and the neo-aortic root to decide whether expansion is needed. If so, the user specifies a cut path (Fig. 2(a)) and two anchor points (Fig. 2(b)) that indicate the join positions of the aorta and neo-aortic root. Then, the system automatically cuts the aorta, expands it, joins it with the neo-aortic root, and computes an appropriate patch to form smooth, leakage-free joins between the various components. The system also measures and visualizes the amount of deformation to help the user evaluate the surgical options. If expansion is not necessary, the cutting and patching steps are not performed.

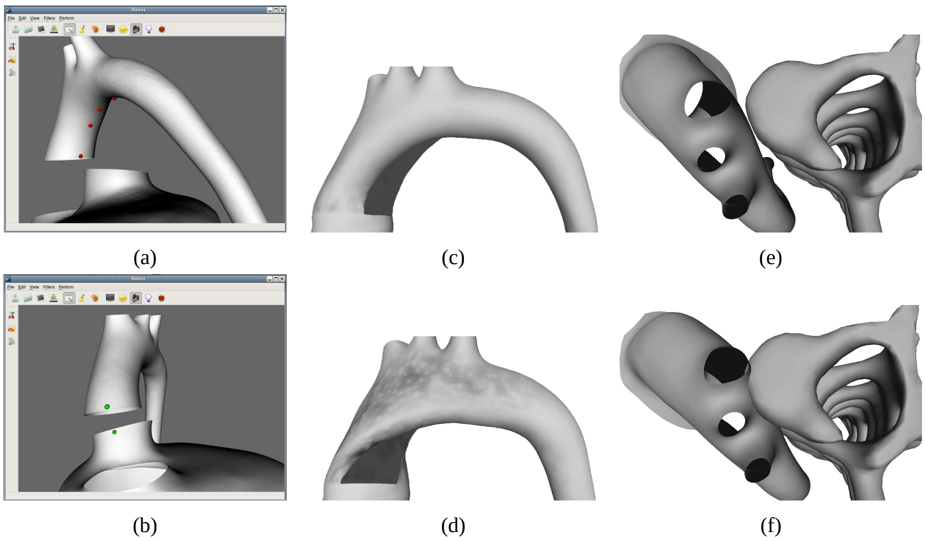

Figure 2. Predictive simulation of aorta reconstruction given a small amount of user inputs. (a) User specifies cut points to quickly indicate a cut path. (b) User specifies anchor points to indicate join positions of aorta and neoo-aortic root. (c–f) Comparison of aorta reconstruction results for different kind of surgical options. (c) Minimum stretching and twisting of aorta. (d) Large amount of stretching and twisting of aorta. Dark shading indicates amount of stretching. (e) Aorta does not penetrate spine. (f) Aorta penetrates spine.

2. Experimental Results and Discussion

Tests were conducted to evaluate the performance of the predictive simulation system. First, the mesh models of the heart and the great arteries were reconstructed from a TGA patient's CT images (Fig. 1(c)). Figure 1(d) shows the result of transection of the aorta and pulmonary trunk. After arterial transection, our proposed algorithm for aorta reconstruction was performed. Figure 1(e–h) shows that our algorithm can correctly expand the aorta and compute the patch to form smooth, leakage-free joins between the various components.

Figure 2(c–f) illustrates the results produced by various surgical options. Specifying proper anchor points generates less stretching and torsion of the aorta (Fig. 2(c)), compared to poor anchor point selection (Fig. 2(d)). Figure 2(e, f) shows that certain input options may cause the aorta to penetrate the spine, which means undesirable compression in real surgery that should be avoided. By evaluating the predicted results for different surgical options, the surgeons can easily choose the best ones for planning the surgery.

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