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A STUDY ON COMPUTER-AIDED FACIAL RECONSTRUCTION IN FORENSIC MEDICINE

Hao-Ren Ke, Hong-Jang Jean**, and Zen-Chung Shih***
*Computer Center, National Chiao-Tung University, Hsinchu, Taiwan, R.O.C.
E-mail: claven@cc.nctu.edu.tw
**Department of Computer and Information Science, National Chiao-Tung University, Hsinchu, Taiwan, R.O.C.
E-mail: gis85547@cis.nctu.edu.tw/zcshih@cc.nctu.edu.tw

Abstract

In forensic medicine, facial reconstruction means the techniques to reconstruct the face of a deceased person giving the skull of his/her cadaver. Using computers to assist facial reconstruction can increase fidelity, reliability, and efficiency; in addition, many advanced functions can also be incorporated. In this paper, we design a computer-aided facial reconstruction system. The primary contributions are:

1. Propose a method to evaluate the thickness relationship between facial soft tissue and skull, and use the relationship to create a statistics database.
2. Design a facial reconstruction system that reconstructs a 3D facial model for a skull according to the statistics database.

Keywords: Facial Reconstruction, Forensic Medicine, Snake Model

1. Introduction

Forensic facial reconstruction is a group of methods to reconstruct the face of a deceased person given the skull of his/her cadaver. Forensic facial reconstruction has long played an important role as an aid to identify facial-destroyed cadaver. Traditionally, forensic facial reconstruction requires skillful experts who understand the structure of skull and skin very well to attach clay on the skull of a cadaver. Experts' experiences and skills dominate the effectiveness of facial reconstruction, and it is not easy to transfer their experiences and skills. Furthermore, although basically we can depend on skillful experts, it is a little subjective.

A well-designed computer-aided facial reconstruction system has many advantages. First of all, it is more objective. Second, it would surely ease the reconstruction process. We probably cannot develop a fully automatic system; however, it is clear that using computers can greatly reduce the amount of time spent. The third advantage is that we can produce several possible facial models from a given skull, depending on a variety of parameters, particularly with the hypothesis that the person was fat, slim, old, or young. In addition, a computer-aided system that produces a 3D model of a reconstructed face allows users to observe a reconstructed face from several viewing directions, and thus can increase the probability of successfully identifying an individual. Although computer-aided facial reconstruction has so many advantages, due to the complexity of the process, researches on this field are far from maturity.

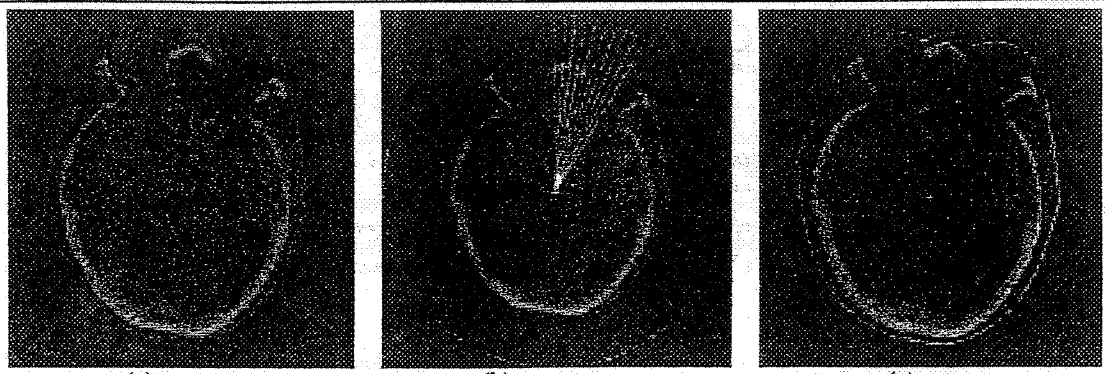
To successfully reconstruct the face of a skull, the most critical issue is to clarify the relationship between soft tissue (i.e. facial skin) and the underlying bony structure of skull. This issue has been discussed by forensic medicine experts for more than 100 years, but up to now, they have not reached into consensus. Many facial reconstruction methods measure the thickness between a skull and its corresponding facial skin (skin-skull thickness, for short). Obviously, if the skin-skull thickness[1] at all positions of a face are known, we can easily reconstruct the face when its skull is given. We also follow this hypothesis to develop our system.

In this paper, we propose a computer-aided system that collects the statistics on skin-skull thickness, and reconstructs a 3D facial model from a skull. This paper is organized as follows. Section 2 reviews related approaches. We show the process of collecting thickness statistics in Section 3. Then the facial reconstruction approach is presented in Section 4. Section 5 gives the experimental results and discusses a few experiences. Conclusions and future directions are described in Section 6.

2. Related Works

Our computer-aided facial-reconstruction system comprises two major components. One component collects the statistics about the soft-tissue thickness of heads, and the other reconstructs a face of a skull from the soft-tissue

[1] We use the two terms "skin-skull thickness" and "soft-tissue thickness" interchangeably in this paper.



(a) (b) (c)

Figure 1 Process of the simplified snake model. (a) The original CT slice. (b) The enclosing circle and a few lines shooting from the circle center. (c) The result of the iteration phase. The yellow vertices satisfy the first criterion, and the blue ones satisfy the second criterion.

thickness statistics. The following briefly describes related researches on the two components.

There has been a long history of researches on quantifying the relationship between soft tissue and the underlying structure of facial skeletons [1, 2, 5, 6, 7, 9, 16]. The earliest research was performed in 1883 by Welcker [16]. Welcker obtained a database of soft-tissue thickness by inserting a thin blade into facial skin of cadavers. The skin positions into which the blade inserted were mainly at selected anatomical landmarks on a skull. He then marked the blade/tissue surface interface, and measured the depth of the blade's penetration. Obvious problems are inherited in this type of approaches [6, 9], for example, the soft-tissue distortion of cadavers resulting from drying and embalming. However, until middle 1980 all studies that determined tissue depth data at landmark sites used cadaverous populations and the 'needle technique.'

After 1980, non-invasive medical systems become popular [2, 7]. There are more and more researches using non-invasive systems to collect the data. Hodson et al. [7] used an ultra-sound technique to obtain in vivo profiles of the tissue depths from 50 children aged from 4 to 15 years.

A few researches [2, 7] tried to discuss the difference of soft-tissue thickness in different race, sex, age, and weight. From their researches, we know that all these factors have impacts on skin-skull thickness.

When the soft-tissue thickness information is available, many artists and anthropologists followed Krogman's recommendation [10] to produce three-dimensional reconstruction of heads. Briefly, Krogman's process involves attaching tissue-depth markers at selected sites around a skull. Clay is then used to fill in between the markers, and the fine features of the face are sculpted. Frequently, glass eyes, a wig, and real clothing are used to make the result as lifelike as possible. This approach is still used in non-automatic forensic facial reconstruction now.

Recently, computer-aided facial reconstruction systems receive more and more attention [3, 11, 12, 13, 14, 15]. Vanezis et al. [15] attempted to establish the use of computers to generate images for facial reconstruction. They used a computer to attach soft tissue, with standard tissue depths obtained by traditional methods, onto the captured digitized model of a skull stored 'virtually' in a computer.

In 1997, Quatrehomme et al. [12] created a database containing several head models with different age, sex, race, and nutrition status. Each head model stored in the database consisted of a skull model and a facial model. They also identified ***crest lines*** for head models. Crest lines are the lines that are absolute maxima of the largest principal curvatures of a head model. While reconstructing, they computed the crest lines of a unknown skull named S_1, and searched the database to find a head S_2 most similar to S_1, by using a registration algorithm based on local point matching. Then a transformation T, which transformed the crest lines of S_2 to those of S_1, was computed. By using the same transformation T, they transformed the facial model of S_2 to generate the corresponding facial model of S_1.

3. Collection of Thickness Statistics

This section describes our approach to computing soft-tissue thickness and creating a soft-tissue thickness statistics database. The whole process consists of three steps: ***boundary segmentation***, ***characteristic point selection*** and ***statistics information computation***.

The inputs are 3D head CT volume data containing information of facial skin and skull, among others. Our method is slice-based. It means that we calculate soft-tissue thickness separately for each slice of a head volume. To build the statistics database, we average the soft-tissue thickness of slices with identical relative position and orientation from all head samples.

3.1 Boundary Segmentation

The purpose of ***boundary segmentation*** is to identify the two boundaries of facial skin and skull in a slice of a head CT volume data. The two boundaries we find are closed, and we can ensure that each point selected on the skull boundary corresponds to exactly one point on the skin boundary. Hence, the thickness between a skull point and its corresponding skin point can be measured as their distance.

We propose a simplified ***snake model*** [4, 8] here for boundary segmentation. Our method comprises two phases: the ***preprocessing phase*** and the ***iteration phase***. The preprocessing phase selects an initial boundary, and the iteration phase approaches the actual boundary by using an iteration strategy. Due to the reasons described later, we need to identify the skull boundary first, and use the center of the skull to find the skin boundary. Furthermore, we have to run the method twice (with different circle centers, see below) for finding the skull boundary.

To find the skull boundary, in the preprocessing phase, a circle enclosing the skull is drawn. We use the center of a CT slice as the circle center. The circle is then divided evenly by lines shooting from the circle center to the perimeter of the circle. The angles between any two consecutive lines are identical. The polygon whose vertices are the intersection points of the lines and the circle is the initial skull boundary. It is clear that the number of lines used to divide the circle will determine the quality of the boundary. We shoot 1024 lines here.

The iteration phase uses the initial boundary to iteratively approximate the actual boundary. In every iteration, the following two criteria are evaluated for the boundary vertices, which are generated from the preceding iteration or the preprocessing phase. When a vertex satisfies any one criterion, it stops moving forward; otherwise, it moves one unit distance toward the circle center along the lines drawn in the preprocessing phase. The first criterion compares the gray level of a vertex with a threshold, which represents the normal iso-value of the material we are interested in (in this case, the skull). If the gray value is greater than the threshold, the vertex stops moving forward. This criterion identifies the boundary of a certain gray value. The second criterion evaluates the relative position of a vertex with its neighboring vertices. If the current position of any neighboring vertex is greater or less than the position of the vertex for more than one unit distance, the vertex stops, too. This criterion makes sure that a vertex and its neighbors are connected, and will be satisfied when the boundary shape changes violently. After all vertices are evaluated according to the two criteria and if no vertices move forward, the iteration phase finishes, and the polygon with the resulting set of vertices is used as the skull boundary; otherwise, the next iteration starts up. Figure 1 shows the process of the simplified snake model.

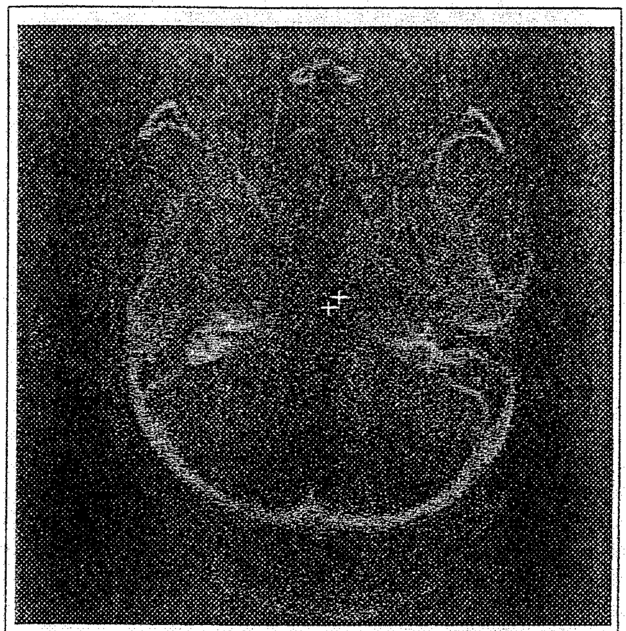


Figure 2 The upper right cross is the center of the CT slice. The lower left cross is the skull center.

The preprocessing phase just described uses the slice center as the center of the enclosing circle. However, it is not a good candidate as the circle center, because our method to collect soft-tissue thickness statistics has to utilize the skull center as a reference point so as to produce correct statistics database. From Figure 2, we can see that the center of a CT slice is not necessarily the skull center.

In spite of this, through the skull boundary obtained by the simplified snake model, we can identify the skull center. Here we take the average of all skull vertices as the skull center because the skull shape is nearly symmetric. The skull center obtained by our method is very close to the actual skull center. After the skull center is found, we apply again the simplified snake model with the skull center as the center of the enclosing circle, and the resulting polygon will be used as the skull boundary in the following steps. The simplified snake model with the skull center can then generate the skin boundary similarly.

We point out two things about the boundary segmentation process here. First, the skull and skin boundaries generated by our method are closed, and the vertices of the skull and skin boundaries are located on the lines shooting from the skull center to the enclosing circle. Moreover, a skull vertex on such a line can match exactly one skin vertex along the line, and the thickness between the two vertices can be measured as their distance. Second, the orientations of the lines drawn in all slices of all head samples are identical.

3.2 Characteristic Point Selection

Although our goal is to build a thickness statistics for every region of a head and use the statistics to reconstruct the face of a skull, not every region of a face exists a soft-tissue thickness relationship. For example, even two heads having similar skull shapes around eyes, noses, and ears, their skin shapes around these regions may not be similar. As a result, it is useless to record the thickness information around these regions into the statistics database. Here we propose a method to identify the regions of a skull where the skin-skull thickness relationship does not exist. Our method makes use of three kinds of characteristic points.

The first kind of characteristic points are located at the regions where the skull shape changes violently. In our implementation, we define this kind of characteristic points as skull vertices satisfying the second criterion described in Section 3.1 and adjacent to a skull vertex satisfying the first criterion. See Figure 3 for an illustration. These points reside at the two ends of the regions that do not have skin-skull thickness relationship, and we do not put the thickness information of these regions into the statistics database. These characteristic points usually appear around eyes.

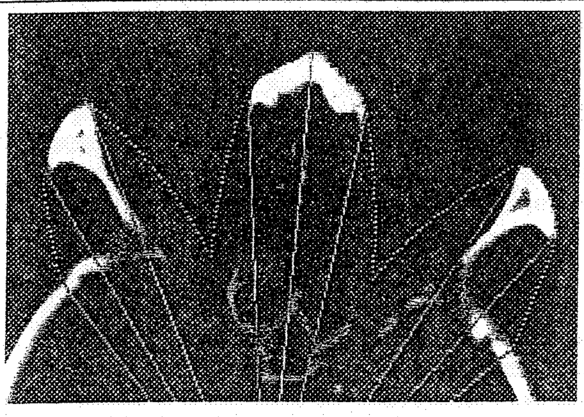


Figure 3 Result of selecting the first kind of characteristic points. The red vertices are stopped by the first criterion. The green vertices are stopped by the second criterion. The green vertices along green lines connecting the skull center are defined as the first kind of characteristic points.

The second kind of characteristic points are selected from the skin boundary. Because the skin boundary is smoother than the skull boundary, we cannot use the same method described in the previous paragraph to select these characteristic points. Instead, we select them interactively. These characteristic points usually appear around ears.

Then, for each head volume data, we must find its up direction, because all head samples do not necessarily have identical orientation while the CT images are taken. We use the skin boundary of one reference slice, usually one of the slice containing the nose, to find the up direction. We identify the point at the top of the skin boundary automatically, and draw a line connecting the point and the skull center. We define the line as the up direction. We then shoot three lines from the skull center. The angles between the three lines and the up direction are 90^0, 180^0, and 270^0, respectively. The intersection points between the four lines and the skull boundary are defined as characteristic points. The four lines are applied to all the other slices of the head volume to identify the third kind of characteristic points.

After these characteristic points are identified, we still have to decide which characteristic points must be kept and which must be deleted. The purpose is to assure that all the slices with identical relative position and orientation in head samples have the same number of characteristic points, so that their thickness information can be correctly averaged and put into the statistics database. Because there are a few small concave shapes on the skull boundary, the procedure to select the

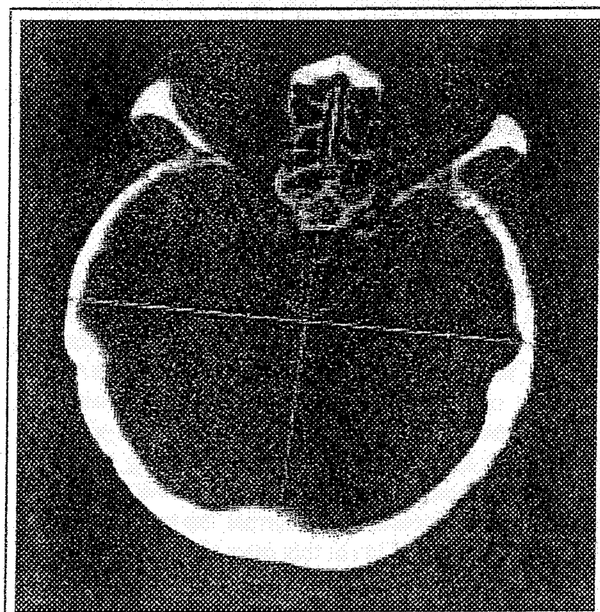


Figure 4 Results of the characteristic point selection. The green lines are selected automatically, and blue ones are added according to the up direction.

characteristic points may select them as well; however, we do not want to use them. Hence, we have to remove them interactively. Because the similarity between the slices for

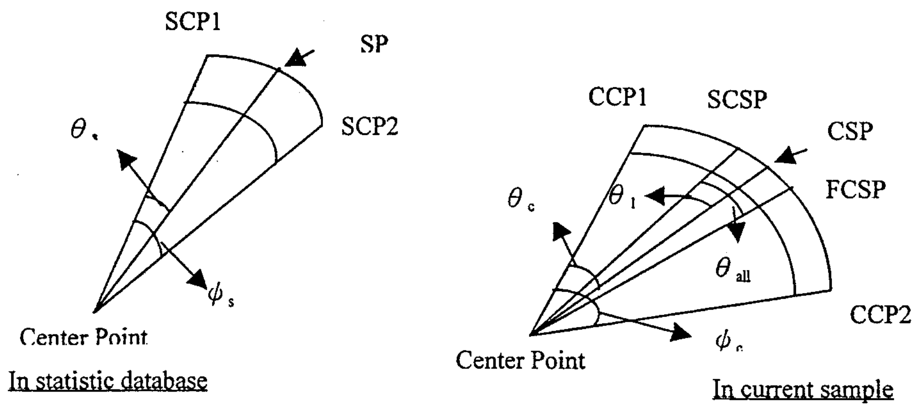


Figure 5 We use (1) $\frac{CSP - CCP1}{SP - SCP1} = \frac{\theta_c / \phi_c}{\theta_s / \phi_s}$, (2) $\frac{T_{CSP} - T_{SCSP}}{T_{FCSP} - T_{SCSP}} = \frac{\theta_1}{\theta_{all}}$, where T is the thickness of that point. SCP1 and SCP2 are the characteristic points in the statistics database. SP is what we want to calculate. CCP1 and CCP2 are the characteristic points in the current sample. SCP1 maps to CCP1. SCP2 maps to CCP2. SP maps to CSP. FCSP and SCSP are the nearest vertices of CSP. After we get the thickness of CSP, we can update the value of SP by the thickness of CSP.

all head samples, we can ensure the number of characteristic points in all head samples are the same. Figure 4 depicts the results of the characteristic point selection.

3.3 Statistics Information Computation

This section presents our method to compute the skin-skull thickness information from each sample and update the statistics database. The basic idea is to store the average soft-tissue thickness at all skull vertices for slices with identical relative position and orientation in head samples. From Section 3.1, we show each skull vertex matches a skin vertex and how the thickness between a skull vertex and its corresponding skin vertex can be measured. Furthermore, the slices with identical relative position in head samples have the same number and orientations of skull/skin vertices; thus, for these slices, we can take an average of the thickness at the positions of the skull vertices with the same orientations, and store the average into the database.

Before adding the thickness information of the current sample into the statistics database, we must map the characteristic points of the current sample to those in the statistics database. From Section 3.1, we know the number of characteristic points in the current sample is the same as that in the statistics database. Thus, we can use the orientations of these characteristic points to decide how to map.

When we want to add the thickness at a characteristic point into the database, we take average of its thickness with the thickness of the corresponding characteristic points of all samples already in the database. For the vertices between two adjacent characteristic points, we decide first if the region between them has skin-skull thickness relationship. If it has, we put the thickness information of this region into the statistics database; otherwise, we do not.

When we put the thickness information of a region between two adjacent characteristic points into the statistics database, we have to take the following situation into consideration. Because the number of vertices between two characteristic points in the current sample may not be the same as that of vertices between the two corresponding characteristic points in the statistics database, how can we add the thickness information of these vertices in the current sample into the statistics database? To solve the problem, we leverage an interpolation approach as illustrated in Figure 5.

4. Reconstruction

This section presents our approach to reconstructing a 3D facial model of a given skull, by using the statistics collected in Section 3. The reconstruction process consists of ***boundary segmentation***, ***characteristic point selection***, ***skin vertices generation***, and ***rendering***. Among these steps, the former two are identical to the corresponding steps in Section 3.

4.1 Skin Vertices Generation

After the skull vertices and characteristic points are obtained by boundary segmentation and characteristic point selection, the position of each skin vertex is calculated by using its corresponding skull vertex and the thickness data in the statistics database.

To generate the skin vertex corresponding to a characteristic point, we can directly retrieve the thickness of the characteristic point from the statistics database and add the thickness to the position of the skull point along the direction of the line mentioned previously. To calculate the skin positions in a region between two adjacent characteristic points, the first step is to determine if the region has statistics relationship between skin and skull. If the region has, we employ an interpolation approach similar to the method shown in Figure 5 for generating the skin vertices within it.

Although we hope every part of a face can be reconstructed by using the information in the statistics database, a few parts of a face cannot be reconstructed in this manner. These parts include eyes, ears, and noses. A better way to reconstruct eyes, ears, and noses are to utilize a database storing models of eyes, ears, and noses, and let users select them interactively. However, in our current implementation, we store the eyes, ears, and nose of a head sample during the statistics collection process, and attach them to any faces while reconstruction.

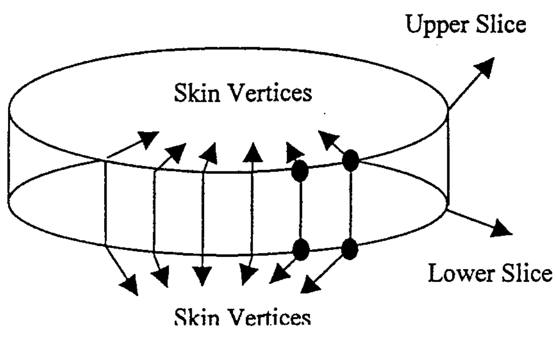


Figure 6 3D-mesh model from two adjacent slices.

4.2 Rendering

After all CT slices of a given skull are processed by the method described in Section 4.1, we have obtained all skin vertices. A 3D-mesh facial model is then generated for rendering. We generate the model by the following two steps. The first step inserts intermediate slices between two adjacent CT slices. Because the two CT slices have the same number and orientations of skin vertices, we can interpolate them to produce the skin vertices of an intermediate slice. The purpose of this step is mainly for better looking of rendering. The second step generates the 3D-mesh model by connecting a skin vertex with its adjacent skin vertices in the same slice, and with the skin vertices having the same orientation in adjacent slices.

Figure 6 depicts the construction of a 3D-mesh model from two adjacent slices. After the model is generated, we can impose shading and lighting to render it.

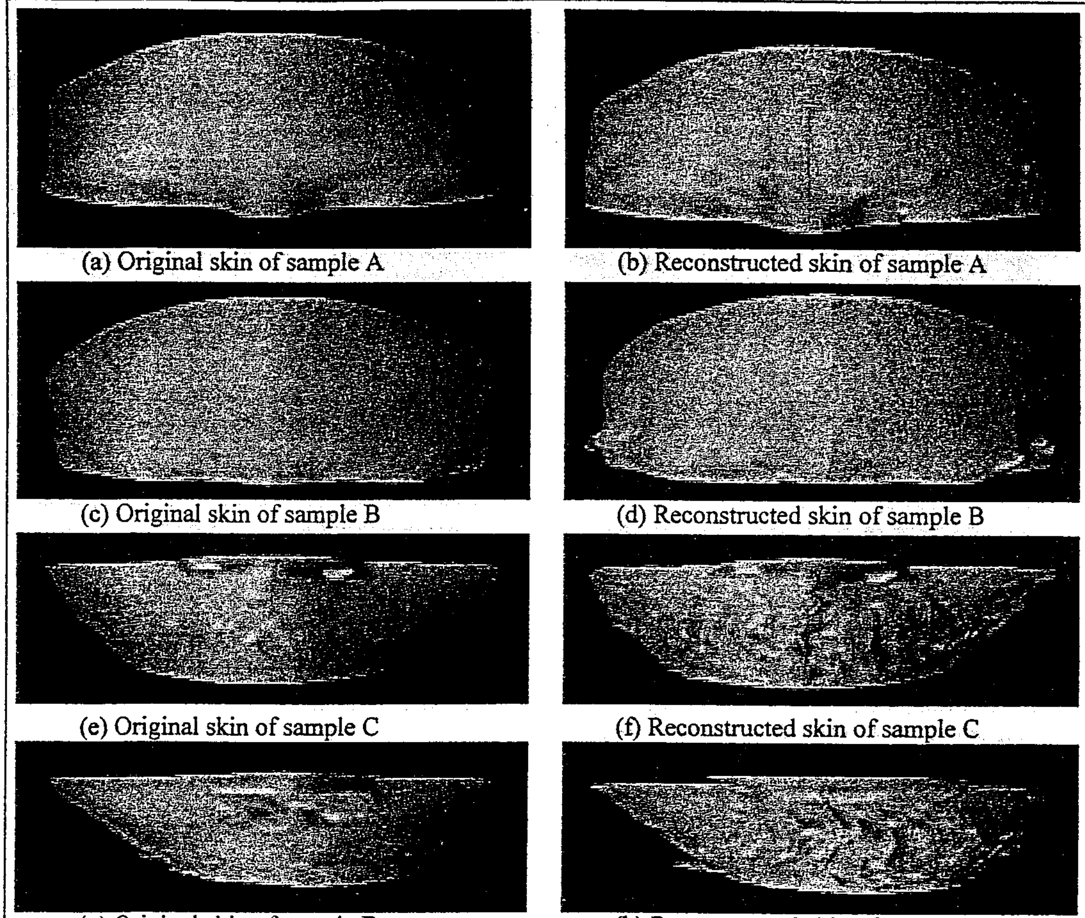
5. Experimental Results

The concepts described in this paper are implemented by the C language with OpenGL library in Visual C++ environment, and run on Pentium PC. The head samples used in our experiments are from patients of Taipei Veterans General Hospital, without their identification and related information. Due to healthy concerns, radiologists only take CT images from the portions of a patient's head where relates to his/her illness; hence, we do not have complete CT head data for our experiments. Specifically, two kinds of head samples are employed in our experiments. The first kind only has the upper part of a head, and we have two male and two female samples belonging to this kind. The second kind only has the lower part of a head, and we have two male samples belonging to this kind.

Three statistics databases are created separately for the male and female samples of the first kind and the samples of the second kind. After the databases are created, we reconstruct the facial skins of these samples from their underlying skull by using the statistics databases. Figure 7 shows our experimental results. Among these figures, Figure 7-(a), (c), (e), and (g) are the original facial skins rendered from the input CT volume data. Figure 7-(b), (d), (f), and (h) are the reconstructed facial skins by exploiting the statistics databases.

In the following, we discuss a few experiences we learn. First, volume registration is an important issue. Our method has to process the slices with identical relative orientation and position from all head samples for successfully creating the statistics; however, this may not be hold when the samples are taken CT images. In our implementation, we do not perform any automatic volume registration, but only interactively select slices with identical relative orientation and position from all samples. Thus, the correctness of the statistics database created is influenced.

By comparing Figure 7-(a) and (b), we can see their differences. Protrusion appears above the right eye in Figure 7-(b). The similar situation also appears in other figures. The reason is that the number of head samples used to create the statistics database is too few. This situation can be reduced when more samples are used.



(a) Original skin of sample A

(b) Reconstructed skin of sample A

(c) Original skin of sample B

(d) Reconstructed skin of sample B

(e) Original skin of sample C

(f) Reconstructed skin of sample C

(g) Original skin of sample D

(h) Reconstructed skin of sample D

Figure 7 Experimental Results

A better understanding of the relationship between facial skin and skull is essential for designing an excellent computer-aided facial reconstruction system. Our experiences show that it is difficult to define this relationship. Furthermore, not very region on a face has a skin-skull relationship. In this paper, we use characteristic points to find regions that do not exist a skin-skull relationship, but we cannot guarantee that all such regions are found by our method.

6. Conclusions and Future Works

In this paper, we perform a preliminary study on designing a computer-aided facial reconstruction system. We present an approach to extracting skin-skull thickness information from each slice, and collecting a statistics database on skin-skull thickness. By making use of the statistics database, we propose a method to reconstruct a 3D facial model of a give skull.

Our method is far from perfect. Volume registration must be incorporated into our system, and further studies on the skin-skull relationship are essential. In addition, there are still several issues that need further investigation to improve our system.

A. *Statistics database Collection*

To practically employ our method in facial reconstruction, we need collect more head samples into the statistics database. In addition, many researches [2, 7] show the influences of race, sex, age, and weight on the skin-skull thickness; thus, we should take these factors into consideration while constructing the statistics.

B. *Development of a database for storing eyes, ears, noses, lips, etc.*

We shall develop a database that contains 3D models of eyes, ears, noses, lips, etc. Users can interactively select models from the database and attach them on a face. We also can store hairstyles and eyebrows in the database. In this manner, the reconstructed face can be more realistic.

C. Development of a friendly user-interface

In addition to the above issues, we shall develop a friendly user interface so that users can perform many operations, such as rotation, on the reconstructed face. Users can also adjust a few parameters, like age and weight, to produce several possible facial models for a skull. In this manner, the probability of identifying an individual from a given skull can be increased.

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