Virtual Surgery Planning of Breast Reconstruction Using Deformation Modeling and Curve Shape Approximation

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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; 4) calculate the approximate curve shape of flap. 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, Deformation Modeling, Surface Flattening, Mass-Spring, Breast Reconstruction**

I. Introduction

In the recent decades, with the developing of the computer aided technology of imaging processing and graphics modeling, virtual surgeries are applied more and more widely.

The medical doctors can learn more details about the surgery in advance via virtual surgery planning. The doctors can also receive trainings which with no risks and low costs.

Virtual surgery planning finally can help the doctors to avoid the risks and improve the result of the surgery. However the requirement and focus varies from case to case and a case - by - case analysis is always needed to solve a new problem.

In this paper, a virtual plastic surgery of breast reconstruction emphasizing curve approximation for the irregular surface is presented.

After the surface flattening and centerline modeling, we get an irregular shape, which is rather inconvenient for the real surgery, so it is necessary to turn the shape to a regular one for representing the surface to be cut on the belly of the patient.

Thus, it has several requirements: 1. The margin of the shape should be smooth, flat, but not very long. 2. The new shape looks like the old one as far as possible. 3. The new shape has almost the same area as the old one.

Moreover, in this paper, it discusses a new method of how to search for the suitable curve to approximate the required area, then, it tries to find the proper surface which has the desired volume as required.

II. Methodology

A. 3 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.

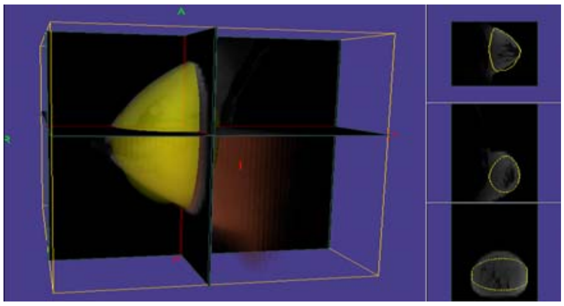

Fig. 1. It shows the Balloon Segmentation Application.

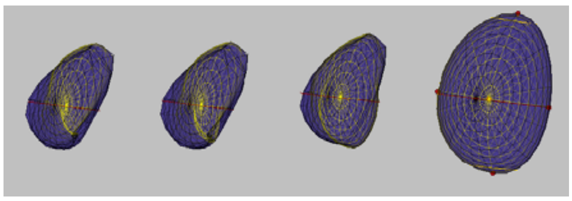

Fig. 2. This shows the Balloon Segmentation Iterative Procedure.

B. 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].

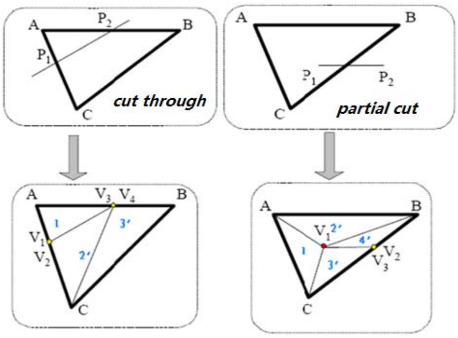

Fig. 3. This shows the cutting algorithm procedure.

C. 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.

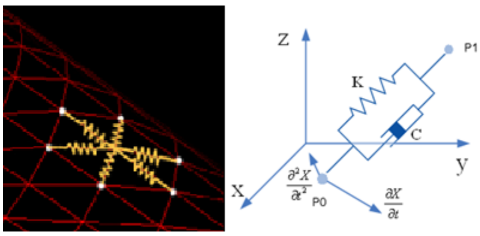

Fig. 4. It shows the Mass-Spring Mesh Structure and the Mass-Spring element in 3D Mass-Spring system.

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).

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

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..

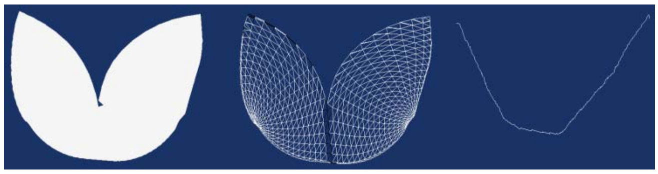

Fig. 5. This shows the flattened flap and its skeleton.

D. Deformable Modeling Based on Centerline

When the flap mesh is obtained, it is heart-like and the flap is a spindle-like one. We need to get the centerline of the mesh data and stretch the centerline to a straight line which will result in the balance state of the Mass-Spring model broken. We apply the deformation with Spring-Mass model once more, and the mesh data will meet the doctors' demands.

In our research, skeleton is used as the centerline of the flattened 2D mesh data. Binary image skeleton extract based on mathematical morphology is a process for reducing foreground regions in a binary image and preserves the topology (extent and connectivity) of the original region. It is based on binary image dilation and erosion, and is widely used in finding the centerline of a 2D image object. The Algorithms returns us a set of coordinates of the centerline and we find the closest mass points in the mesh data, and smooth the line.

We calculate the length of the center line and generate a new line which stands for the result of stretching the line to straight. We modify the coordinates of the mass points which are on the centerline and use the Mass-Spring model to achieve centerline-based deformation, as shown in Fig 7.

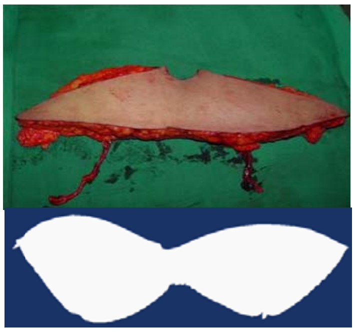

Fig.7. This set of pictures shows the comparison between the real flap and the virtual calculated flap.

E. Curve Shape Approximation

This is the key step and it is also devided into several small steps. For we take the center point of the original shape as the (0, 0, 0) point and the center line as the X axis. The paracurve is simplified as:

$$Y = a * X ^\wedge 2 + b$$

Thus, we have to decide the value of a and b. As the property of the paracurve, "a" decides for the shape of the curve, "b" decides for the location of the curve. For it requires that the new shape should be as similar as to the original one. So finding a suitable "a" is crucial to the problem.

For another requirement, the two curves, ie. the up curve and the down one should have two junctions which are just on the center line. So if one curve is decided, its junction points on the center line is decided, and they will influence the other curve. For all consideration, I decide to calculate "a" parameter of the down curve. The standard for the judge of the "the new shape should be as similar as to the original one" is that "the variance between the two shapes should be as smaller as possible", described by the doctors.

Then cells are inserted into the poly data. But in this way, there may be obtuse triangles in the data. So the next step is to search all the cells in the poly data and find the obtuse triangles. I make a perpendicular line from the point of the obtuse triangle to the opposite edge. Insert the point of the junction of the perpendicular line and the opposite edge into the end of the poly data. Replace the original obtuse triangle with one of the new triangle and insert the other triangle into the end of the poly data.

After the curve approximation, cells are inserted in to the flap shape.

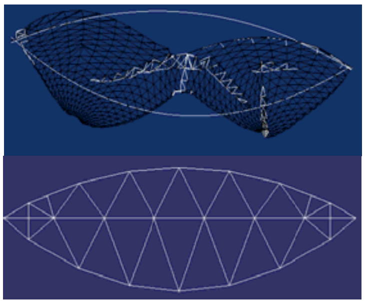

Fig.7. Curve Approximation.

IV. 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.

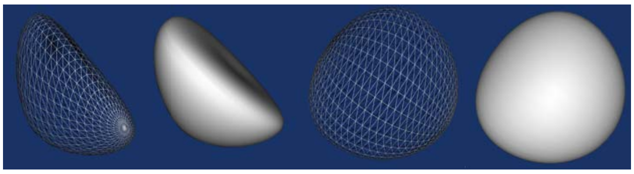

Fig. 8. Segmentation and smoothed meshing for breast data.

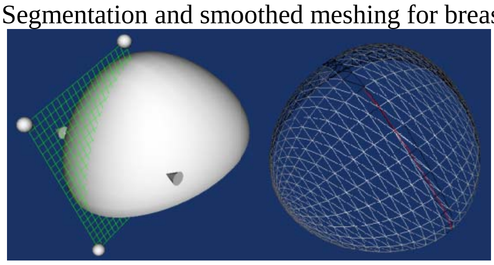

Fig. 9. This shows the Flattened Surface.

Fig. 10. Curve surface is flattened to plane surface with its meshing structure.

Fig. 11. The realistic photo of flap design for patient.

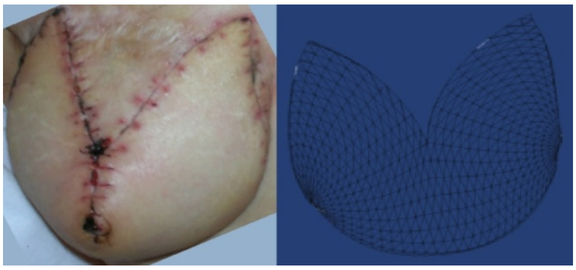

Fig. 12. This shows the comparison between computer-designed flap and the skin flap.

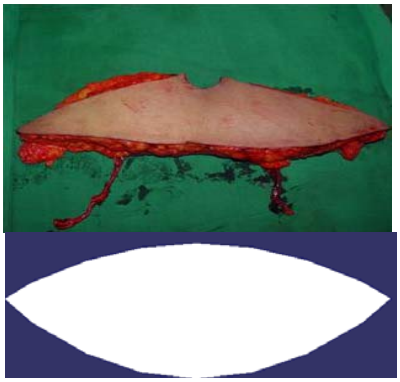

Fig. 13. This set of pictures shows the comparison between the real flap and the virtual calculated flap with curve shape.

V. Conclusion

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.

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