Medical Image-Guided Surgery Planning for Breast Reconstruction Using Deformable Modeling and Surface Flattening

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ABSTRACT

In this paper, a virtual breast plastic surgery planning method is proposed, which reconstructs the breast after excision for certain diseases such as cancer. In order to achieve a rational result, we calculate shape, area, volume and depth of the skin and muscle for the reconstruction, based on the other healthy breast. The steps are as follows: 1) input breast's MRI data of patient; 2) get the healthy breast using balloon segmentation algorithm and get triangle mesh on breast surface; 3) flatten the triangulated skin of breast using deformable model to attain the shape and volume of the flap for breast reconstruction. Other methods such as mesh smoothing and cutting of triangulated surface are also introduced. The doctors validation and evaluation process are also provided to ensure the robust and stable result of virtual surgery planning.

Keywords: Virtual Surgery, Surface Flattening, Deformable Modeling, Mass-Spring, Breast Reconstruction

1. INTRODUCTION

In the recent years, the promising virtual surgery applications benefit a lot from computer aided technology of imaging processing and graphics modeling. Via virtual surgery planning, now it is feasible that the medical doctors receive repeatable and maintainable training from virtual surgery system, at the same time, avoid the risks of injuring patients during the debut practices, and reduce the substitute tests made on animals.

Since the requirement and focus varies from case to case, it is almost impossible to build up a versatile virtual application for all kinds of surgeries. Thus, in a practical way, a case-by-case analysis must be considered and implemented. In this paper, a virtual plastic surgery of breast reconstruction emphasizing surface flattening is presented [1-5].

The patients who desire breast reconstruction become popular due to the increasing of the incidence of breast cancer, the development of living standard, and the development of therapeutics of breast cancer. The healthy breast is an organ with three-dimensional structure, but the design of the flap for breast reconstruction is two-dimension. Traditionally, it depends on the experience of the doctor to change the two-dimensional flap to three-dimensional breast.

In 2001, Jean-Yves Petit, from Plastic and Reconstructive Surgery Unit, reviewed the surgical methods for the lost breast reconstruction, but their surgery did not have feasible support from computer assisted system for the flap design [15]. In 2006, Oren M. Tepper, from New York University Medical Center, proposed a virtual 3-dimensional modeling as a valuable adjunct to breast surgery, however it only provided the imaging tool for data viewing [16].

In this paper, we propose a novel set of methods of image-guided surgery planning for breast reconstruction flap design. Three dimensional segmentation and modeling is employed first. Then the curved surface is deformed to flatten plane in the method of Mass-Spring, and the design of flap is achieved. The validation and evaluation are also to be discussed.

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2. METHODS

2.1 Three Dimensional Modeling Using Balloon Segmentation

Balloon Segmentation, proposed by Miller in 1991, is a dynamical volumetric segmentation algorithm by approximating a sphere using polygons. The basic idea of balloon algorithm is to add image forces on an initial spherical mesh object, making it expand or shrink towards the surface of soft tissue. The mesh will adjust its shape to conform to the boundary of ROI as closely as possible after iterating the calculation for specified times, just like a balloon inflated or deflated.

Mathematically, it reaches the minimization or maximization of a cost function with three terms of deformation potential, image edge features and topology constrains.

To generate surface models with smooth and extensible quality, the entire modeling process was divided into three steps. Firstly, a 3D Gaussian smoothing was employed on the pseudo-grey-scale volume data, which was the output of segmentation. Then surface models were generated by using the balloon segmentation algorithm, and each ROI is output with its triangular mesh data. Finally, a butterfly triangle smoothing algorithm was used to improve the appearance of the models [6, 13]. The segmentation application is shown as Fig. 1, and the balloon algorithm is shown as Fig. 2.

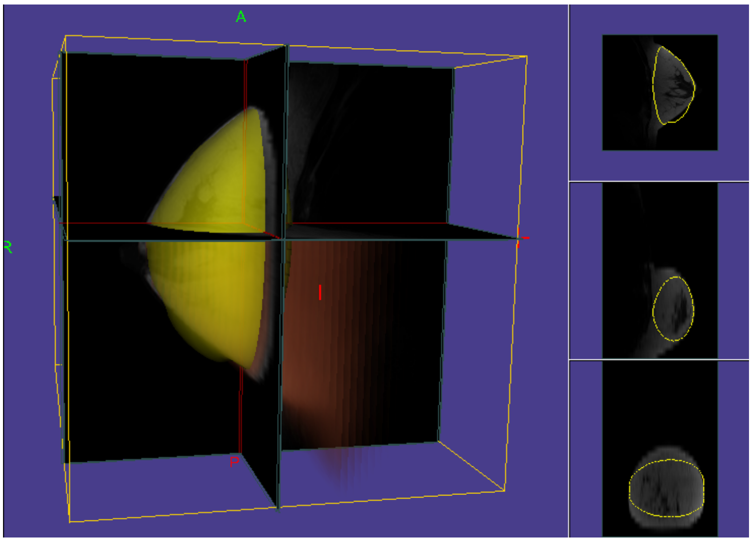

Fig. 1. This shows the Balloon Segmentation Application Interface.

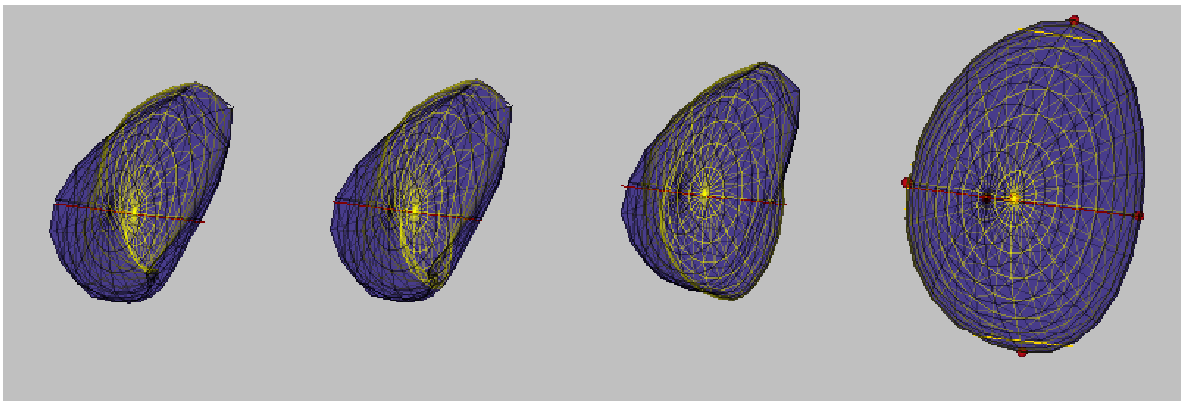

Fig. 2. This shows the Balloon Segmentation Iterative Procedure.

2.2 Mesh Division Method for Surface Cutting

However, in order to make the breast shape meshing extendible to plane surface, the cutting algorithm is conducted on the data. Otherwise, the reasonable result is not attainable. The cutting algorithm employed here is Mesh Division Method. It divides the original triangles according to the cutting path, and at the same time preserves the total area of surface, as shown in Fig. 3.

However, it generates more and more triangles, so that the computation for deformation becomes slower. The re-meshing procedure is to be considered as future work, to reduce the amount of fragmental meshes [7-10].

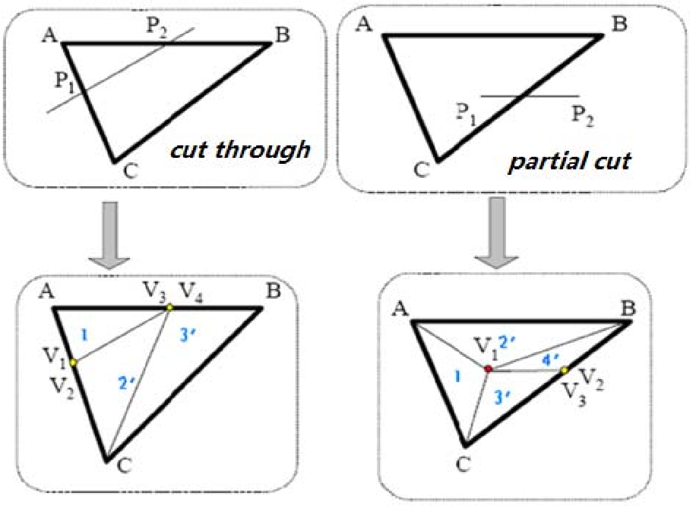

Fig. 3. This shows the cutting algorithm procedure.

2.3 Deformable Modeling for Surface Flattening

Mass-spring modeling is one physically based technique that has been used widely and effectively for modeling deformable soft tissue. A non-rigid object is modeled as a collection of point masses connected by springs in a lattice structure. The spring forces are often linear, but nonlinear springs can be used in a more realistic way to model tissues such as human skin's inelastic behavior, as shown in Fig. 4.

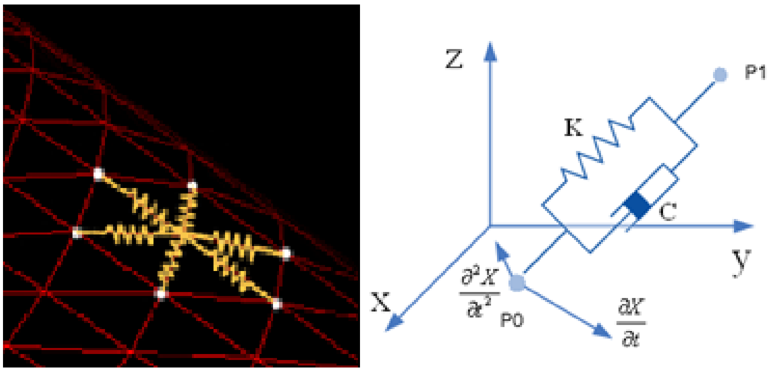

Fig. 4. It shows the Mass-Spring Mesh Structure and the Mass-Spring element in 3D Mass-Spring system.

Mass-Spring is especially effective in simulating the dynamic behavior of the objects; however, it is unsuitable to simulate the static behavior due to its unstable vibration among the spring system and the shape distortions of the topology. To reduce vibration and improve stability of the deformable model, damping factor and non-linear elasticity methods are used. In the dynamic Mass-Spring system, the equilibrium equation has the following form as equation (1).

$$M\frac{\partial^2 X}{\partial t^2}+D\frac{\partial X}{\partial t}+KX=F(X) \quad (1)$$

where $\frac{\partial X}{\partial t}$ and $\frac{\partial^2 X}{\partial t^2}$ are the first and second derivatives of x with respect to time, M is the mass matrix, D the damping factor matrix, and K the stiffness matrix. F denotes the external forces. Equation (1) defines a coupled system of 3n ordinary differential equations for the n position vectors contained in X. To solve them, we could transfer equation (1) into a coupled system of linear equations based on Euler's first order method.

In our research, based on the deformable modeling concept, we propose a novel flattening method which takes the advantage of the deformation model of Mass-Spring. All the triangles on the curved cone-like or hemisphere-like surfaces are mapped and extended onto a plane, preserving the original connected edges and points. The initial flattened surface is restricted by the spring forces on mass points, thus it will stretch due to the deformation effects, and then extends to a spindle-like flap shape. When the flap mesh is obtained, we will also compute its skeleton centerline [11-12, 14], as shown in Fig. 5. and Fig. 6.

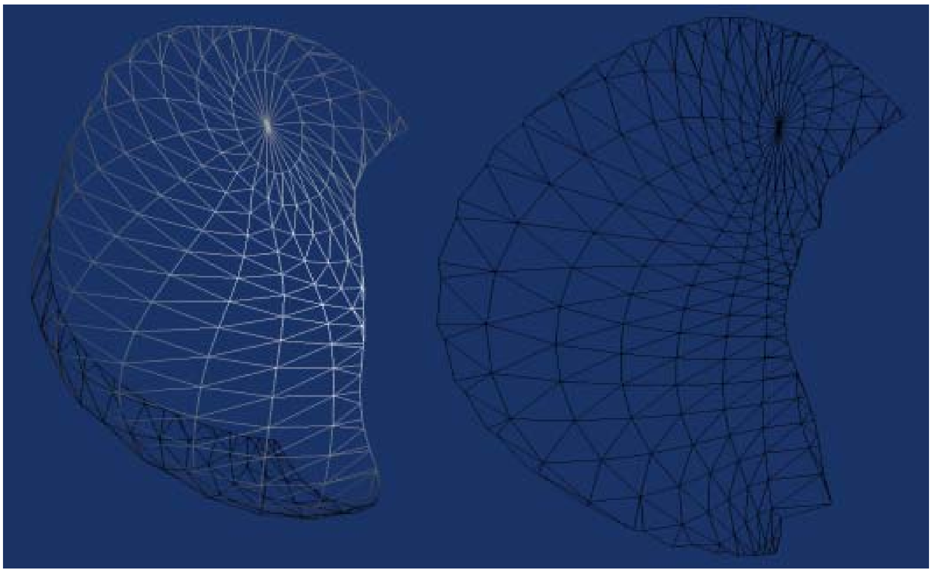

Fig. 5. This shows the experimental flattened surface.

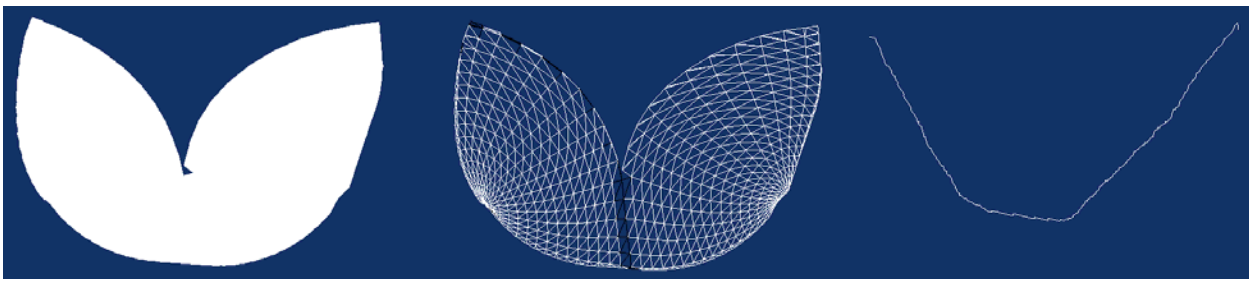

Fig. 6. This shows the flattened flap and its skeleton.

3. RESULTS

For practical planning purposes, the experimental results are conducted on five sets of patient MRI data provided by Shanghai 9th People’s Hospital. The application is developed and run on a PC machine of Windows XP environment, with 2.79GHz multi-core CPU and 2.0G DDR2 RAM.

The MRI data dimensions are 512*512*75, and the 3D surface modeling consists of 994 points and 256 triangles. The volume is 621745 mm^3 and surface area is 282341 square mm. After the flattening, surface area increases to 308958 cubic mm because of the stretch deformation. The width of the flap shape is 322 mm, and the height is 119 mm.

The flattened mesh is sensitive to both the density and consistency of the triangulation on the curve meshing structure. When the variation of curve mesh triangulation is up to 5%, the flatten mesh result exceeds the triangle distortion rate of 10%, that is unacceptable for flattening.

In order to verify the results, experienced plastic surgeries evaluate the output data, and they accept them as dependable directive designs for the real surgeries.

In Fig. 7 to Fig. 9, the computer assisted design for reconstructive flap is shown. In Fig. 10. and Fig. 11. The comparison between real flap and planning flap is shown.

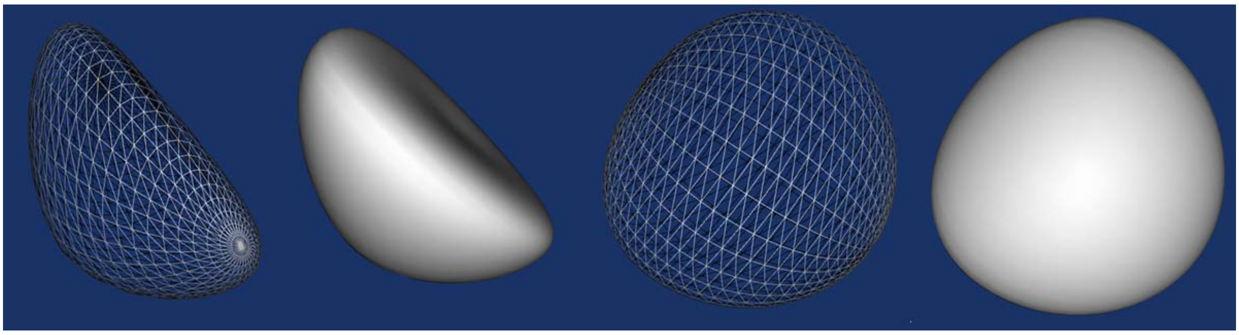

Fig. 7. The final segmentation result and the smoothed meshing for breast data are shown.

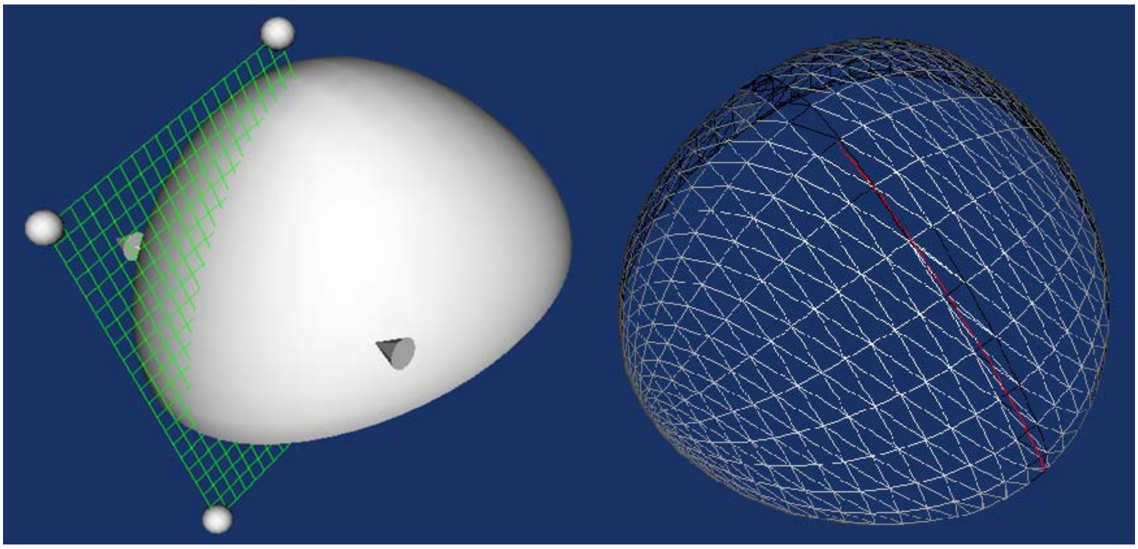

Fig. 8. This shows the Flattened Surface.

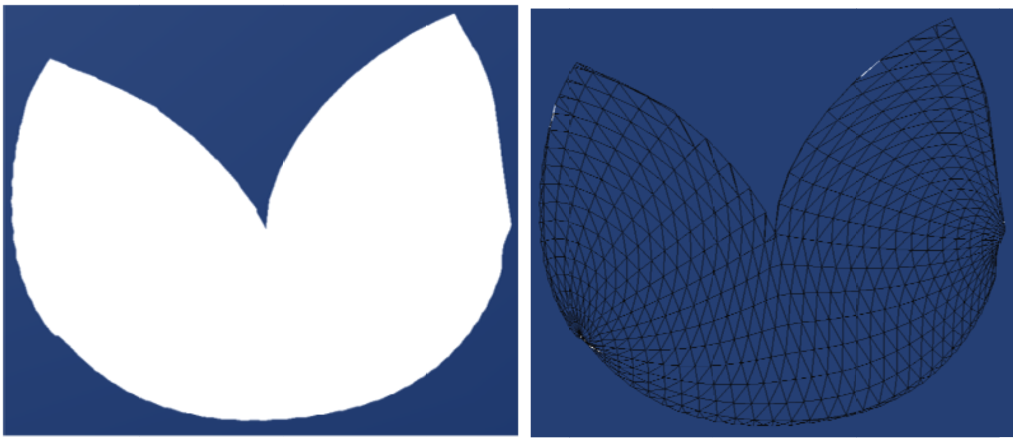

Fig. 9. The curve surface is flattened to plane surface with its meshing structure.

Fig. 10. The realistic photo of flap design for patient.

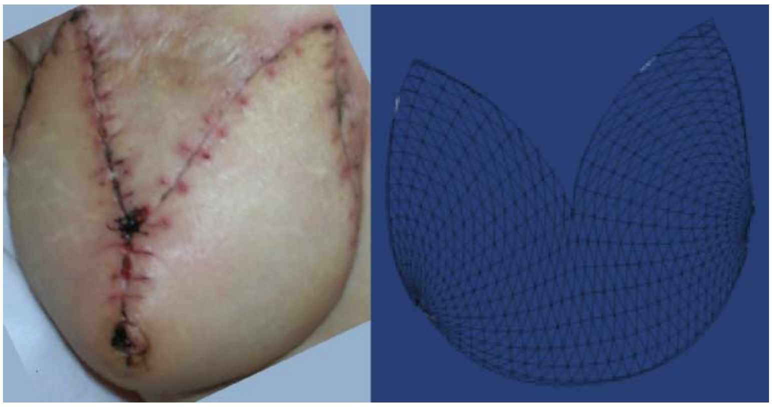

Fig. 11. This shows the comparison between computer-designed flap and the skin flap.

4. CONCLUSIONS

In summary, we propose a novel hybrid deformable modeling as the kernel module for image guided virtual surgery simulation. The combination of the technique of computer and medical imaging and clinical practice is tightened with the rapid development of hardware and software. The domain of the operation draws more and more of our attentions.

The computer aided application aims at helping the patient after mono-lateral mastectomy. When the input data of MRI is processed, a three-dimensional model is outputted and the area and volume of the opposite breast can be calculated. The surface of the breast can be separated and cut into parts and flattened to plane. Then the shape and model of the flap for breast reconstruction is achieved. This application is used in design for breast reconstruction with flap pre-operation and high quality symmetry post-operation.

The future work includes more realistic biomechanical computing for soft-tissue deformation, adaptive meshing, parallel computation on multi-core CPU machine and especially their integration.

ACKNOWLEDGMENTS

The authors would like to thank the medical doctors and surgeons from Shanghai 9th People's Hospital and Shanghai Renji Hospital for providing the experiment data and surgical advices. We are also grateful to all the members at the Image-Guide Surgery and Therapy Laboratory, Shanghai Jiao Tong University. We are also grateful to the intellectual and financial support of National Natural Science Foundation (60571061), National High Technology (863) Research Foundation (2007AA01Z312), and the Shanghai Municipal research Foundation (06dz15010).

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