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Computerized Three-Dimmensional Craniofacial Reconstruction from Skulls Based on Landmarks

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Abstract—**Human identification from a skull is a critical process in legal and forensic medicine, specially when no other means are available. Traditional clay-based methods attempt to generate the human face, in order to identify the corresponding person. However, these reconstructions lack of objectivity and consistence, since they depend on the practitioner. Current computerized techniques are based on facial models, which introduce undesired facial features when the final reconstruction is built. This paper presents an objective 3D craniofacial reconstruction technique, implemented in a graphic application, without using any facial template. The only information required by the software tool is the 3D image of the target skull and three parameters: age, gender and Body Mass Index (BMI) of the individual. Complexity is minimized, since the application database only consists of the anthropological information provided by soft tissue depth values in a set of points of the skull.**

I. Introduction

THE goal of forensic craniofacial reconstruction is the identification of human and osseous remains, estimating the facial appearance of the individual associated to an unknown skull. It is a critical process in legal and forensic medicine, specially when no other means are available to identify the person [1]. So far, this task has been performed by traditional 'plastic' methods, using clay. This process is carried out by an artist, who models the soft tissue knowing tissue depth in some landmark points on the skull. Depths elsewhere are interpolated between these points by intuition. In that process, replicas of real skulls are used, in order to avoid damaging them [1]. This procedure has important disadvantages: on the one hand, it is an artistic method, which means the process is subjective. In fact, it is non-repeatable, since obtained results always differ between practitioners, and also between reconstructions. On the other hand, the technique is slow, and it usually takes one or two days, even for skilled practitioners. The method is also dirty and expensive, due to the materials required. In fact, a repetition of the process (the creation of a new reconstruction from the same skull using different individual parameters) means the use of new additional materials. Finally, the generated reconstructions are not easily transportable, which makes difficult their distribution or sharing.

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All these disadvantages result in an increasing importance of the computer-based facial reconstruction techniques [2]. Based on this fact, several works and proposals have been developed from the 90's until nowadays [3]-[8]. They all suggest the different advantages of computerized 3D craniofacial reconstruction: it is a consistent process (the output results are the same when the same input data is used), and objective (it does not depend on any practitioner). Moreover, computerized methods can be executed in a short time, and they do not require extra material resources to repeat the reconstruction process from the same skull. All the previous facts make computer-based methods better than traditional procedures.

Current computer-based reconstruction techniques build the final reconstruction starting from a reference facial model. Most published computerized techniques ([3], [4], [8], e.g.) use a generic facial template, or a specific best look-alike template, based on several subject properties (BMI, gender and age). This reference template is then fitted to the target skull knowing tissue thickness in some landmarks on that skull, and interpolating thickness in between these reference facial points, based on a generic smooth deformation. Finally, they add some extra information to improve the results, such as manual modeling features (nose, eyes, etc.) or a texture simulating the skin. The main problem of these procedures is they focus on human resemblance, instead of reliability: using a specific facial template, unwanted facial features of that template remain visible in the final reconstruction. Besides, applying a generic deformation means a problem when the differences between the reference depth tissue values in landmarks and the reference face thickness are considerably large. On the other hand, the results are not skull-specific, but just "smooth".

In attempt to solve the previous shortcomings, some techniques ([6], for example) use specific deformations over the generic facial template. This deformation is obtained from a reference skull, which is deformed towards the target skull. Then, that deformation is extrapolated and applied to the facial template. Other computer-based facial reconstruction proposals (for instance [5], [7], [9]), instead of starting from a generic facial surface, they build a reference statistical model from a database of 3D-scanned real faces. Thus, the problem of unrealistic and unreliable characteristics of the reconstructions is minimized.

All the previous methods and their results are limited, though, in the shape of the reference facial template they use to build the final craniofacial reconstruction: the output results will always contain specific features present in the reference template, which may distort the physical appearance of target person to identify. In addition, those techniques only use the information given by some points on the skull, instead of considering the complete skull surface; this disregards any individual particularity which should affect the final reconstruction morphology. Moreover, all these techniques require high-complexity databases and procedures to perform the final reconstruction. In order to decrease complexity, and to avoid any unsuitable information which may be introduced by that reference facial surface, and also trying to consider as much information as may provide the skull geometry, we propose an alternative computer-based craniofacial reconstruction technique, which is not based on a reference facial template. This reconstruction technique has been implemented in an application, which only starts from anthropological information, consisting in statistical soft tissue depth values in a set of points on the skull. Thus, complexity of the application database is considerably reduced. The only input data required by the application to generate the facial soft tissue mesh are the 3D image of the target skull, and a set of parameters of that skull: age, gender and BMI range. Facial features (eyes, nose, ears and mouth) are not included in the generated reconstruction, as they cannot be confidently deduced only from skull [1].

In the following section, a general description of the application is presented. Section 3 and 4 concentrate on examining the two main functional modules in the application: Landmark Insertion Module and Skin Mesh Generation Module. Then, in Section 5, a comparison of different results is presented. Finally, Section 6 discusses the conclusions of the computer-based facial reconstruction technique here presented.

II. Application Description

The application presented in this paper can be represented by the scheme shown in Fig. 1.

The application input data is introduced by the final user (the forensic doctor). It comprises the following elements: firstly, a 3D image of the target skull. Secondly, 66 landmark points placed on the skull surface, where soft tissue depth is known (user will be able to decide whether introducing these positions manually or automatically by the application). The last input data required by the application is a set of characteristic parameters of the target person: age, gender and BMI range. Age and gender can be deduced from skull morphology [1], so they will always be known by the user. However, BMI range will be an unknown parameter, which will have to be estimated.

The Landmark Insertion Module is in charge of placing each landmark point in each position over the skull, and assigning the corresponding soft tissue depth value, according to age, gender and BMI parameters. This functional block will be described in Section 3 of this paper.

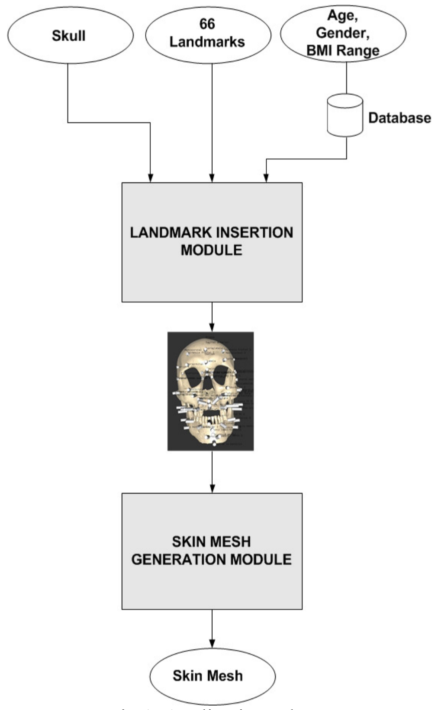

Fig 1: Application scheme

Finally, the Soft Tissue Generation Module is the responsible for generating the skin mesh from the set of landmarks, where soft tissue depth is known. This block will be analyzed in Section 4. The application database consists of a set of tissue depth values in each reference point, varying according to age, gender and BMI attributes. This fact means that the database complexity is very small compared to those consisting of CT images, as in [5], [7], [9]. Consequently, the calculation of tissue thickness values in all the landmark points is very fast.

III. Landmark Insertion Module

The Landmark Insertion Module (LIM) is in charge of placing 66 reference points on the skull surface, and assigning them a tissue depth value, based on a set of parameters of the person: age, gender and BMI range (previously introduced by the user in the system via the graphic user interface). The reference points used for this purpose are two sets of points traditionally used in forensic medicine, as depicted on Fig. 2.

The first set (black points on Fig. 2) results from an anthropological study, presented in [10]. They are compulsory points, since they make possible to generate soft tissue in frontal and lateral sides of a skull. However, that set of points would leave empty the top and the back of the skull. A second set of points has been considered to generate soft tissue around the whole skull (see red points on Fig. 2). That set of points has been selected so that any user can recognize them unequivocally. Moreover, the soft tissue depth variations in that zone can be disregarded, and their magnitude can be approximated by tissue depth in point 1.

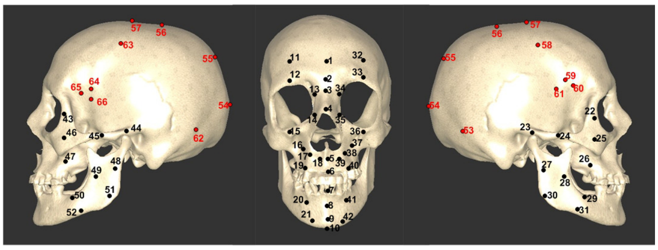

Fig 2: Landmark definition used for craniofacial reconstruction in this work (left, front and right views). In black: set of 52 points to generate the facial reconstruction in facial zone [10]. In red: set of 14 points to generate the craniofacial reconstruction in neurocranium [11]

Based on the previous fact, the system will take 66 positions on a skull 3D image, and the age, gender and BMI range of that person (which will be introduced via the graphic user interface). Then, tissue thickness will be determined in all those reference points according to the parameters of the person. In the following subsections, these two processes (landmark insertion and tissue depth load) will be analyzed.

A. Landmark Insertion

The landmark insertion process places the set of 66 reference points on the skull 3D image. Two different ways to accomplish this task have been implemented: manually and automatically.

In the manual procedure, user inserts all landmarks directly on the skull image. The list of 66 reference points is displayed in the graphic user interface, via a combo-box element. The user only has to select one reference point and click on the skull image on its corresponding position. The procedure is order-independent.

In the automatic procedure, all the landmarks will be placed automatically on the image. In order to perform that task, the skull 3D image is projected on the front, right and left planes, and landmark positions are calculated into these projection planes, since those positions are quasi-invariant in every skull. For this purpose, the skull needs to be oriented previously, in order to place it in front position respect to viewer camera. Once all points have been placed on the projected images, an inverse transformation is applied over them to recover the whole 3D image, with all the landmarks placed on it. Likewise, user is allowed to modify any resultant position, if inaccurate.

B. Tissue Depth Load

Once all reference points have been placed on the skull 3D image, tissue thickness is assigned to each one, according to the age, gender and BMI range parameters previously introduced. Soft tissue depth values in reference points are known thanks to an anthropological study to characterize tissue depth information of Spanish population, performed by Legal Medicine School of Madrid, and based on a previous study of Belgian population [10]. This study is still in progress, and until this moment, it has been carried out with 160 people, men and woman, aged between 20 and 90 years old. Tissue thickness values are classified into several groups: according to gender, men and women; according to age, five groups can be found: between 20 and 29 years, between 30 and 39, between 40 and 49, between 50 and 59, and older than 60; and finally, according to BMI, population can be divided into 3 groups: people with BMI lower than 20, people with BMI between 20 and 25, and people whose BMI is higher than 25.

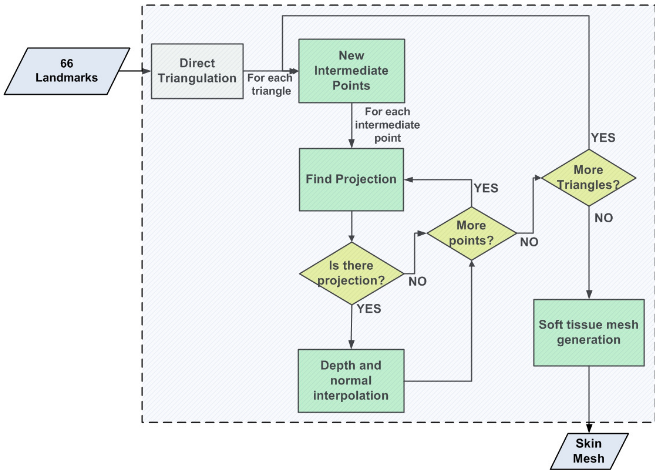

Fig 3: SMGM block diagram

Considering this classification, 30 groups of population result. For each one, a tissue thickness mean value is available in the database for every landmark. Based on that fact, and depending on the gender, age and BMI range values of the corresponding person, the system will access to the corresponding entry in the database (population group and landmark), and will assign its depth value to each landmark.

IV. Skin Mesh Generation Module

The Skin Mesh Generation Module (SMGM) represents the main functional module in the application here presented. From output data generated in LIM, it manages to construct a full 3D mesh representing soft tissue (skin) belonging to the skull. The general aim of this module is to generate a set of intermediate points on the skull surface, whose depth values can be interpolated from thickness values in reference points. The whole set of points (landmarks and intermediate points) will integrate the final skin mesh. For this purpose, the module receives the set of 66 reference points (their positions and depths), and determines new tissue thickness values in each intermediate point, attending to its location (closeness to the rest of landmarks). For this reason, the presented craniofacial reconstruction technique considers all the information contained in the skull geometry, not only soft tissue thickness in the landmark points. Fig. 3 illustrates this procedure.

Therefore, the main functions participating in the whole process are the intermediate points generation and projection, the interpolation of intermediate depths and normals, and the soft tissue mesh generation. In the subsequent subsections, these four processes will be analyzed.

A. Intermediate Points Generation

First step in skin mesh generation process is the creation of a set of new intermediate points, which will integrate the resulting final mesh. Those new intermediate points are created by using a new triangulation (transparent to the user). In a further process, those new generated points will be projected towards the skull geometry, so that new tissue depth can be obtained on them.

Therefore, the whole process of intermediate point generation comprises two main tasks: the construction of the reference triangle network, and the creation of the new intermediate points in those reference triangles. First task is carried out from the 66 landmarks positions. Then, a manual triangulation is performed, to optimize the amount of resulting triangles, and their shape and distribution. Fig. 4 illustrates the definition of the reference triangle network.

Regarding the second task (creation of new intermediate points), for each resulting triangle, several intermediate positions are calculated, both inside the triangle and on its edges.

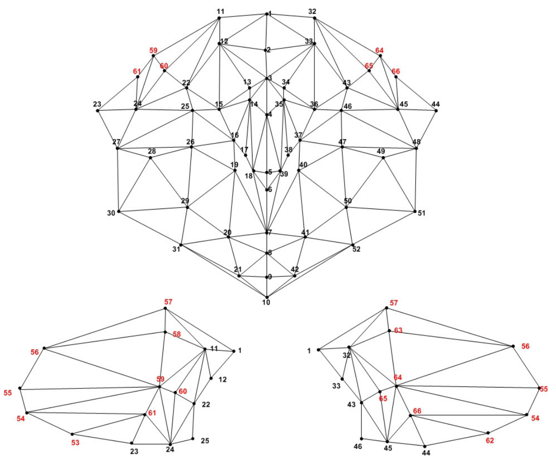

Fig 4: Reference triangle network. The 52 facial points (black), and the 14 extra points (red) are indexed using the same numerical sequence as in Fig. 2

Creation of intermediate points in each edge consists in dividing that edge in equally-sized segments. Generation of intermediate points inside each triangle attends to a regular triangle subdivision [12]. This triangle subdivision is performed according to the *level of detail,* LOD, defined as the number of evaluation points on one edge minus two. The number n of intermediate points generated inside a triangle can be obtained from LOD, following equation 1. Fig. 5 illustrates this relation.

$$n=\sum_{i=1}^{LOD-2} i \qquad (1)$$

B. Intermediate Points Projection

Once a set of numerous intermediate points has been generated, next step is to project all those points on the skull surface, in order to obtain a set of intermediate points where soft tissue depth can be added. Projection process is different depending on the location of the intermediate point to be projected. Based on this fact, two types of projections are performed: projection of points inside a reference triangle, and projection of points in a triangle edge.

Projection of intermediate points located inside a reference triangle is performed using the normal vector of that triangle. Projection of intermediate points located on an edge will be carried out using the vector defined by equation 2:

$$\vec{p}=\vec{n}_1+\vec{n}_2 \qquad (2)$$

Where n_1 and n_2 are the normal vector of the triangles sharing that edge. In both cases, projection will not be performed unless the condition $d< d_{max}$ is satisfied, being d the distance between the original intermediate point and the point projected on the skull mesh, and d_{max} is a threshold value. This condition prevents an intermediate point from being projected too far from its 3 nearest landmarks, which constitute the reference triangle. This may happen in several regions, for example, inside eye sockets. It is a fundamental condition, since tissue depth associated to the new intermediate points on the skull mesh will be obtained0 from tissue depth values on those 3 nearest landmarks (as it will be described in section C). Therefore, it is very important to ensure all the projected points have the same landmark neighbors as their corresponding original intermediate point.

C. Intermediate Depth and normal interpolation

In the previous step, a set of intermediate points on the skull surface were calculated. Next task is to calculate their tissue depth values, in order to obtain the final set of points which will integrate the skin mesh. In all cases, an intermediate skin position can be obtained as:

$$\vec{p}\,'=\vec{p}_i+\vec{n}_i\cdot l \qquad (3)$$

Where p_i is the position vector of the projected intermediate point, n_i is the normal vector in that point, and l_i the thickness associated to it. The way to compute l_i and n_i will differ, depending on the location of the original intermediate points in the reference triangles.

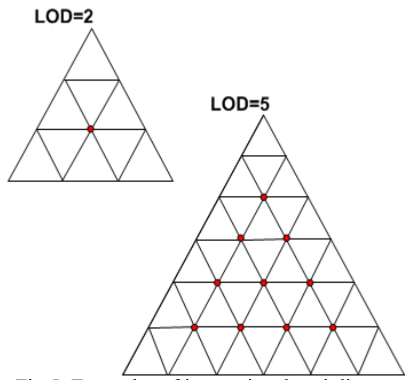

Fig 5: Examples of inner triangle subdivision, with LOD=2 and LOD=5. Intermediate points are highlighted

For skull intermediate points coming from projection of points located inside a reference triangle (p_i'), n_i and l_i are interpolated from l_1, l_2, l_3, and n_1, n_2, n_3, the depth and normal values associated to the three landmarks integrating the reference triangle (influence landmarks). The subsequent equations are used:

$$l_i=u\cdot l_1+v\cdot l_2+w\cdot l_3 \qquad (4)$$

$$\vec{n}_i=u\cdot\vec{n}_1+v\cdot\vec{n}_2+w\cdot\vec{n}_3 \qquad (5)$$

$$u=\frac{area(\vec{p}_i{}', \vec{p}_2, \vec{p}_3)}{area(\vec{p}_1, \vec{p}_2, \vec{p}_3)} \tag{6}$$

$$v=\frac{area(\vec{p}_1, \vec{p}_i{}', \vec{p}_3)}{area(\vec{p}_1, \vec{p}_2, \vec{p}_3)} \tag{7}$$

$$w=\frac{area(\vec{p}_1, \vec{p}_2, \vec{p}_i{}')}{area(\vec{p}_1, \vec{p}_2, \vec{p}_3)} \tag{8}$$

For skull intermediate points coming from projection of points located in a triangle edge (p_i'), n_i and l_i are interpolated from l_1, l_2, and n_1, n_2, those depth and normal values associated to the two landmarks integrating that edge (influence landmarks). The following equations are used:

$$l_i=u\cdot l_1+v\cdot l_2 \tag{9}$$

$$\vec{n}_i=u\cdot\vec{n}_1+v\cdot\vec{n}_2 \tag{10}$$

$$u=\frac{distance(\vec{p}_i{}', \vec{p}_2)}{distance(\vec{p}_1, \vec{p}_2)} \tag{11}$$

$$v=\frac{distance(\vec{p}_1, \vec{p}_i{}')}{distance(\vec{p}_1, \vec{p}_2)} \tag{12}$$

D. Mesh Generation

Once the set of intermediate tissue points has been generated (from the original 66 landmarks), the next step is to build a 3D mesh from both sets of points. Considering that the final number of points is greater than 11000, an automatic triangulation algorithm is required. For this purpose, a Delaunay triangulation has been implemented. In Fig. 6, a skull and its point sets (landmarks and intermediate points) are shown. Fig. 7 and Fig. 8 shows some examples of reconstructions obtained from different skulls, by means of the proposed application.

In the previous images, the achievements and limitations of this craniofacial reconstruction method can be detected. Regarding the achievements, zones where skull geometry shows soft variations are well reconstructed; this is the case of the forehead, the chin, the upper part and lateral faces of the nose. However, limitations can be found in zones where skull varies, for example, in zigomatic arch zones and near eyes and mouth, especially. In those zones, a greater number of landmarks would be needed, in order to obtain an appropriate soft tissue depth interpolation.

V. Comparison of Results

In this section, different results are presented, in order to prove that the craniofacial reconstruction method here described verifies these four statements: firstly, craniofacial reconstructions are different for different skulls. Secondly, they are different for a certain skull, using different BMI ranges. Thirdly, craniofacial reconstructions depend on the skull geometry, existing correspondance between skull morphology and skin mesh. And finally, the procedure is not subjective, since craniofacial reconstructions only depend on tissue thickness values in the 66 landmarks and skull geometry.

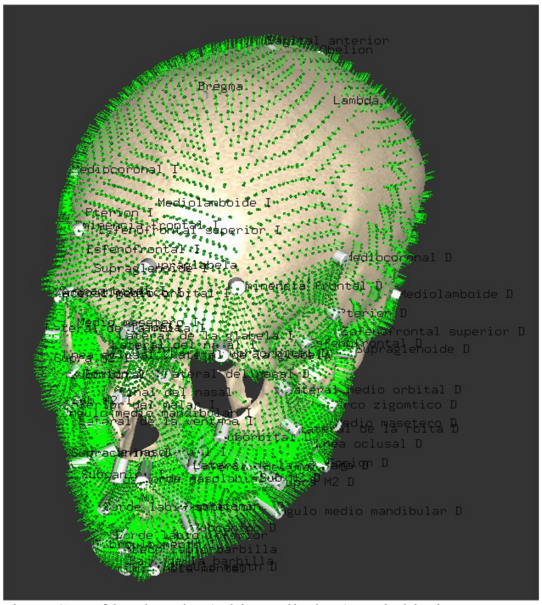

Fig 7: Set of landmarks (white cylinders) and skin intermediate points generated (green spheres) for a generic skull

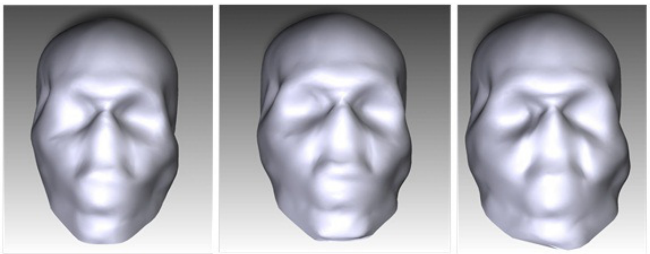
Fig 8: Examples of reconstructions using the skull of a 27-year-old man. (Left): BMI<20. (Center): 20<BMI<25. (Right): BMI>25

To perform the test, 145 3D-scanned skulls (69 women and 76 men) have been used: 4 samples aged between 20 and 29, 14 samples between 30 and 39, 9 samples between 40 and 49, 18 samples between 50 and 59, and 100 samples older than 60 years old.

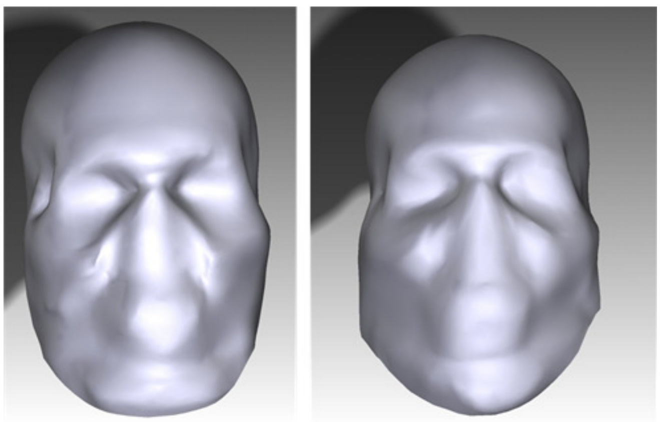
Fig 6: Examples of reconstructions using different skulls. (Left): 53-year-old man with BMI>25. (Right): 34-year-old man with BMI>25

TABLE I.
LIST OF MEASURES (IN CM.) TAKEN IN 7 SKULLS AND RECONSTRUCTIONS

Individual	Distance 1-10 (facial length)			Distance 23-44 (bizigomatic breadth)		
	Skull	20<BMI<25	BMI>25	Skull	20<BMI<25	BMI>25
25-year-old man	15.19	15.85	15.9	10.99	13.65	14.06
34-year-old man	16.18	17.17	17.26	11.64	13.24	13.85
39-year-old man	15.29	16.27	16.39	12.21	13.85	14.67
45-year-old woman	14.09	15.06	15.15	11.22	13.21	13.57
53-year-old man	15.42	16.62	16.9	12.2	14.23	14.59
73-year-old woman	14.18	15.37	16.45	11.9	13.65	13.87
75-year-old woman	14.51	16.62	16.7	11.15	12.96	13.24

Using these skulls, several reconstructions have been performed varying BMI range values in each skull. In order to contrast objectively all existing changes, two representative measures have been taken in each skull and its corresponding reconstruction: distance between landmarks 1 and 10 (facial length) and between landmarks 23 and 44 (bizigomatic breadth). Table I shows the measures taken from 7 different sample skulls. Measures corresponding to BMI<20 are not presented due to the fact that there are not tissue depth values available in some population groups, since the anthropological database is still being completed.

According to those results, differences between reconstructions belonging to the same skull using different BMI values have been proved, and also differences between reconstructions from different skulls. Based on this fact, the objectivity of the present craniofacial reconstruction method can be ensured.

In order to improve the validation process of the proposed method and test its accuracy, some further tests are being performed to study the variations of the surface in the reconstruction meshes, in comparison with the variations corresponding to real skin meshes (extracted from TAC images). This process is still in progress, since there are not enough TAC images available to construct a reliable sample of real soft tissue.

VI. CONCLUSION

In this paper, a computerized 3D craniofacial reconstruction technique has been presented. A graphic application has been developed implementing this technique, which enables to generate objectively the soft tissue of any individual, starting only from the skull and a set of 66 reference points where tissue depth is known.

The method consists in generating a great number of intermediate points, where tissue depth is interpolated from tissue thickness in landmark points. This process only comprises projections, normal calculations, arithmetic operations, and finally, a triangulation to build the final reconstruction. Moreover, the complexity of the application database is low, as it only consists of a set of soft tissue thickness values in the reference points. These two facts contribute to the low computational cost of the application.

The presented craniofacial reconstruction technique was developed to ensure the objectivity of the process, since it only considers skull geometry and individual parameters (age, gender and BMI range). On the other hand, it extracts all the local information contained in the target skull, since its entire surface is sampled. This means an important advantage in regions with smooth variations (forehead and chin, for example), where every irregularity will affect the final reconstruction; otherwise, they would be disregarded in case of only considering the set of reference landmarks. However, in places where skull geometry is variant, this tendency to replicate the skull variations is not suitable and it must be improved. In those places, more landmarks would be necessary.

Tests with 145 skulls have been performed, in order to compare the corresponding generated reconstructions. Future work focuses on improving the validation process, comparing reconstructions with real skin meshes extracted from TAC images.

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REFERENCES

[1] C. Wilkinson, *Forensic Facial Reconstruction*. New York: Cambridge University Press, 2004.
[2] S. D. Greef and G. Willems, "Three-dimensional Cranio-Facial Reconstruction in Forensic Identification: Latest Progress and New Tendencies in the 21st Century," *Forensic Science International,* vol. 50, pp. 12-17, 2005.
[3] A. W. Shahrom, P. Vanezis, R. C. Chapman, A. Gonzales, C. Blenkinsop, and M. L. Rossi, "Techniques in facial identification: computer-aided facial reconstruction using a laser scanner and video superimposition," *International Journal of Legal Medicine,* vol. 108, pp. 194-200, 1996.
[4] A. J. Tyrrell, M. P. Evison, A. T. Chamberlain, and M. A. Green, "Forensic three-dimensional facial reconstruction: historical review and contemporary developments," *Journal of Forensic Sciences,* vol. 42, pp. 653-661, 1997.
[5] P. Tu, R. I. Hartley, W. E. Lorensen, M. Allyassin, R. Gupta, and L. Heier, "Face Reconstructions using Flesh Deformation Modes," in *Computer Graphic Facial Reconstruction*, J. G. Clement and M. K. Marks, Eds.: Elsevier Academic Press, 2005, pp. 145-162.
[6] G. Subsol and G. Quatrehomme, "Automatic 3D facial reconstruction by feature-based registration of a reference head," in *Computer-graphic Facial Reconstruction*, J. G. Clement and M. K. Marks, Eds.: Elsevier Academic Press, 2005, pp. 145-162.

[7] D. Vandermeulen, P. Claes, D. Loeckx, S. D. Greef, G. Willems, and P. Suetens, "Computerized craniofacial reconstruction using CT-derived implicit surface representations," *Forensic Science International,* vol. 159, pp. 164-174, 2006.

[8] R. Liang, Y. Lin, L. Jiang, J. Bao, and X. Huang, "Craniofacial Model Reconstruction From Skull Data Based on Feature Points," in *Computer-Aided Design and Computer Graphics, 2009. CAD/Graphics '09. 11th IEEE International Conference* Huangshan, 2009, pp. 602-605.

[9] P. Claes, D. Vandermeulen, S. D. Greef, G. Willems, and P. Suetens, "Statistically Deformable Face Models for Cranio-Facial Reconstruction," in *Proceedings of the 4th International Symposium on Image and Signal Processing and Analysis— ISPA2005*, S. Loncărić, H. Babić, and M. Bellanger, Eds. Croatia, 2005, pp. 347– 352.

[10] S. d. Greef, P. Claes, D. Vandermeulen, W. Mollemans, P. Suetens, and G. Willems, "Large-scale in-vivo Caucasian facial soft tissue thickness database for craniofacial reconstruction," *Forensic Science International,* vol. 154, pp. S126-S146, 2006.

[11] P. M. Moore-Jansen, S. D. Ousley, and R. L. Jantz, *Data Collection Procedures for Forensic Skeletal Material*. Knoxville: University of Tennessee: Forensic Antrhopology Center, Department of Anthorpology, 1994.

[12] A. Vlachos, J. Peters, C. Boyd, and J. Mitchell, "Curved PN Triangles," in *2001 symposiuim on Interactive 3D Graphics* New York, 2001, pp. 159-166.