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Superquadrics Deformation Method for Medical Image Visualization

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Abstract

Deformable model was initially applied in the domain of computer vision. Recently, it has been applied in medical image fields that are one of the subjects having development potential. This paper presents a left ventricle model, which combines physical and geometric characteristics and can be easy to manipulate. It is available for computer to present various shapes of left ventricle in three-dimensional (3D) manner. In this paper, superquadrics and Lagrangian equations of motions are combined to establish a 3D deformable model. Constructing three-dimensional visulizations will effectively help doctors to evaluate the left ventricle tissue.

Introduction

Various medical tomographies present the important information of organs of body to medical professionals in noninvasive way. The information can provide physicians to evaluate patient's situation exactly. Because of the correct and exact information from medical images, the success rate of various cures can be raised. In additions, the physical, metal and economical loads of patients are also reduced. Following the development of computer, medical imaging techniques change the concepts of traditional medical diagnosis greatly. The medical images raised from two-dimension plan to three-dimension cubic world. After other new three-dimension imaging techniques, such as MR and PET, appeared, the accurate and repeat information of medical images provides as authorities on which medical experts analyze and measure. And medical researchers are interested in them.

Recently, combining the three-dimension digitized medical images and computer graphic deformation techniques is one of the subjects with more potential to be studied. Because the situations of taking images are different, deformable model can develop to be a robust technique reconstructing important parts in the three-dimension medical images exactly and stably.

This paper provides a convenient tool that combines geometrical graphic and physical characters and is controlled easily to show the computational ability of calculator to deform three-dimension objects. Based on superquadrics model and Lagrangian motion equation, this paper uses the information of medical images to reconstruct a detail three-dimension shape of tissue organs of body dynamically. Using the three-dimension images reconstructed by this model can help physicians to understand and evaluate the situation of tissue more accurately. The deformable model developed by this paper can reconstruct various structures of body tissue gotten from three-dimension medical images. This model combines physics, geometry, and approximation theories to increase degree of freedom for reconstructing medical images more exactly.

Many research works are very related to this study. The paper wants to mention the research work of Barr and Bajcsy on their characters and applications of superquadrics model [5], [6], [14]. Especially, the later provides volumetric model that can describe shape of single object in computer vision. This model is superquadrics model combining three parameterized deformations (bending, tapering, and cavity) and provides important authority for global deformation of this paper. These works fully support theories and uses of basis of superquadrics model and its parameterized deformations.

The other category of related work is presented by Pentland and Ayache. Their stydies are mainly describing deformations in model analysis [1]-[4]. This category of method is based on techniques of finite element to display and build models with complete shape of various cubic objects. Metaxas uses superquadrics model to deal with deformation problem of cubic objects. [9]-[13]. This work uses techniques based on physics to describe complex three-dimension shapes.

This article has total four parts, and is organized as follows:

In Section 2, this article introduces theories that are applied to reconstructing three-dimension deformable model. In Section 3, this article demonstrates the capability of this deformable model with examples. These examples show how to apply the deformable model presented by this article to various cubic medical images. They will show how to operate model to generate time-varying shape of three-dimension objects dynamically. This article concludes the all characters of deformable model and introduces possible future work in Section 4.

Method

The parameterized models are often used in computer vision domain. If some parameters are set, this kind of models can describe large amount of data of images. First of all, the deformable model presented in this paper applies superquadrics and its parameterized deformations to simulate the geometric characters of objects. Then the difference between real data and global model are the source of local deformation that fixes the global model to increase the freedom degree of deformation of model. The following sections will demonstrate the model presented by this paper, and how to reconstruct various shapes according information of medical images.

1 Data of Three-Dimension Tissue

The three-dimension tissue contour data used in this paper are obtained from various medical images. An example shows in Fig.1(a). It is a three-dimension image stacked by a set of planer MR images of head. The contour of head is directly extracted from MR images in Fig. 1(a) and depicted in Fig. 1(b). Because each MR image has very clear structural, the contours of each slice can be extracted simply using threshold technique. These coordinates of contour in the images just have two dimensions, so defining the third coordinate according to the parameters set at taking medical images as resolution in x-y plane, and distance between slices. According to these parameters on the medical images instruments, the reasonable Z coordinate can be defined.

2 Global Deformation

It is mentioned that the three-dimension hybrid model is composed of global deformable model and local deformation. The superquadrics deformable model is the primary technique for the global deformation model of this paper. The main goal of global deformable model is to establish a reference configuration for the extracted contour data points dispersing the three-dimension space messily. This paper will find one set of parameters of superquadrics model to construct its reference configuration. And this set of parameters describes the superquadrics shape that is qlobally fit the outline of image contour data points. This fitting would achieve almost all of the data points falling on the surface of the modeled superquadrics shape.

However, it is hard to decide which one set of parameters of model can generate the superquadrics model that can be catch the spatial distribution of data points. Because the shape of superquadrics model is fully controlled by its parameters, this paper defines the function of parameters of model to calculate the matching degree about the shape of superquadrics model constructed by the set of parameters and the shape described by contour data. The function, called cost function, can measure the distance between the shape composed of data points and the shape described by the model parameters.

The cost function is based on the inside-outside function of superquadrics model in this paper. For example, to find a set of model parameters that are the most suitable to fit the N contour points(x_i, y_i, z_i), $i=1, \ldots, N$ means that the cost function obtains an optimum value. The function shows in Equation 1.
is the evaluate function, where $1-F(x_i, y_i, z_i; a_1, \ldots, a_{13})$ is the cost function.

$$\min \sum_{i=1}^{N} \left[1 - F(x_i, y_i, z_i; a_1, \ldots, a_{13})\right]^2 \qquad (1)$$

This paper uses Powell optimization method for searching a set of optimal parameters that makes cost function has the minimum value.

For most optimization method, initial parameters usually would affect the convergent result. This paper adopts some suggestions introduced by other studies to decide the initial parameters of model. It will ensure the optimal result can be achieved to the desired shape informed by data points.

First, the barycenter of these data points is set as initial center of superquadrics model. Then the orientation of model will be estimated. But the data processed by this paper is often cross-section medical images from various medical imaging techniques. When taking medical images, body of people is fixed. So the initial orientations of model don't need to be estimated. The inertial coordinate system in this paper sets the medical images as X-Y plan, Z-axis runs through all slices of cross-section images.

Once the orientation of model is decided, the radiuses in each direction are the maximum distance between origin and data points. And the shapes of body organs are often like ellipsoid. So the initial superquadrics model are set as an ellipsoid surface for medical images, i.e. squareness are all set 1 and tapering parameters are all set zero as initial values.

The presented model uses thirteen parameters to adjust its shapes, and only nine parameters will be modified in the optimization procedure. The four fixed parameters are X, Y coordinate of central points of model and the angles at which model rotates to its X, and Y-axis, respectively. The cross-section medical images are taken at almost the direction that is perpendicular to the axis of body. The four parameters fixed would ensure that the Z-axis defined in medical images is parallel to this axis of body. The optimization procedure searches the Z coordinate of model center, the angles model rotating, radius of three directions, squareness parameter ε_1 and ε_2, and tapering parameters of X- and Y- axes.

Fig. 2(a), and Fig. 2(b) show the shapes of initial model and resultant model of the data.

3 Local Deformation

In this section, the deformable model presented in this paper will be introduced in characters complying with physical laws to have enough deformable degree of freedom. The local deformable model assumes all non-rigid motions are elastic deformations. In other words, if all forces causing local deformations are removed, the shapes of the original models will back to the reference configuration of initial state. The model combines the global deformation model (Superquadrics model) constructing in last section as reference configuration.

For introducing physical characters of model, this paper will put some imaginary mass points on the defined superquadrics surface. After searching parameters of superquadrics model, it can be decided that whether the data points are falling on the surface of superquadrics model. Although superquadrics model can describe various shapes, it can't fully represent all shapes.

The contour data points will project on the surface of superquadrics model to point out the position of their imaginary particle. Then the distance between contour data points and their corresponding points are recorded for analyze and design the forces affecting the shape of model. In general, the longitudinal coordinate of superquadrics model surface is between $\pm\pi$, and the range of latitudinal coordinate is decided by the optimization result which is limited between $\pm(\pi/2)$. The separation between contour and the contour mapping on the model surface will not have distance in third coordinate for simplifying calculation process.

Because data points and their corresponding particles (mass points) disperse the surface of the superquadrics model abnormally, this paper will redefine the positions of each mass point for continuing the next process. These redefined mass points will separate the same space with each other. This will easily be used in the fast fourier transform method. And the local changes corresponded by these redefined mass points will be obtained by linear interpolation. Then the data can meet the requests of the fast fourier transform. Fig. 3(a) and Fig. 3(b) show the local displacement of X, Y axies. The local displacement means the distance of difference between surface of deformable model and source data points, i.e. mass point can move in this distance to meet with its corresponding data point.

The local changes obtained from last step seem complex, but the energy of their spectrum of fourier transform concentrates in low frequency range. This means the spectrum can be described excellently by some parameters less than original parameters.

Fig. 4(a) shows the model that is global superquadrics deformable model fixed by the parameters of local deformation gotten by transferring all energy of spectrum. Fig.4 (b)~ Fig. 4(f) shows the model that is global superquadrics deformable model fixed by the parameters of local deformation gotten by transferring part energy of spectrum. The numbers of parameters of local deformation in Fig.4 (b) is 5 percent of number of original parameters, Fig. 4(c), (d), (e), and (f) are differently saving the parameters in low frequency domain from 3 percent to 1 percent number of original parameters. They are all saving more than 90 percent energy of spectrum. The difference between the models in Fig. 4(a) and in Fig. 4(b) is not very obvious. And the model in Fig. 4(a) is finer than the model in Fig. 4(f). Saving more part of spectrum can fix finer shapes, however, the difference can be seldom observed by eyes.

Hence, Saving part of information of spectrum of local deformation is enough to get back the original recorded signals. So far this section demonstrates all steps of this method to construct the deformable model presented in this paper form medical images. Next section will show more real examples to exhibit how to manipulate the shapes of the models dynamically and statically.

Experimental result

1 simple model

The first experiment is to proof the validation of optimum method. The optimum method should search a set of parameters to construct a superquadrics model which shape seems to be the same with the shape gotten form medical images. This experiment gets data points from surface of a superquadrics model which parameters are known (see Fig. 5). Then optimum method reconstructs the global deformation model by the data created.

The experimental result shows that this method can search the parameters that are very close to the parameters by which data is created (see Fig. 6(a)). Table 1 lists respectively the parameters of superquadrics model generating experimental data and parameters of the superquadrics model found by optimum method based on the data. This table also shows errors which are the found parameters subtracting the original parameters then divided it. The values of this column can tell us the cost function and optimum method can search an excellent set of parameter to describe the shape constructing by the data in three-dimension space.

Table 1 : List the know parameters of superquadrics model and the parameters found by optimum method in this experiment and the errors.

	Source parameter	Optimum parameter	Error
Center	(128,128,96)	(128 ,126 ,110)	6.902%
Rataton angles	(0,0,0)	(0,0,0.003270)	
X-axis radius	90	89.756801	0.27%
Y-axis radius	90	94.038700	4.4487%
Z-axis radius	135	136.230400	0.9114%
Latitudinal squareness	2	1.950420	2.479%
Longitudinal squareness	0.5	0.586020	17.204%
X-axis apering arameter	0	0.032850	
Y-axis tapering parameter	0	0.001300	
Cost function value	0.0000	417.883338	
Thickness(mm/slice)	16.000000	16.000000	

2 Experiments for Medical Images

The example is two sets of MR images of the same patient. But Fig. 7(a) is longitudinal sectional images of head, Fig. 8(a) is cross sectional images. According the two sets of medical images, the resultant models are respectively shown in Fig. 7(b) and Fig. 8(b) in different lines of sight. Because the shapes gotten form MR images are smoother than shapes gotten form PET images, the local deformation can save lesser numbers of parameters as fixing factors. However, the energy of spectrum is almost saved all. And the shape with lesser local deformation parameters is very like the shape with more parameters.

From the reconstructed models, we know that these each set of MR images only contain part information of head. The one set of images contains information contained or lacked in the other set of images. If these two sets of images could be combined, more information can be integrated together.

Fig. 9 shows the hybrid three-dimension model. This model combines the deformable models which are respectively reconstructed form longitudinal and cross sectional MR images of head. Notwithstanding information is not enough to complete shape of head, this model is more complete than models reconstructed based on one set of MR images. And lack shape of head is little part of entire head. It can be estimated by some techniques as interpolation to complete all three-dimension shape of head.

The hybrid model can integrate tow sets of medical images by reconstructing three-dimension model to provide doctors the information that can't be supported by one set of images.

3 simulation for dynamic images

In this section, we will interpolate more detailed changes of shape between two different shapes of model by adjusting the local deformation parameters for the dynamic deformation three-dimension objects.

This paper assumes the particle speed of dynamical deformation is fixed, so the displacements at every time are fixed. This paper transfers the deformation change into frequency domain, and saves part of spectrum. Then the process adjusting the deformation change by fixed displacement can save more resource and will be more efficient. And this interpolation process is non-linear.

In the first experiment of dynamical deformation, two simple superquadrics model are set as beginner and terminal. The begin superquadrics model ($\varepsilon_1=2$, $\varepsilon_2=1$) will be deforming to terminal superquadrics model ($\varepsilon_1=1$, $\varepsilon_2=0.1$). The deformation process is generated by adjusting the parameters of local deformation of beginner model and depicted in Fig. 10.

The other example is simulating the deformation of systolic process by controlling the local deforming. Hence simple superellipsoid surface is set as the global model of left ventricle. The forces pulling the surface of global model are designed for displaying the dynamic process of deformation. These forces do not only make volume of global model bigger, but also twist it (see Fig.11).

Conclusion

Because the three-dimension models used in computer vision in past lack complex shapes and descriptive ability of non-rigid motions, many objects existing in natural word can't be described accurately in using these models. This paper presents a suitable three-dimension deformable model to visualize the tissue of body in the medical images conveniently, and integrate information of medical images further by computer.

The deformable model that this paper presents to descibe three-dimension medical images is capable of excellent descriptive ability for various tissues and organs of body, and fit to visualize medical images for computer. This model cooperates with drawing tool of ROI (Region of Interest) to construct three-dimension images for clinical doctors. This will make doctors more understanding for the spatial position of body tissue. Through deformable model, a series of two-dimension cross-sectional medical images can be made up three-dimension information of body tissue which doctors can see clearly. This will help medical professionals catch illness of patients.

Because local deformation with physical characters can simulate the reactions of objects that inflicted external forces on, this deformable model is capable of simulating the realistic shapes of objects. If the realistic characters of body could be gotten, this deformable model can simulate some physiological activities as respiration of lung and beating of heart. So far the goal need be achieved is to get realistic physical characters of body tissue to let this deformable model simulates real situation fully.

Moreover, this deformable model can be used to construct dynamic environments of visual reality of body after getting all characters of organs or tissues required. This can be an effect tool to help medical professionals learn anatomic and physiological knowledge. Furthermore, it also can be refined to discipline medical techniques of medical professionals. Then the risks of existent exercise can be avoided. This will the subject developed continuously in the future.

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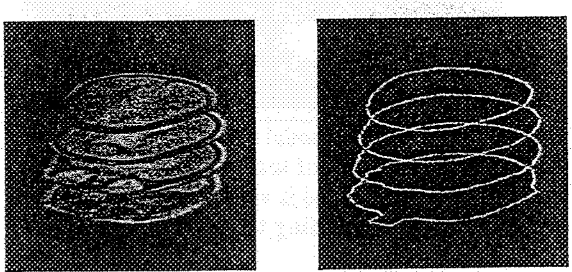
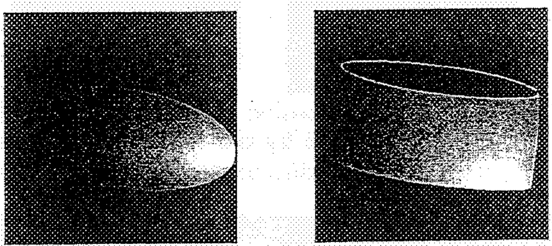


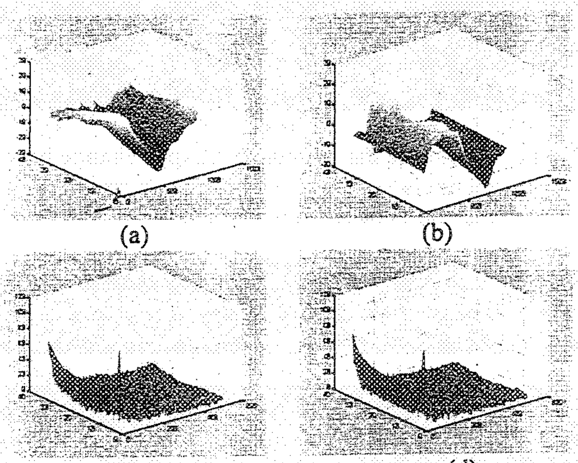
(a) (b)

Fig. 1 The MR cross-section medical image (a) the source data and (b) the contour were extracted from the corresponding medical images in (a).



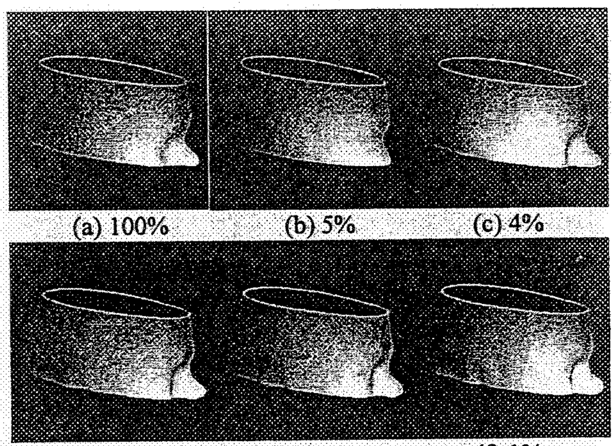
(a) (b)

Fig. 2 The superquadrics model is made by (a) initial parameters and (b) optimum parameters.



(a) (b) (b) (d)

Fig. 3 The local change in (a) X-axis direction and (b) Y-axis direction. The decibel distribution of spectrum of local deformation: (c) in X-axis direction and (d) in Y-axis direction.



(a) 100% (b) 5% (c) 4%

(d) 3% (e) 2% (f) 1%

Fig. 4 The three-dimension deformable model reconstructs the MR medical images of head, and (a)~(f) are the global model fixed by different part of spectrum of descriptive parameters of local deformation.

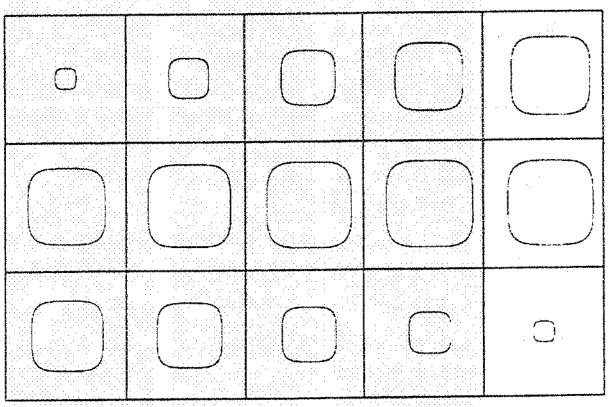
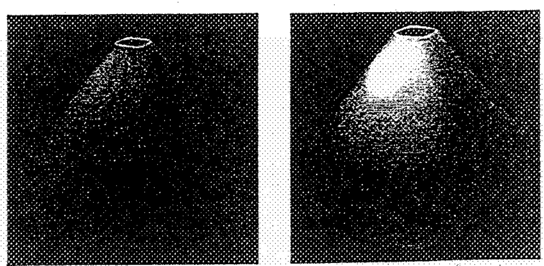


Fig.5 The contour created by the superquadrics model which parameters are know.



(a) (b)

Fig. 6 The three-dimension shape constructed by (a) source data, and (b) the method presented in this paper.

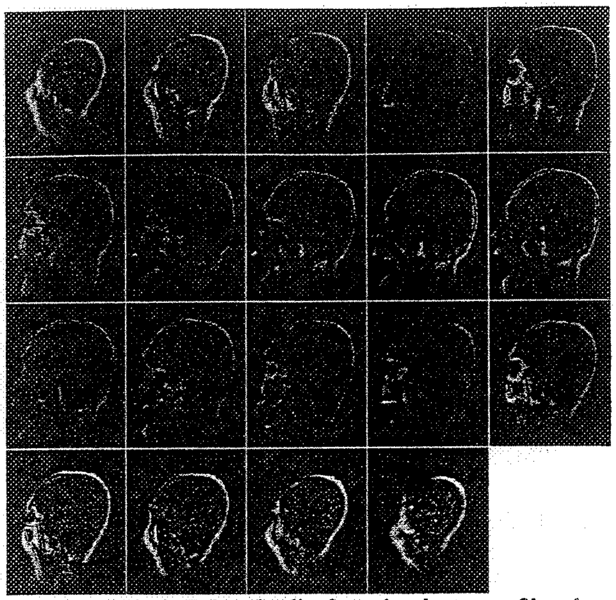


Fig.7(a) The MR longitudinal section images of head.

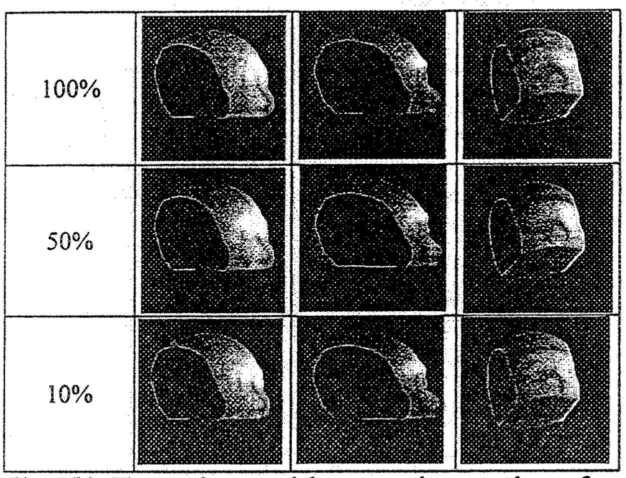


Fig. 7(b) The resultant model saves various numbers of parameters of local deformation (10%, 50%, 100%) and is viewed in different lines of sight according the medical images in Fig. 7(a).

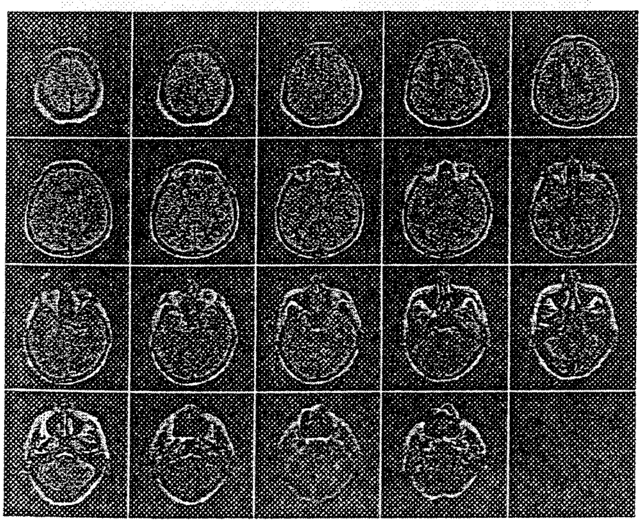


Fig. 8(a) The MR cross-section images of head.

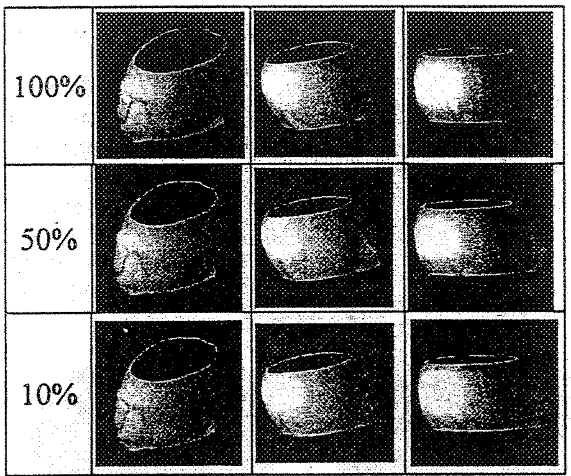


Fig. 8(b) The resultant model saves various numbers of parameters of local deformation (10%, 50%, 100%) and is viewed in different lines of sight according the medical images in Fig. 8(a).

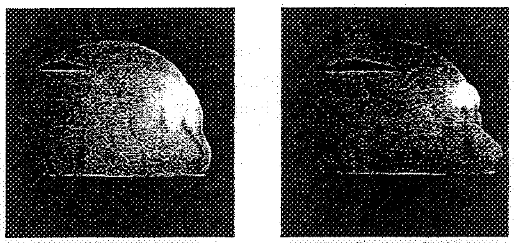


Fig. 9 The three-dimension model combines the models reconstructed by the MR cross-section and longitudinal section images of head.

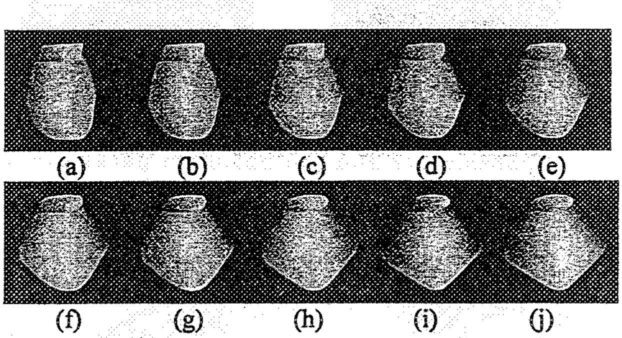


Fig.10 Generate the dynamical shapes change between model (a) and model (j) by the linear interpolation method in parameters spectrum.

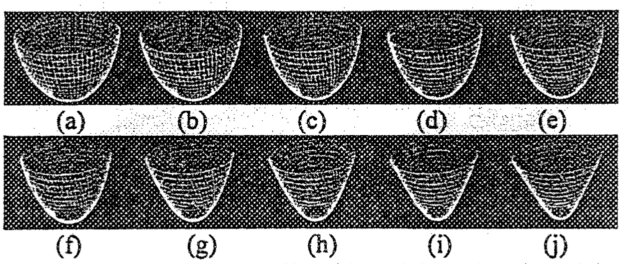


Fig.11 Set the half superellipsoid model as global model to dynamically simulate the change of shape of ventricle in the systole period.