Computer-aided Craniofacial Reconstruction

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Abstract: This paper presents a novel craniofacial reconstruction algorithm based on moving least squares deformation. The 3D skull mesh model is obtained with Marching Cube Algorithm, which extract the iso-surface from a complete head CT slice datum. The holes detected in the 3D skull model can be repaired with different methods after the holes are clarifed . Then, the craniofacial is reconstructed using MLS deformation with the constraint of a reference facial model. The experimental results show that the methods can produce more desirable results than other's.

Key-Words: Craniofacial reconstruction, Deformation, MLS, Feather points, Hole repairing

1 Introduction

Cranio-Facial Reconstruction (CFR) is founded on the science of forensic medicine, anthropology and anatomy. It's widely used in the identification of an unknown body. The progress in computer science and the improvement of medical imaging technologies during recent years has significant repercussions on this domain. Numerous research groups in universities and research institutes have pursued computer-aided CFR research, e.g. University of Washington, Sheffield University, and Waseda University. However, one of the major problems in reconstructing facial models is how to do it with high efficiency for achieving a high level of realism[1][2][3].

At present, there are two methods on computer-aided craniofacial reconstruction. One is interpolation based on feature points. The other is deformation based on reference model. The former which only considers the relationship between the feature points on the skull to be reconstructed makes the reconstruction result not realistic enough. What's more, no one has found which of these feature points should be taken to produce the best result. In the method of deformation based on reference model, it obtains the final skin surface by warping the model template[6]. And It's very important to select the deformation function. Currently, many computer-aided craniofacial reconstruction methods deform the model in partitions, or deform it using RBF. But the result is not very desirable.

Some experts like Giuseppe [12] used spiral CT to obtain the skull which needs to be reconstructed, and marked a series of feature points on the skull and reference skull correspondingly, then established a matrix according to the feature points between the two skulls, deformed the reference skull's corresponding craniofacial model using interpolation algorithm to get the final facial model.

Vanezis and his colleagues [4] abandoned the way of using a single reference data set. They set up a database of reference facial models instead. After analyzing the skull using anthropological knowledge, they selected a reference skull and its corresponding facial model which is the most similar to the skull in anthropological information. Finally，they adjusted facial model template to fit the feature points to the ones on the skull which needs to be reconstructed.

Khler and his colleagues [7] marked some feature points on the skull model according the ratio of the skull and the depth of the soft tissue. Then the RBF interpolation is used to generate the human head. The experiment results show that this method could reconstruct the face model quickly, and is able to adjust some individual facial characters. But its realistic has not been proved so far.

Peter Claes and his colleagues [8] adopted the alterable model based on statistics. This statistical model is constructed from 118 independent facial databases. And it limits the reconstructions to statistically plausible outlooks. The reconstruction is obtained by fitting the model skull feature points to the corresponding feature points indicated on a digital copy of the skull to be reconstructed. The fitting process changes the face-specific statistical model parameters in a regularized way and interpolates the remaining feature points fitting error using a minimal bending thin-plate spline (TPS)-based deformation.

Now there are two methods on realizing the deformation of reference face model: one is interpolation of a sparse set of 3D reconstructed points. It establishes a position interpolating function between the reference face model and the final face model corresponding to the skull [9]. Here the interpolating function should be smooth enough. The other is free-form deformation [10]. It deforms the reference model directly. But its operation is really complex. We find that the result doesn't have the high degree of realism if we adopt the former method. And it's not very good if we use the global deformation function either.

Inspired by the property of high smoothness of Moving Least square(MLS), we adopt it as the deformation function. This method doesn't need to divide the model into partitions. It computes the control range through weight function and weight radius. Since all the feature points have taken part in the computing process, the smoothness of the reconstruction could also been ensured. In other words, this method can fully satisfy our requirements. In order to improve the results of the craniofacial reconstruction, we have studied the hole repairing algorithm, and present a craniofacial model reconstruction based on MLS. Our method could get the target face model just by modifying only one reference face model.

2 Craniofacial Model Reconstruction Based On MLS Deformation

2.1 Algorithm Overview

We depict the algorithm flow in figure 1. Firstly, we obtain the skull model and its corresponding facial surface using CT scanning. Typically the skull mesh model contains holes due to disqualified scans or standard long-term damage (especially in the soft-bone area around the nose). We should repair the holes to guarantee consistency among the reference facial model and the source skull model. Secondly, we mark feature points on the reference skull model, and get the corresponding feature points on the skull model. Finally, we use a MLS deformation to reconstruct the facial model.

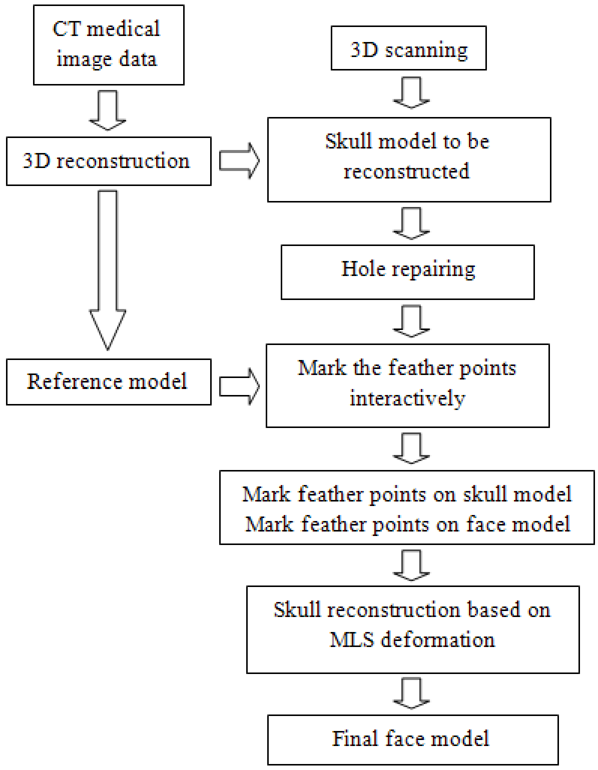


Fig.1: The Algorithm Flow Of Craniofacial Model Reconstruction Based on MLS

2.2 Data Preparation

Before facial reconstruction, you must obtain a number of original skull models. First of all, We obtain the 3D digital model of skull directly using the 3D scanners. Using a complete head CT slice data as a source, we can use Marching Cube Algorithm to extract the iso-surface for getting the corresponding facial model as a reference facial model. Usually, the skull we collected has a certain degree of damage. Therefore, we must repair the damaged skull first in the pretreatment process. After getting the complete skull model, we also need the thickness data of soft tissue. Then we can reconstruct the skull. In addition, we must obtain a standard reference model as the deformation template before the reconstruction. After the collection of soft and hard tissue data, we need to mark some feature points on the reference face model. Then we can deform the model. We adopt the positions of feature points and the thickness of soft tissue referred to Lan YuWen[14]'s statistical data. Figure 2 show the models and the feature points on the face model.

The skull model affected by various factors maybe has some damage and comes to be a hole. These holes will affect the marking of feature points. This is because all feature points must be marked on the surface of the model. If there was a hole in this skull model, then the feather point on the hole would have a error which would seriously affect the follow-up deformation. Therefore, it's very important to repair the hole in the skull model.

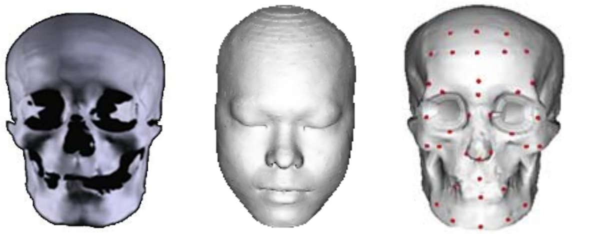


Fig 2. (left) Original skull model. (middle)reference facial model. (right) skull to be reconstructed and its feature points

2.2.1 Hole Repairing in Three-Dimensional Skull Model

The skull model is complex and diverse. So we can't use a unified method to repair the hole. Thus, we classify the holes we detect, then repair the holes according to their corresponding method. See the detail algorithm in the paper we have published[13]. Here we only show you the overall process.

Firstly, we insert discrete points to the holes and then triangulate it. Secondly, we create implicit surface in the hole and adjust the discrete points. Finally, we smooth the mesh. For the general holes, this method will get a good result. In addition, the creation of hole implicit surface and the mesh smoothing solves the matching problem between the repaired grid and the surface surrounding the holes. Therefore, this method is appropriate for the complicated holes in the irregular region. We adopt this general hole repairing algorithm as a basic approach for three-dimensional skull model hole repairing, and use it to handle general holes and complicated holes in irregular region. However, if the holes are big, it is usually impossible to control the shape with the points around the hole for the implicit surface is usually flat. Therefore, we first use these points around the hole to get the shape of the adjacent area and generate the implicit surface, we and then adjust the insertion points in this implicit surface to generate the new points, and finally we repeat the two steps and repair the holes. In addition, there are some special parts on skull, such as the nose. It would be wrong for us to simply take the geometry and topology information around the hole as a basis. Since this method for such holes in special areas is difficult to meet people's nose shape, we adopt the template matching method to repair the particular part. Using standard template as a constraint, we deform the standard template by feature points to make the result keep the structure of this region. Our experiment shows that it could obtain a realistic effect.

2.2.2 Mark Feature Points

Skull feature points refers to the points that are meaningful in the geometry or anatomy, and these points are easy to be located in the skull surface. Through these points, we can uniquely identify individuals and meet the needs of reconstruction of three-dimensional human face. Thus, in the set of the set of skull feature points, the paper adopts X-ray photography method and computer 3D scanning ranging method to establish a target system for three-dimensional skull recovery proposed by Yuwen Lan[14] especially for the Chinese people. We use this system to set the corresponding facial feature points. We marked 28 feature points as basic feature points in the three-dimensional digital skull model and reference model; In addition, we also added 14 feature points as supplementary feature points to make results more accurate.

Craniofacial control point is the facial surface point corresponding to the skull feature points. In anatomy, each skull control point corresponds to a craniofacial control point, between them filled with the soft tissue. Soft tissue thickness can be regarded as normal length that the skull surfaces at the skull control point, and the skull surface contains the skull control point. The method in this paper is calculating the thickness along the normal direction of surface at the skull control point, the method can automatically calculate the craniofacial feature points which correspond to the skull feature points. Suppose P(x_0, y_0, z_0)is a skull control point, N(n_x, n_y, n_z) is the normal direction at point P, h is the soft tissue thickness at point P, Q(x, y, z) is craniofacial control point corresponding to the point P. Calculated as equation(1):

$$x = x_0 + \frac{n_x}{\sqrt{n_x^2 + n_y^2 + n_z^2}} \times h$$

$$y = y_0 + \frac{n_y}{\sqrt{n_x^2 + n_y^2 + n_z^2}} \times h$$

$$z = z_0 + \frac{n_z}{\sqrt{n_x^2 + n_y^2 + n_z^2}} \times h \qquad (1)$$

2.3 Craniofacial Reconstraction base on MLS Deformation

To accurately and quickly reconstruct the skull face, we use the reference facial model as constraint and reconstruct the original face of the skull. It's essentially the problem of a deformation from the reference facial model to the target facial model. Firstly, we mark the feature points on the skull model, and then get the facial points of these points, and mark corresponding feature points interactively on the reference facial model. Finally, deformation algorithm is applied to the reference facial model to match the feature points to their corresponding feature points on the source skull model. As a result, the target face of the source skull model is formed.

The problem can be represented as a spatial deformation, that is to say, given the position of n feature points and all the grid vertex of three-dimensional model, how can we calculate the new position p' of mesh points which are located at p when the feature points are moved from p_i to a new position p_i' (0≤i≤n, note that p_i' is equal to p_i if the point is not moved). In other words, the displacement of given feature points $\Delta p_i = p' - p_i$ (0≤i≤n, and Δp_i is equal to 0 if the point is not moved). The key problem is to calculate the displacement of mesh point Δp.

Since the free-form deformation is really complex, we use scattered data interpolation to deform the reference face model. Currently, scattered data interpolation method which is widely used includes radial basis function method and moving least squares method. Radial basis function interpolation deformation method is a global-based method. Its local effect is poor. Therefore, in this paper, moving least squares method which we improved is adopted in the craniofacial reconstruction. A craniofacial reconstruction method based on MLS is proposed. In the next section, we will briefly describe moving least squares method.

Let p_i be a set of feature points and q_i the new positions of the feature points p_i. The key idea of moving least squares method is to find the best affine transformation $T_v(p_i)$ that minimizes

$$\min \sum_i w_i \left| T_v(p_i) - q_i \right| \qquad (2)$$

where p_i and q_i are composed with x, y, z three dimensions. w_i is weight function, R is effect radius, the nearer distance from v to p_i is, the less value of weight function is.

Let deformation function be $f(v) = T_v(v)$, $T_v(v)$ is an affine deformation function, consisting of two parts: a rotation transformation matrix M and a translation T.

$$T_v(v) = xM + T \qquad (3)$$

The translation transformation can be rewritten as

$$T = q^* - p^* M \qquad (4)$$

where p^* and q^* are weighted centroids given by equation 5.

$$p^* = \frac{\sum_{i=1}^{n} \omega_i p_i}{\sum_{i=1}^{n} \omega_i} \qquad q^* = \frac{\sum_{i=1}^{n} \omega_i q_i}{\sum_{i=1}^{n} \omega_i} \qquad (5)$$

then $T_v(v)$ can be rewritten as.

$$T_v(v) = (v - p^*)M + q^* \qquad (6)$$

and equation 2 can be rewritten as

$$\min \sum_i w_i \left| \hat{p}_i M - \hat{q}_i \right| \qquad (7)$$

where $\hat{p}_i = p_i - p^*$ and $\hat{q}_i = q_i - q^*$.

Finding an affine deformation that minimizes equation 7 is straightforward using the classic normal equations solution.

$$M = (\sum_{i=1}^{n} \hat{p}_i^T w_i \hat{p}_i)^{-1} \sum_{j=1}^{n} w_j \hat{p}_j^T \hat{q}_j \qquad (8)$$

The deformation function f(v) is then

$$f(v) = (v - p^*)(\sum_{i=1}^{n} \hat{p}_i^T w_i \hat{p}_i)^{-1} \sum_{j=1}^{n} w_j \hat{p}_j^T \hat{q}_j + q^* \qquad (9)$$

We usually select spline function as the deformation function. According to the latest MLS review [11], the result is better when they use the following weight function.

$$w(x) = \begin{cases} (1-x)^4 (1+x) & (0 =< x <= 1) \\ 0 & (x > 1或x < 0) \end{cases} \qquad (11)$$

So we select equation 11 as the deformation function in this paper.

Finally, craniofacial reconstruction based on MLS deformation can be described as following steps.

(1) mark the feature points on the skull and calculate the corresponding facial feature points

First, according to skull feature points defined by Lan[14], we mark feature points on the source skull model as the primary feature points, and a certain number of auxiliary feature points if needed. When all skull feature points are determined, we need to mark reference face feature points at corresponding positions on the reference face model.

For each control point i, the position on the reference facial model is marked by p_i, and the position of facial control point associated with skull control point on the source skull model is marked by q_i. q_i and is calculated by $q_i = s_i + d_i$,where s_i is the position of source skull control point, d_i is the depth of soft tissue associated with s_i. This equation means that facial control point associated with skull control point is calculated the surface normal of this control point plus the depth of soft tissue.

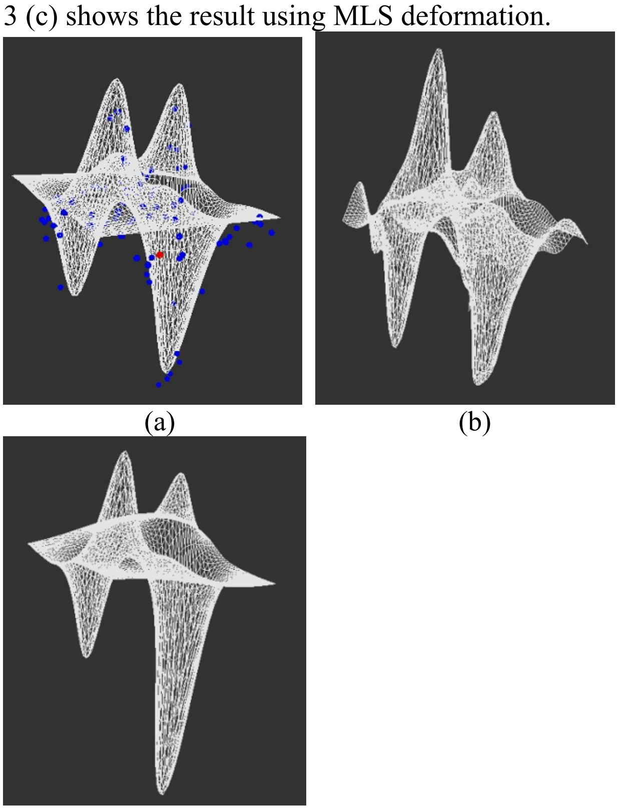
(2) take moving least squares function $f(p)$ meeting $q_i = f(p_i)$ as the deformation function.

(3) solve the target deformation function using MLS deformation method, and then the reconstruction is finished .

3 Experiments Results and Discussions

Our algorithms have been implemented in VC++ with the Visualization toolkit. And the source skull data is obtained from a hospital. The experimental environment is core 2 T5450 with 1.66 GHz main frequency of CPU and 1.5GB memory.

To prove the effectiveness of craniofacial reconstruction method based on MLS deformation, first of all, we compare the results of RBF deformation and MLS deformation shown in Figure 3. Among them, Figure 3 (a) shows the original surface on which 100 feature points are placed as constraint points. The blue points are the target positions which the 100 feature points will move to. Figure 3 (b) shows the result using RBF deformation, and Figure 3 (c) shows the result using MLS deformation.



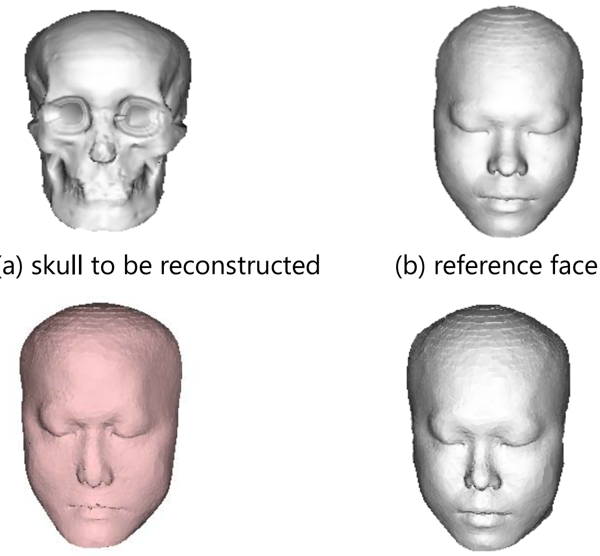
(a) (b)

(c)

Fig 3. the comparisons of results between RBF and MLS deformation. (a) original surface and target points. (b) RBF deformation. (c) MLS deformation.

As seen from the experiment results of the two methods, MLS method has the good property of preserving details. Because of the weight function and the effect radius, current feather point's movement has no effect on the points that are far away from it. In a word, the farther distance it is, the less effect it has. While RBF method considers the all distances from the feature points to the current point. It may bring about great variation of a point that ought to have little or no movement of resulting in fluctuation in the whole deformation. Thereby the accuracy of the deformation is decreased.

We use RBF deformation method and MLS deformation method, making the same reference face model deform the same objective skull. Figure 4 is the result of these two methods. We can find that the craniofacial reconstruction which is based on RBF deformation has unexpected effect in detail, because this method takes the whole model into consideration. The RBF deformation in one feature point is constraint by the all feature points on the model. It considers the distance between the current feature point and all the other feature points, and then calculates the distance to obtain a deformation function. While towards the facial model, deformation in one feature point may only be affected by the feature points around it and the feature points far away from it can't affect it. The MLS method is based on the least squares method, and weight function is used to control fitted area. In other words, only the points around the current point can affect it, and the farther the point is to the current point, the smaller influence it is to the current point. Thus, this method has a good deformation in detail.



(a) skull to be reconstructed (b) reference face

(c) RBF deformation (d) MLS deformation

Fig 4. Comparison between the RBF deformation and MLS deformation

Table 1 efficiency of MLS and RBF reconstruction method

	Number of points of the mesh	Number of feature points	Time Consume(/ms)	
			RBF deformation	MLS deformation
Surface Deformation	2601	100	32	39
Craniofacial Reconstruction	265749	36	1045	1281

The two experiments prove the feasibility of the MLS deformation method. This paper leads the MLS deformation to the craniofacial reconstruction, and present a reconstruction method based on MLS deformation.

In the efficiency of the algorithm, table 1 shows the time cost of our algorithm. In the process of MLS deformation reconstruction, set the k=4, d=18.2

According to the result of our experiments and analysis, this method has the following characteristics:

(1) MLS deformation reconstruction method has a good effect in detail

(2)In the efficiency of the algorithm, MLS deformation reconstruction method is similar to RBF deformation reconstruction.

4 Conclusions and Future Work

In this paper, the traditional moving least squares deformation method is improved, and then it is introduced into the craniofacial reconstruction, and a craniofacial reconstruction method based on MLS is proposed. Using the source skull and the reference facial model as the experiment data, through measuring the differences between the target facial feature points and the reference facial feature points, we can calculate the deformation function based on the improved MLS.

Then we can get the target face through deforming the reference face model. As the experimental results show, the reconstructed three-dimension human facial model is accurate and efficient. But there are still many weaknesses in our implementation of reconstruction algorithm, so the next step of our study will focus on the following aspects:

(1) The establishment of model database. In this paper, only one standard head model is used as the reference model and deformed for reconstruction. In order to make the reconstruction result closer to the appearance of the dead, model database need be established, and the models should be stored classifiably, so the basic information can be extracted more conveniently according to the basic data .

(2) The study of deformation method based on MLS. Since only the affine transformation function is selected as the fitting function in this paper, there are probably some problems in implementation process, such as the matrix is not invertible and can't be solved. Therefore, the detailed deformation method should be studied and improved in the future.

(3) The verification problem of reconstruction result. Since there is no quite objective method to verify the reconstructed facial model, therefore, a more objective verification method is hoped to be established in the future. The photos of the dead will be used to analyze our reconstruction result qualitatively and quantitatively in our future study.

References

[1] Greef S D, Willems G. Three-dimensional craniofacial reconstruction in forensic identification. Latest progress and new tendencies in the 21st century. J.Forensic Sci.,2005,50 (1): 12-17.

[2] Iscan M Y. Global anthropology in the 21st century. Forensic Sci Int, 2001,117:1-6.

[3] Stephan C N. Anthropological facial "reconstruction"—recognizing the fallacies, "unembracing" the errors, and realizing method limits. Sci Justice, 2003, 4(2):193-200.

[4]Vanezis P, Vanezis M, Mecombe G, et al. Facial reconstruction using 3D computer graphics. Forensic Science International,2000,108:81-95.

[5]Quatrehomme G ,Cotin S ,Subsol G ,et al .A fully three-dimensional method for facial reconstruction based on deformable models[J]. J Forensic Sci, 1997,42(4): 649-652.

[6]Attardi G, Betr M, et al. 3D facial reconstruction and visualization of ancient Egyptian mummies using spiral CT data Soft tissues reconstruction and textures application[A]. Los Angeles, CA: ACM SIGGRAPH Publications[C], 1999:223 -239.

[7]Kahler K, Haber J, Seidel H P. Reanimating the dead: Reconstruction of expressive faces from skull

data[A]. Proceedings of SIGGRAPH’03[C]. San Diego: ACM,2003 22(3):554–561.
[8]Claes P, Vandermeulen D, et al. Craniofacial reconstruction using a combined statistical model of face shape and soft tissue depths: Methodology and validation[J]. Forensic Science International 159S 2006: 147–158.
[9]Zhang Z Y, Liu Z C. Adler D, et al. Robust and Rapid Generation of animated faces From Video Images: A Model –Based Modeling Approach [J], International Journal of Computer Vision, Hingham, MA, USA:Kluwer Academic Publishers, July 2004,58(2):93-119.
[10]Waters K, Levergood T M. Decface: An Automatic Lip-Symchronization Algorithm for Synthetic Faces [R], DEC, Cambridge Reaserach Laboratory Technical Reprot Series, 1993.
[11]CHENG Z Q, WANG Y Z, LI B, et al. A Survey of Methods for Moving Least Squares Surfaces. IEEE/EG Symposium on Volume and Point-Based Graphics[C], 2008.
[12] The Visualization ToolKit[EB/OL]. http://www.vtk.org/index.php.
[13] Jiarui Bao, Ronghua Liang, Fuli Wu, Xianping Huang et al. The Study On the Algorithm of Complex Hole Repairing on 3D craniofacial model. Journal of Image and Graphics，2009.
[14] Yuwen Lan, Yuewei Li, ShouRong Chen et al. The research on the indices of 3D Craniofacial reconstruction system [A]. The 11th Scientific Meeting of the International Association for Craniofacial Identification [C], dalian, 2004: 102-121.