

Software Tools for Craniofacial Growth and Reconstruction

Katrina Archer^a

Kevin Coughlan^a

David Forsey^b

Sonja Struben^b

^aRadical Entertainment

1052 Homer Street

Vancouver, British Columbia

Canada V6B 2W9

e-mail: karcher,kcoughlan@radical.ca

^bDepartment of Computing Science

University of British Columbia

201-2366 Main Mall

Vancouver, British Columbia

Canada V6T 1Z4

e-mail: forsey,struben@cs.ubc.ca

Abstract

Forensic artists use tissue thicknesses at well known landmarks on the craniofacial skeleton to generate a potential likeness of an individual from a skull. This is a very subjective and time consuming process. We present two prototype software packages: one for simulating the growth of a craniofacial skeleton either forwards or backwards in time, and the other for generating a facial reconstruction over a skeleton. The craniofacial growth model uses three-dimensional data from specific landmarks through time to drive the growth process. Tissue depth markers on the craniofacial model determine the interpolated shape of the facial reconstruction and can be altered to cover the range of potential likenesses. Examples of a facial reconstruction and a grown craniofacial skeleton are shown.

Résumé

Les artistes d'expertise médico-légale utilisent l'épaisseur des tissus situés à des points de repère prédéterminés de la boîte crânienne pour créer le portrait possible d'une personne à partir d'un squelette crânien. Ce processus tient beaucoup à la subjectivité et requiert beaucoup de temps.

Nous présentons deux prototypes de logiciels : le premier peut simuler soit la croissance du squelette crânien, soit un recul de croissance. Le deuxième logiciel génère une reconstruction du visage à partir du squelette.

Le modèle de croissance utilise des données en trois dimensions recueillies à des endroits spécifiques sur une base chronologique pour générer le processus de croissance. Des indicateurs de la profondeur des tissus sur le modèle crânien déterminent par interpolation la forme reconstruite du visage. L'introduction de variables dans ces indicateurs permet d'établir toute une gamme de ressemblances possibles à partir d'un même squelette.

Des exemples de reconstruction d'un visage et d'un squelette crânien sont inclus.

Keywords: hierarchical surfaces, interpolation, craniofacial reconstruction, craniofacial growth, forensic

Introduction

Many fields outside of computer graphics are showing growing interest in the development of graphical tools to aid in both research and data analysis. The field of forensic pathology is one such discipline. One aspect of forensic pathology is the determination of an individual's appearance prior to death, through facial reconstruction techniques. Current methods for three dimensional facial reconstruction use a cast of the skull over which a sculptor builds up facial features with clay. The depth of the clay is regulated by a set of known tissue depths at standard landmarks. This process relies heavily on artistic interpretation and requires roughly 3 days to create a single facial estimate. This likeness is publicized in the hope of generating leads that could ultimately confirm the identity of the individual in question. The positive identification success rate is on the order of 50%.

The process is further complicated in situations where the skeletal remains are from someone who has been missing since they were a child. Current forensic approaches use a specialized artist to combine the facial features of the parents and child to predict the appearance of the child years later. While the results can be quite convincing, it is a very subjective process. Clay reconstruction techniques are not applicable since the craniofacial skeleton¹ would need to be grown backwards in time before a facial reconstruction could be sculpted to match against a missing child's portrait.

This paper describes two prototype software applications, one for simulating craniofacial growth [5] and one for interactive 3D facial reconstruction over a craniofacial model [1]. These applications are the foundation for a fully integrated software tool for forensic artists. The Craniofacial Growth section describes our craniofacial growth modelling tool which relies upon three-dimensional movement data of specific landmarks on the

¹For our purposes, the craniofacial skeleton is composed of two major bone structures: the mandible and the skull.

craniofacial skeleton to drive the changes in the shape of the rest of the skeleton (there is currently no data of complete three-dimensional CT or MRI scans of the same individual's head over time). The reconstruction algorithm presented in the Facial Reconstruction section simulates the artist's technique of using tissue depth markers to rough in a facial shape. Varying the lengths of the markers allows the artist to quickly produce a number of three-dimensional facial reconstructions that cover the range of possible variations. Examples of output of the two software applications are shown in the Combined Results section. The Future Work section and the Conclusions section discuss additional avenues for research and concluding remarks.

Previous Work

While there is an abundance of works that explore in detail the physiological processes that dictate craniofacial growth and development, attempts to create computer graphical models of these processes are scarce. Cahoon and Hannam [4] simulate the "growth" backwards in time of an adult human mandible to that of a six year old child. The mandible was reconstructed from CT scans. Data on mandibular growth from the Saksena studies [16, 17] drives a simple, three-dimensional free-form deformations algorithm that is controlled by certain landmarks on the mandible. The main drawback is that their technique is very unwieldy, which makes it difficult to properly control the deformation. A related avenue of research, for the purposes of anthropological study, is in use at the Jorvik Viking Centre [12]. They reconstruct three dimensional figures of Vikings by using three dimensional scans of skeletal remains and then superimposing a human face that closely matches the details of the craniofacial skeleton.

Craniofacial Growth

Method

Ideally the inputs to the algorithm would only consist of a polygonal model of a craniofacial skeleton, possibly from CT or MRI scans, a starting age and a target age. The output is a polygonal model of the craniofacial skeleton, grown either forwards or backwards in time to the specified target age. However, to accurately simulate the growth process would require an extremely complex, full physiological model of bone growth and its variation among individuals - which does not exist. In our application, an anatomist or a forensic artist with knowledge of the physiological bone growth process provides additional inputs to the system to guide bone growth.

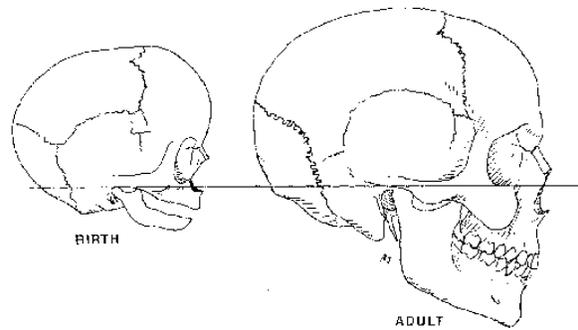


Figure 1: In the newborn the face is roughly 1/8 the size of the cranium, whereas in the adult the ratio is closer to 1/2. Adapted from Figure 1-15, page 12, in Jacobson and Caufield [9]

In the study of craniofacial skeleton growth, there exists a set of agreed-upon points of reference, or landmarks [14, 3, 15]. The physiologist or artist designates a subset of the vertices on the input skeleton mesh that correspond to landmarks. He provides the coordinates for those landmarks at the target age (typically less than 1% of the vertices are landmarks) and also provides an estimate of the influence that each landmark has on the surrounding vertices.

Growth model

A tremendous number of physiological factors affect the growth of the craniofacial skeleton. Attempting to include all of the factors into our growth model is beyond the scope and intent of this project. Our growth model is vastly simplified compared to the physiological model, yet allows an expert practitioner to quickly recreate the results of those physiological processes.

Enlow and Hans [6] define two basic kinds of growth movement that guide the facial growth process: *remodelling* and *displacement*. Remodelling is the process by which a bone's shape changes through time. As shown in Figure 1, a bone does not appear in a prenatal infant in its final shape, and does not grow by new additions keeping the same form. Rather, some areas of the bone grow faster or to a greater extent than others, thus the term *remodelling*. Displacement is the process by which contiguous bones push away from each other as they grow to allow for enlargement of the separate bones. To simulate these processes, the growth model incorporates both an expansion and shift term.

The expansion term controls how parts of the bone increase or decrease in size while the shift term describes the relocation. In order to assign an expansion and shift

term to the non-landmark vertices in the mesh, an expert in craniofacial growth prediction uses the auxiliary tool *Krayola* (described in the next section) to define the influence that landmarks exert on the other vertices. If a vertex lies within the area of influence of more than one landmark, then the effects of the landmarks are summed.

The expansion term is a vector in the direction of the normal to the surface at the vertex and has a magnitude given in Equation 1

$$\|e(v)\| = \sum_{\text{all } l} (\|g_e(l)\| \times E(v, l)) \quad (1)$$

where $E(v, l)$ is the expansion weight of vertex v from landmark l , as specified through *Krayola*, and $g_e(l)$ is the expansion growth vector. The expansion growth vector is the projection of the growth vector of the landmark onto the normal vector to the surface at the landmark. The shift vector is in the direction of the growth vector at the landmark and has a magnitude given in Equation 2

$$\|s(v)\| = \sum_{\text{all } l} (\|\Delta\mathbf{I}\| \times S(v, l)) \quad (2)$$

where $S(v, l)$ is the shift weight and $\Delta\mathbf{I}$ is the growth vector of the landmark.

The following Equation describes how to compute the new vertex

$$v_{new} = v + \sum_{\text{all } l} (\mathbf{N}_v \cdot \|g_e(l)\| \cdot E(v, l) + \Delta\mathbf{I} \cdot S(v, l)) \quad (3)$$

where v is the old vertex and \mathbf{N}_v is the normalized surface normal at v .

Auxiliary Tools

Several auxiliary tools were created to aid the artist in generating the inputs. *Landmark Picker* allows the artist to interactively select landmark vertices on the 3D input mesh of the bone. *Krayola*² is used to identify the influence that a landmark exerts on the surrounding vertices. The artist interactively “paints” the vertices of a triangulated mesh, where the colours correspond to the landmark’s influence. Painting is done in two separate layers, one for the shift weights and one for the expansion weights. Figure 5 shows a craniofacial skeleton with landmarks and their regions of influence. The *Transfer Weights* module eases the workload of the artist in subsequent craniofacial growth sessions. It generates a first approximation of the weights of a new triangular mesh, given the weights of another, similar mesh. This initial approximation can subsequently be edited with *Krayola*.

²*Krayola* and *Landmark Picker* are external modules for use with *Geomview*, a software package provided by the Geometry Center at the University of Minnesota [13].

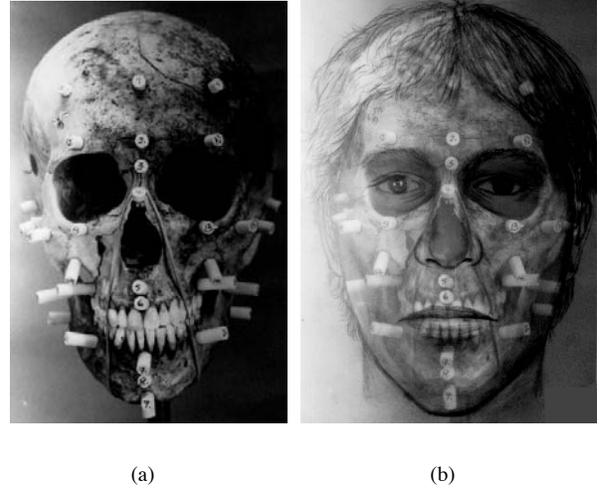


Figure 2: Two-dimensional reconstruction. [Source: Cam Pye, Royal Canadian Mounted Police]

Facial Reconstruction

Goals and methodology

Craniofacial reconstruction involves a trained forensic artist placing dowels, representing known average tissue thickness, at specific landmarks³ on the craniofacial skeleton, and building up facial features around these landmarks using clay or pencil drawings (Figure 2). This process is open to considerable interpretation and many equally possible reconstructions can be built from a single craniofacial skeleton. Because of this potential variation, experts believe that additional reconstructions, taking into account body fat content and variations in nose, eye and lip configurations could cover the range of possible reconstructions and increase the identification success rate. A motivation for employing computer graphics techniques for facial reconstruction is that once the initial manual work of placing and orienting the dowels is performed, additional reconstructions are fast and easy to create by specifying alternative sets of tissue depth information.

A software application that performs facial reconstruction needs to be easy to use and must closely simulate the process already familiar to the artist. The workflow for the prototype application is described as follows. A three-dimensional digitized polygonal model of the craniofacial skeleton is obtained, either as output from the craniofacial growth algorithm described in the Craniofacial Growth section or from laser scanning or some other

³The landmarks used in facial reconstruction are not necessarily the same as those used in craniofacial growth.

digitizing process. The artist places and orients virtual dowels on the craniofacial model. A generic surface of the face and head, described in the next section, is placed around the model and then fit to match the virtual dowels and to smoothly and evenly interpolate between them. Nose, lips and eyes must be directly edited by the artist because tissue depth information does not uniquely specify detailed facial features. After the dowel placement, new tissue depth information, reflecting factors like body fat content, can be read in from a data file to generate a new reconstruction.

Generic head model

The surface model used for the reconstruction is the Hierarchical B-spline (H-Spline) [7] which allows the forensic reconstruction application to approximate the artist's technique of first roughing in the general shape of the face and then layering on the facial details. The use of H-Splines for the generic head model provides multiple levels of detail that allows the tissue depths to be approximated while the surface details such as lips and eyes remain intact and seamlessly integrated with the rest of the face.

The artist begins with the generic head model with appropriate hierarchical refinement, and places and orients the virtual dowels at known landmarks on the polygonal skeleton model. For the surface approximation to work, each dowel must be associated with a parametric (u, v) location on the spline surface model. This determines the point on the surface model that will interpolate the dowel tip. This can be done manually, or the artist can rely on the default associations supplied with the generic head model. Ideally, in later versions of the prototype application, this step will be automated, perhaps through the use of cephalometric markers. Dowels can be grouped into data sets. Each data set can be associated with differing refinement levels of the surface, so that the artist can control how much of the fitting is done at a given level of detail.

Interpolation of dowels

Previous work in facial surgery simulation uses the finite-element method [10] to obtain the final face shape. We chose to use H-Spline surfaces because of the quality of the resulting surface (curvature continuous overall rather than positional continuity) and because an interactive interpolation method is required for subsequent editing of the face. To accomplish this, we chose an extension to Bartel and Beatty's [2] single point direct manipulation technique for multiple scattered surface points, very similar to Lee, Wolberg and Shin's multilevel B-spline approximation (MBA) algorithm [11]. As well, we have in-

cluded the ability to approximate the tangent plane orientation at the interpolation point.

The scattered data interpolation technique is described as follows. A uniform bicubic B-spline surface $Q(u, v)$ with control vertices

$$\mathbf{P} = \begin{bmatrix} p_{00} & \cdots & p_{0n} \\ \vdots & \vdots & \vdots \\ p_{m0} & \cdots & p_{mn} \end{bmatrix} \quad (4)$$

is defined by

$$Q_{i,j}(u, v) = \mathbf{B}_u \mathbf{P}_{i,j} \mathbf{B}_v^T \quad (5)$$

where \mathbf{B}_u and \mathbf{B}_v are the B-spline blending functions for u and v and $\mathbf{P}_{i,j}$ is the sub-matrix of control vertices for the given parametric intervals. To interpolate the q_k data points, where $k = 0, \dots, n$, the control vertices must be displaced. The displacement of a particular control vertex due to a particular data point is given by

$$\Delta p_{i,j,k} = \Delta q_k \frac{B_{u_i,k} B_{v_j,k}}{\sum_{l=0}^3 \sum_{m=0}^3 (B_{u_l} B_{v_m})^2} \quad (6)$$

where $B_{u_i,k} = B_i(u_k)$, $B_{v_j,k} = B_j(v_k)$ and Δq_k is the displacement of the curve for data point k . The actual displacement of a control vertex $p_{i,j}$ for all data points is the weighted sum of all the $\Delta p_{i,j,k}$ displacements

$$\Delta p_{i,j} = \sum_{\text{all } k} W_{i,j,k} \Delta p_{i,j,k} \quad (7)$$

where the weights are found to be

$$W_{i,j,k} = \frac{(B_{u_i,k} B_{v_j,k})^2}{\sum_{\text{all } k} (B_{u_i,k} B_{v_j,k})^2} \quad (8)$$

This technique lends itself well to multi-resolution fitting [8], using hierarchical B-splines. Refining the surface before fitting produces a much more local fit, due to the more restricted influence of the B-spline basis functions. We have also added the ability to select a displacement fraction (DF) that controls the percentage of the fit to be performed at each resolution level. Performing a greater percentage of the fit at coarser refinement levels produces a smoother overall shape to the surface. Performing a fraction of the fit at a coarser level, and subsequently refining and re-interpolating produces a more localized fit. This is shown in Figure 3.

Combined Results

Growing the craniofacial skeleton

The craniofacial skeleton in Figure 4a was obtained from Viewpoint Data Labs. The model is that of a male, most

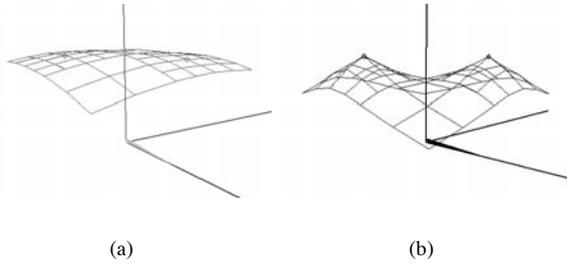


Figure 3: B-spline patch interpolation 2 data points. (a) DF = 1.0 (b) DF = 0.4

likely an american caucasoid. Figure 4a shows the position of four skull landmarks and two mandible landmarks. The landmark on the side of the skull is the *Zygoma*, the landmark on top of the skull is the *Apex*, the landmark on the bridge of the nose is the *Nasion*, and the landmark on the bottom of the nose is the *Anterior Nasal Spine*. The landmark on the tip of the jaw corresponds to the *Menton*, and the other visible landmark is the left *Gonion*. Aging the skeleton yields the mesh displayed in Figure 4b and Figure 4c shows the overlapping wireframe models of the initial and resulting mesh.

Objective validation of our growth model is difficult because there is no hard data on craniofacial growth with which to compare the output of our software. While it is possible to get three-dimensional data for the craniofacial skeleton of any given individual, data from the same individual from childhood has just not been recorded. For now, we must be content with the expert opinion of our colleagues in the field of craniofacial growth, who are satisfied with our results so far. Their feedback indicates they like the amount of control the software gives over the growth process but that assigning weights to the triangular mesh is time consuming.

Constructing the face

The facial appearance of the individual from whom the craniofacial skeleton in Figure 4a was obtained is unknown so the body fat content is estimated as average for an american caucasoid male. A standard set of 32 dowels (Figure 6a), was used for an initial attempt at reconstruction but was found, as expected, to be insufficient because the dowels are quite sparsely spaced. The process of interpolating the tissue depth markers by placing clay between the markers was simulated by placing additional dowels on the skeleton. Additionally, tangential information (see Appendix A) for the surface is calculated at each dowel so the interpolation algorithm can produce a better fit around areas of high curvature. The addition of 89 extra dowels

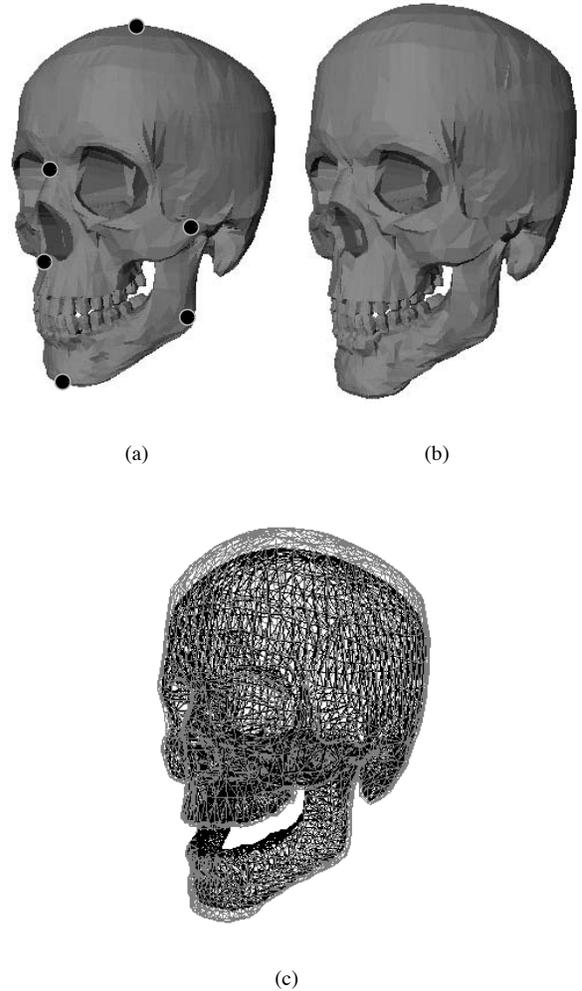


Figure 4: Applying growth algorithm to craniofacial skeleton. (a) Initial mesh. (b) Resulting mesh. (c) Initial and resulting meshes overlapped. The teeth were not grown and are removed for clarity.

(Figure 6b) produce a good fit (Figure 7).

Modification of detailed facial features is done by interactively editing the interpolated surface. Figure 8 shows how the nose shape, lip shape and jowl size can be significantly changed without affecting large portions of the underlying facial shape. Dowel lengths were altered to reflect the tissue depths of an obese american caucasoid male in Figure 9.

Preliminary evaluation by two RCMP forensic artists, Cam Pye and Peter Petersen, indicate the ability of our method to generate a reasonable likeness of a face is good, though many features will need to be added before it can be used in actual practice. Part of the current shortcom-

ings of the head model is that it was created by an artist for animation and is thus not anatomically correct (the mouth is too wide and there is a hole at the peak of the head rather than at the neck).

Future Work

There are many open issues that demand more thorough investigation.

- Validating the growth model. While the preliminary results are encouraging, the current algorithm requires much more rigorous testing and analysis. Comparison of the output against real craniofacial growth data is desirable but such data is currently not available. So far, tests of our software have only used on the order of 5 landmarks. It seems obvious that the accuracy of the simulation would increase with the number of landmarks used.
- Improving the growth model. The current model is at least loosely based on the actual physiological processes that dictate bone growth but further research into making the model more physiologically accurate would be worthwhile.
- Preventing interpenetration. Another aspect of the growth model that needs to be addressed is the ability to detect and prevent interpenetration. As two vertices grow towards each other it is possible they will intersect, causing unwanted artifacts. This situation is not currently being detected.
- Stock facial features and head models. For faster reconstruction, the forensic artists who evaluated the system indicated a set of stock shapes for eyes, nose and lips would be desirable. Sliders would ideally control the sizing parameters for these features. Stock head models for differing head types are needed.
- Additional body features. A forensic artist often adds in ears, neck and shoulders after the reconstruction. These additional features aid the artist and are factors in the identification success rate.
- Improved reconstruction algorithm. Although extrapolated dowels produced a reasonable reconstruction, the interpolation of tissue depths between dowels, possibly along isoparametric lines over the skeleton surface, would be a worthwhile area of study.
- Evaluating the facial reconstruction. The system must be put through a series of double-blind tests, in

which the craniofacial skeletons of known individuals will be scanned. A forensic artist would then use the system to generate a likeness of each individual, without having seen an actual photograph of the individual. The results would allow an evaluation of the effectiveness of the techniques.

Conclusions

We re-emphasize that this work presented two prototype applications in the development of a complete software package for craniofacial reconstruction. The main goals were met, in that we have created a software system that simulates the growth of the craniofacial skeleton and creates a reconstructed face over the skeleton. The craniofacial growth model has two components that determine the direction of growth: the *expansion vector* and the *shift vector*. Specification of several standard landmarks and their coordinates through time by the forensic artist are inputs to the algorithm. An auxiliary tool, *Krayola*, is used to assign the influence a landmark has on the surrounding vertices of the mesh. Given a craniofacial mesh, the facial reconstruction algorithm presented generates a facial estimate around the mesh based on virtual dowels that represent body fat content. An expert in facial reconstruction places and orients the dowels. A direct manipulation interpolation algorithm interpolates a generic surface smoothly through the dowels to form a base facial shape for later refinement. A lack of lateral craniofacial growth data makes validation of the model difficult; for now we must be content with the expert opinion of our colleagues in the craniofacial reconstruction group. They are quite pleased with our results so far as our software gives them a tremendous amount of control over the process by which the mesh is grown and they are encouraged that the facial reconstruction algorithm generates a reasonable facial estimate from a relatively small amount of tissue depth information.

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Appendix A: Extension to Tangent Fitting

The B-spline scattered data interpolation algorithm may be extended to fit points on the surface to specific tangent

planes. This is desirable since in forensic reconstruction, the orientation of the dowels provides some additional information about the curvature of the craniofacial skeleton. The bicubic B-spline surface defined by Equations 4 and 5 has partial derivatives with respect to u and v defined by

$$\begin{aligned}\frac{\partial Q_{i,j}}{\partial u} &= \frac{d\mathbf{B}_u}{du} \mathbf{P}_{i,j} \mathbf{B}_v^T \\ \frac{\partial Q_{i,j}}{\partial v} &= \mathbf{B}_u \mathbf{P}_{i,j} \frac{d\mathbf{B}_v^T}{dv}\end{aligned}\quad (9)$$

where \mathbf{B}_u and \mathbf{B}_v are the B-spline blending functions for u and v and $\mathbf{P}_{i,j}$ of Equation 4 is the sub-matrix of control vertices for the given parametric intervals. From these equations it is evident that to fit a B-spline surface to a tangent plane, it is only necessary to displace the control vertices appropriately.

The partial derivatives of the surface are projected onto the desired tangent plane at data point k and normalized. The projected and normalized partials represent the required values of the partial derivatives needed for the surface to conform to the tangent plane at data point k .

For each data point k , to fit to the partial derivative with respect to u , the resulting displacement of each control vertex becomes

$$\Delta p_{i,j,k} = \Delta q_k \frac{\frac{dB_{u_i,k}}{du} B_{v_j,k}}{\sum_{l=0}^3 \sum_{m=0}^3 \left(\frac{dB_{u_l}}{du} B_{v_m} \right)^2} \quad (10)$$

As well, when accumulating the results of interpolation of the partial with respect to u , over all points k for control vertex (i, j) , the weights given to each displacement are

$$W_{i,j,k} = \frac{\left(\frac{dB_{u_i,k}}{du} B_{v_j,k} \right)^2}{\sum_{\text{all } k} \left(\frac{dB_{u_i,k}}{du} B_{v_j,k} \right)^2} \quad (11)$$

To complete the fit to a given tangent plane, the surface must be fit to the partial derivative with respect to v , which is done by substituting \mathbf{B}_u for $\frac{d\mathbf{B}_u}{du}$, and $\frac{d\mathbf{B}_v}{dv}$ for \mathbf{B}_v in Equation 10 and Equation 11.

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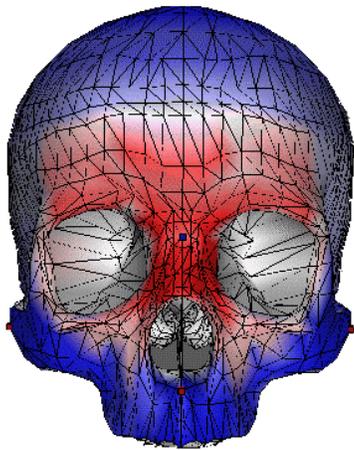


Figure 5: Influence of landmarks on skull mesh. The influence from the active landmark on the bridge of the nose is shown in red.

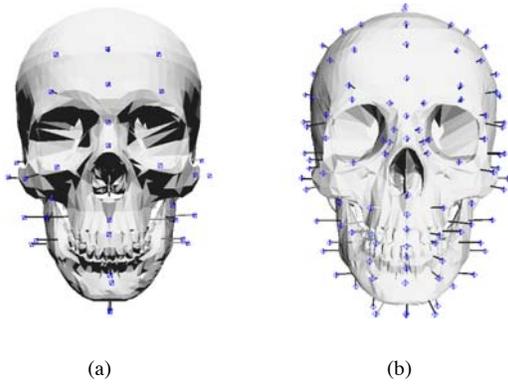


Figure 6: Polygonal model of a craniofacial skeleton displaying dowels placed by a forensic artist. (a) Skeleton model with standard 32 dowel set. (b) Skeleton model with standard plus extrapolated dowels totaling 121.

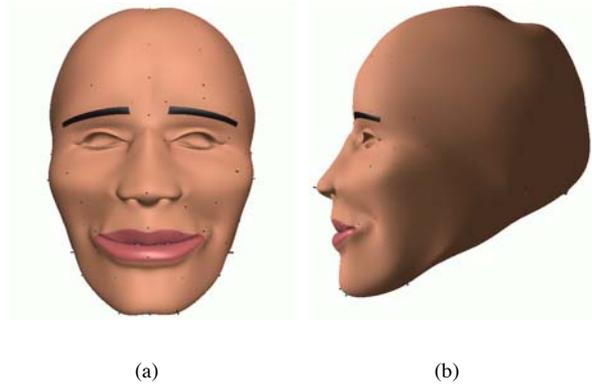


Figure 7: Frontal and lateral view of reconstructed face.

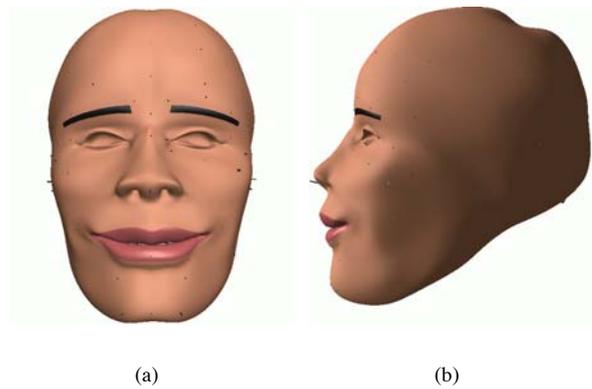


Figure 8: Modification of surface details through editing the hierarchical surface to add jowls and raise the nose tip.

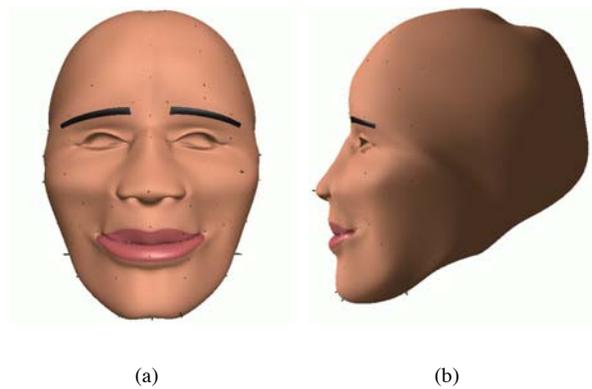


Figure 9: Dowel lengths from the reconstruction shown in Figure 7a and 7b were changed to those of an obese american caucasoid male.