A Craniofacial surgery simulation testbed

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Abstract: We present a craniofacial surgery simulation testbed that makes extensively use of virtual reality techniques. The skull, skin and muscles are represented with simplex meshes, characterized with a constant vertex to vertex connectivity. Surfaces and volumes are respectively described as a three and four connected meshes. This representation is well suited for the implementation of surface deformations such as those exerted on the face skin under the action of muscles. Furthermore, cutting surface parts may be easily achieved due to the local nature of simplex meshes. The user proceeds by cutting skull fragments and reorganizing them with the help of a virtual hand. Muscles attached to both skin and skull adjust the face shape to the reconstructed skull.

(Résumé : tsvp)

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Simulation de Chirurgie Craniofaciale

Résumé : Nous présentons une maquette de simulation de chirurgie craniofaciale utilisant des outils de réalité virtuelle. Le crâne, la peau et les tissus mous sont modélisés par une nouvelle représentation appelée "maillage simplexe". Dans un maillage simplexe, les sommets ont un nombre constant de voisins, trois pour les surfaces et quatre pour les volumes. Ces maillages permettent de modéliser aisément le découpage de surfaces ainsi que les déformations du visage sous l'effet des muscles.

L'utilisateur simule une opération en découpant des fragments de crâne et en les repositionnant grâce à une "main virtuelle". Les muscles attachés entre la peau et le crâne agissent alors sur le visage ce qui permet de visualiser le résultat de l'opération.

1 Introduction

The aim of craniofacial surgery [MR90] is to modify the shape of the skull in order to deal with accidental injuries or congenital malformations. The surgeon cuts several skull fragments and sets them into a normal configuration. Those procedures are very tedious, often very long and involve a lot of specialists. So, they must be very thoroughly planned, in particular with the help of numerous data available from medical imagery.

The first computer applications involved the reconstruction of skull and face models from CT Scans, MRI images. Marsh et al. [MVK85] adapted CAD software to simulate the surgery but modelling non polyhedral structures was quite difficult and consequently their system was difficult to handle. Craniofacial surgery simulation was pioneered by Cutting and al. [Cut91] in 1986. They defined three main functionalities for completing a craniofacial surgery simulation:

- Cutting the skeleton model into several fragments.
- Handling the patches according to the six degrees of freedom.
- Measuring distances or angles on the skull to detect feature points and quantify deformations.

Nevertheless, they do not simulate the patient face after modifications of the skull in order to check the operation results. Other teams haved achieved promising experiments in the field of craniofacial surgery simulation[YHYT90][SCKF92][Kik92] or computer-aided surgery[Cin93][Tay92].

Furthermore, a surgery simulation has to be intensively interactive. Virtual reality tools are very suitable for handling three dimensional data as described in [BFO92] and in [Tay92].

We have developed a craniofacial surgery simulation testbed that makes use of virtual reality techniques. This testbed is based on a new representation called "simplex meshes" and integrates the first two functionalities proposed by Cutting and a post-operation visualization of the face.

2 Modeling

The "virtual environment" where the user evolves, consists in a set of deformable surfaces or volumes. The skull as well as the face of a patient are represented with three dimensional surfaces of complex topology. In addition, we have modelled the tissue between the skin and the skull with "muscles" organized in layers that will deform the face of a patient in response to the surgery operated on the skull. In order to provide an intuitive interface, we should be able to perform the following actions on the surface and volume models:

- Cutting and merging of surface fragments.
- Deformation and smoothing of surfaces.

- Creation of muscles between a part of the skull and a part of a face.
- Interaction between muscles and the skin.

In order to satisfy those constraints, we use an original representation of surfaces and volumes called *simplex meshes* introduced by Delingette[DWS93]. This representation authorizes local changes of connexity of a mesh, which are not possible with regular structures such as those used by Waters[Wat87][TW90].

Every model may be deformed under the influence of both internal or external forces, similarly to the scheme of deformable surfaces[DHI91] or snakes[KWT88]. We formulate the deformation of surfaces and volumes in terms of law of motion, as in classical mechanics theory. The external forces applied on a given model, are exerted either by another model of different nature (interaction skin-muscle) or by the user who may help the deformation process. The internal forces constrain the models shape to stay close to a reference shape.

2.1 Representation of the skull and face

2.1.1 Definition

Among all surface representations, triangulations and regular grids are the most commonly used. Triangulated surfaces may be of complex topology and furthermore may be refined or decimated locally. But, it is rather difficult to formalize their deformation and smoothing because of the varying vertex connectivity. Regular grids, on the other hand, may be represented as B-splines, and their deformation may be easily computed. However, their connectivity cannot be locally altered and furthermore, they cannot represent surfaces of certain topology without exhibiting poles.

In our simulation tested, we represent all surface models with 2-simplex meshes that are dual of triangulations. The duality exchanges triangles into vertices, edges into edges and vertices into polygons (see Figure 1). An fundamental property of 2-simplex meshes is their constant connectivity equals to three. Therefore, at each vertex, we can define a tetrahedron, a 3-simplex, with a vertex and its three neighbors. It is important to note that even though 2-simplex meshes and triangulations are dual topologically, they are not dual geometrically. Consequently, we cannot define an isomorphism transforming a 2-simplex mesh into a triangulation.

A major advantage of simplex meshes is their ability to be locally altered with a small number of operations. We have defined four basic operations T_i $(i = 1, \ldots, 4)$ that generate all possible transformations while keeping the 3-connexity of a 2-simplex mesh (see Figure 2). The first two T_1 and T_2 correspond respectively to an edge collapse and face splitting operations. Those operations modify the density of vertices and are guaranteed to keep the genus of a mesh constant. T_3 operates on two faces and results in either the merging of two 2-simplex meshes or the creation of a handle (increase of the genus number). T_4 consists in cutting a mesh along a contour and results in either the removal of a handle (decrease of the genus number) or the breaking a mesh into two pieces. A contour on a 2-simplex mesh is defined as a cycle of neighboring vertices (see Figure 3). In order to perform the surgery

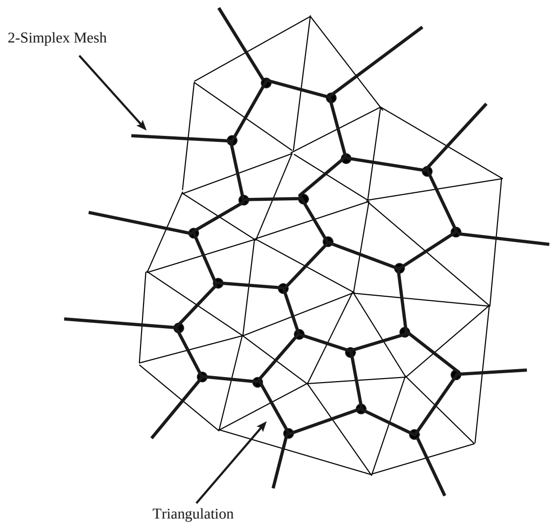


Figure 1: 2-simplex mesh and a dual triangulation.

simulation, we will use the T_3 operation to merge skull fragments and the T_4 operation to cut those fragments.

2.1.2 Mesh Deformation

The vertices of a simplex mesh are moved under the influence of internal and external constraints. Using a mechanical analogy, we can formalize the mesh deformation the following law of motion:

$$m\frac{d^2P_i}{dt^2} = -\gamma\frac{dP_i}{dt} + \vec{F}_{int} + \vec{F}_{ext} \tag{1}$$

where m is the mass of a vertex and γ the damping factor.

Simplex meshes have a compact and non-ambiguous shape representation that makes them well-suited for deformations. At each vertex P_i of a 2-simplex mesh, we define three scalars $(\varepsilon_{1i}, \varepsilon_{2i}, \phi_i)$ that encode the position of P_i with respect to its three neighbors (see figure 4). The first two parameters $(\varepsilon_{1i}, \varepsilon_{2i})$ are *metric coefficients* whereas ϕ_i is the simplex angle at P_i. The simplex angle is related to the discrete mean curvature H_i:

$$H_i = \frac{\sin(\phi_i)}{r_i} \tag{2}$$

where r_i is the radius of the circumscribed triangle $(P_{N_1(i)}, P_{N_2(i)}, P_{N_3(i)})$. The expression of the internal force $\vec{F_{int}}$ is designed to control the simplex angle at P_i and consequently its

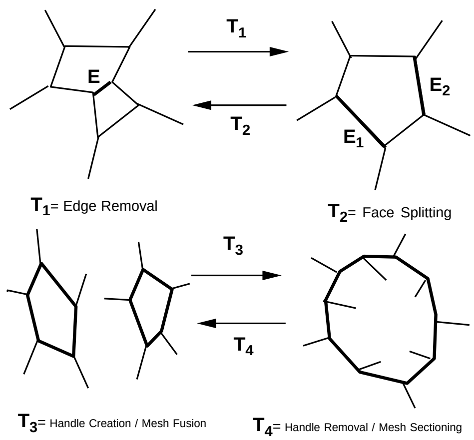


Figure 2: The four basic mesh transformations

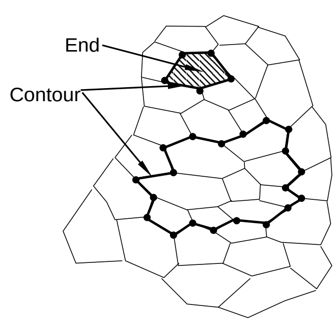
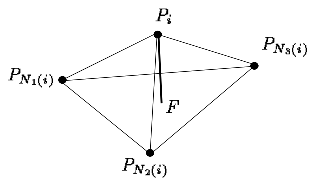


Figure 3: Two contours defined on a 2-simplex mesh

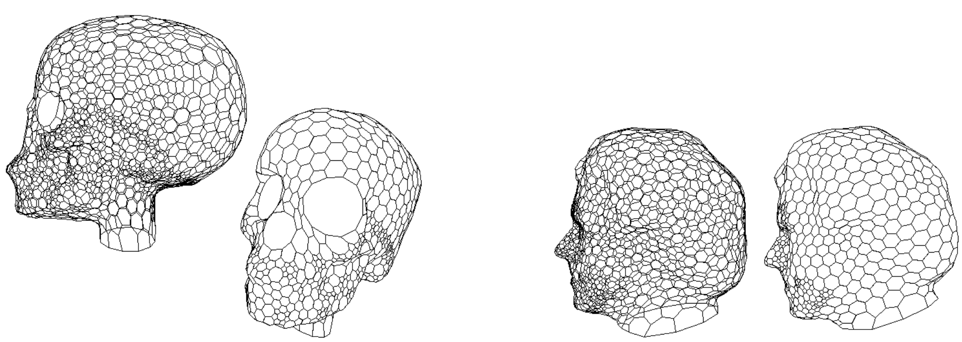


$F = \varepsilon_{1i} P_{N_1(i)} + \varepsilon_{2i} P_{N_2(i)} + \varepsilon_{3i} P_{N_3(i)}$
$\varepsilon_{1i} + \varepsilon_{2i} + \varepsilon_{3i} = 1$
$P_i = F + L(r_i, d_i, \phi_i)\vec{N_i}$

Figure 4: Relations at a vertex of a 2-simplex mesh

mean curvature. Several expressions of the internal force are possible depending on the type of constraints we want to enforce. For instance, we will apply a shape constraint on a face model when submitted to the muscle actions. This constraint will ensure that the resulting face model is as close as possible to its original shape. On the other hand, when merging two skull fragments, we will smooth both models to perform a realistic surgery. A detailed description of those internal forces may be found in [DWS93].

The external forces integrate the interaction between a model and its environment. The user may interact with a surface model with the virtual hand by exerting a repulsive force. Furthermore, a model may be deformed by a local potential field created at the neighborhood of some three dimensional data. We use an algorithm similar to [DHI91] in order to create face and skull models (see Figure 5).



a) b)

Figure 5: a) Skull modelled with a 2-simplex mesh; b) Face modelled with a 2-simplex mesh

2.2 Muscle Representation

2.2.1 Definition

Muscles are represented with 3-simplex meshes. A 3-simplex mesh is dual topologically of a tetrahedrisation and is characterized by its four connectivity. The use of 3-simplex meshes in conjunction with 2-simplex meshes allows to automatically connect a part on the face and its corresponding part on the skull. We have developed an algorithm that builds a 3-simplex mesh with a prescribed number of layers between two given parts of 2-simplex meshes (see Figure 6).

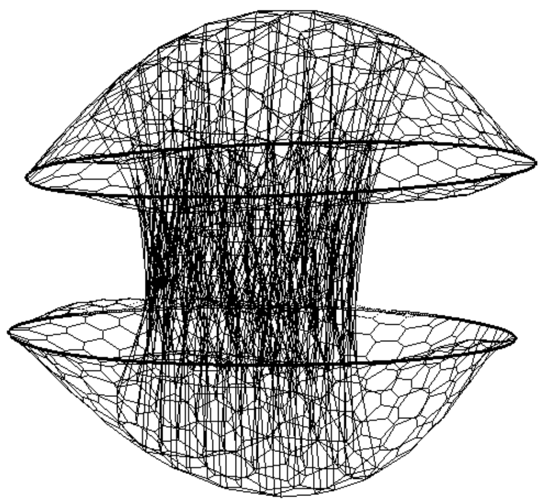


Figure 6: A 3-simplex mesh linked to two 2-simplex meshes

Consequently, we are able to vary the thickness the muscle layer between the skull and the face for enhancing the realism of the face deformation. For instance, at the location of the scalp, we define a one layered 3-simplex mesh whereas between the jaw and its corresponding part on the skull, we create a three layered muscle.

2.2.2 Muscle Action

It is important to note that the deformation techniques presented in this paper are designed for surgery simulation. Therefore, the notion of muscles is different from the one introduced by Terzopoulos and Waters[TW90], Viaud[Via92]. On the other hand, our model of face-skull interaction is close to Waters[Wat92].

Vertices of a 3-simplex mesh are moved according to the law of motion presented in equation 1. We have defined two functional modes for the muscles. The first mode consists in smoothing the vertices of a 3-simplex mesh such that they nicely fit between the two parts where they are anchored. The muscle has then no influence on the face shape. The internal force is then:

$$\vec{F}_{int} = \frac{(P_{N_1(i)} + P_{N_2(i)} + P_{N_3(i)} + P_{N_4(i)})}{4} - P_i \tag{3}$$

The second mode consists in keeping the original shape of a muscle, which brings the deformation of the face model, the skull being fixed. We then consider that a spring of rest length l_{ij}^0 exists between each vertex and its four neighbors. The rest length is computed with the position of each vertices after the smoothing process. The internal force is :

$$\vec{F}_{int} = \sum_j \frac{k_0(l_{ij} - l_{ij}^0)}{l_{ij}} \overrightarrow{P_i P_{N_j(i)}} \quad l_{ij} = \|\overrightarrow{P_i P_{N_j(i)}}\|$$

where k_0 is the stiffness of the springs. We have added to the spring model, a dependency of the stiffness k_0 with the elongation l_{ij} in order to model the non-linearity of the skin

3 Interaction

3.1 Testbed overview

The craniofacial surgery simulation testbed has been programed in C language on a DEC Alpha 3000/500 workstation. The interaction is supplied by:

- A mouse for the common interface functionalities.
- A virtual reality glove to interact in three dimensions with the simulation through a *virtual hand* (see Figure 7).

Two trackers Polhemus 3-Space Fastrack are fixed on the glove, one on the forefinger and the other on the thumb. They continuously measure the position and orientation in relation to an emitter box. In the simulation, the objects and the virtual hand are displayed in Gouraud shading. We have also implemented a stereo mode in wireframe using the anaglyph method that allows a depth perception.

3.2 The virtual hand

Once the calibration process completed, the virtual hand follows the movements of the hand of a user, according to the translation and rotation information sent to the computer via a serial port. For each motion, the closest point in the forefinger direction of the virtual hand is computed and the object to whom it belongs is considered as pointed. When the user closes his hand, the change of distance between the two trackers is detected and the virtual hand closes and grabs the pointed object. Then, the user is able to move the object and to rotate around the hand center. Opening the hand releases the object (see Figure 8).

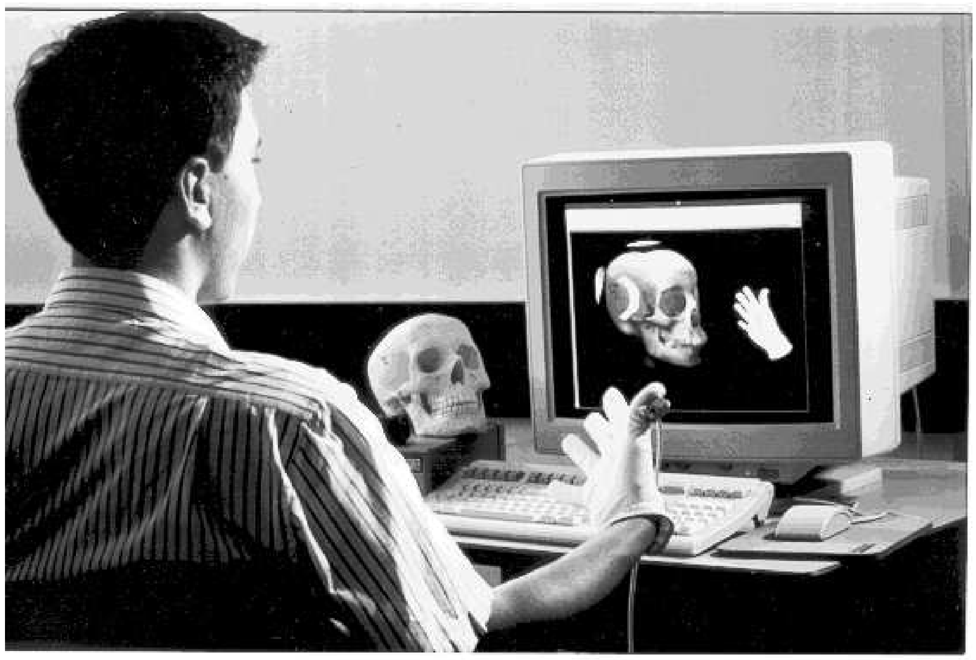


Figure 7: The craniofacial surgery simulation tesbed

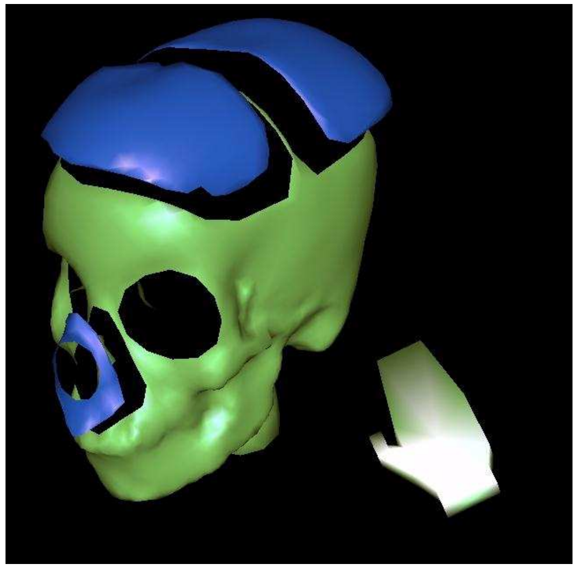


Figure 8: The virtual hand is used for cutting and moving skull fragments

This pointing mode is very convenient for handling objects. But, it is too inaccurate to select a point, for instance to perform a precise cutting. Indeed, a small rotation of the hand may lead to a large displacement of the pointer on the object.

So, we have developed a *surface cursor* : once an object is selected, the cursor moves continuously on the surface in the direction of the virtual hand. The displacement vector of the tracker, defined by two successive positions is mapped into a displacement on the surface. The surface cursor is really tridimensional as the user is able to move on the whole surface: in particular, he can pick points that are hidden from the user with a surrounding gesture. Furthermore, by changing scale between the movements of the real hand and the virtual hand, the cursor can be as precise as possible. In conclusion, the surface cursor keeps the swiftness and the precision of the mouse but in three dimensions.

3.3 Functionalities

At the beginning of the simulation, the user displays the surfaces of the skull and the face of the patient segmented from CT-Scan, MRI or Cyberware. On both surfaces, he selects with the mouse or the surface cursor the opposite parts he wants to link with muscles. He then activates the muscles building procedure and enters their parameters (number of layers, stiffness coefficient) (see Figure 9). At the end, the muscles are smoothed to regularly fill the space between the two parts.

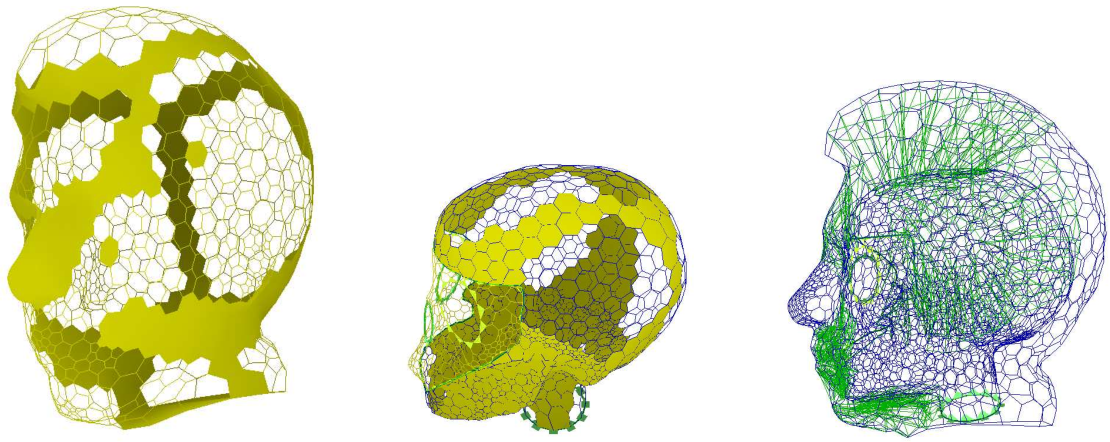


Figure 9: **Left and center** The different parts on two models that are attached with muscles; **Right** The muscles, face and skull models

In order to cut the skull, the user draws a cutting line either along the continuous path of the surface cursor, or along segments joining points selected manually with the mouse. A contour is then created, splitting the object into two independent parts that retain their initial attributes. Cutting can be forbidden according to the object topology. Finally, with the virtual hand, the user moves the different skull fragments to modify the skull shape. Once the cutting process is completed, muscles deform the face according to the skull modifications. A rendered and texture-mapped images of the deformed face is displayed in figures 10 and 11

4 Conclusion and Future Work

The main advantage of virtual reality tools is their ability to provide intuitive tridimensional interaction. Nevertheless, we do not use at the moment a stereoscopic visualization system because their resolution is not high enough for medical objects. Furthermore full tridimensional interaction requires an important and expensive graphic hardware. An extension of our system would include a force and tactile feedback to guide the user with moving the different skull fragments.

In the future, we plan to improve our testbed and integrate some tools developed in the Epidaure project:

- Mean curvature, distances, angles measurements and visualization.

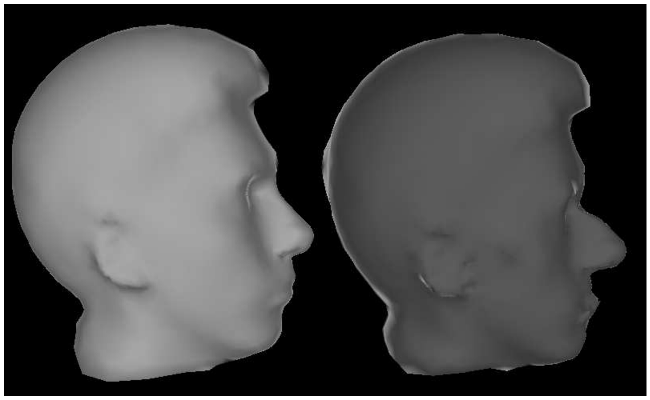


Figure 10: Rendered face before and after surgery simulation

Figure 11: Rendered face before and after surgery simulation

- Superposition of a abnormal skull with a healthy one or an anatomical atlas to help the physician during the simulation and to check results[TG92][TMS+92].
- Automatic detection of abnormalities by registering featuring lines or points[Thi93].
- Automatic sorting for skull fragments with respect to geometrical criteria to provide an automatic skull reconstruction.
- Multimodality registration, for instance, to visualize the brain inside the skull in order to improve the realism of the simulation.

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References

[BFO92] Michael Bajura, Henry Fuchs, and Ryutarou Ohbuchi. Merging virtual objects with the real world. *Computer Graphics*, 26(2):203–210, July 1992.

[Cin93] Ph. Cinquin. Gestes medico-chirurgicaux assistes par ordinateur. *Annales de Radiologie*, 36(6/7):386–406, 1993.

[Cut91] Court B. Cutting. Applications of computer graphics to the evaluation and treatment of major craniofacial malformations. In Jayaram K. Udupa and Herman Gabor T., editors, *3D Imaging in Medicine*, chapter 6, pages 163–189. CRC Press, 1991.

[DHI91] H. Delingette, M. Hebert, and K. Ikeuchi. Shape representation and image segmentation using deformable surfaces. In *IEEE Computer Vision and Pattern Recognition (CVPR91)*, pages 467–472, June 1991.

[DWS93] H. Delingette, Y. Watanabe, and Y. Suenaga. Simplex based animation. In *Models and Techniques in Computer Animation (Computer Animation'93)*, 1993.

[Kik92] R. et al. Kikinis. Interactive visualization and manipulation of 3d reconstructions for the planning of surgical procedures. In *Visualization in Biomedical Computing*, pages 559–563. SPIE, 1992.

[KWT88] M. Kass, A. Witkin, and D. Terzopoulos. Snakes: Active contour models. *International Journal of Computer Vision*, 1:321–331, 1988.

[MR90] Daniel Marchac and Dominique Renier. New aspects of craniofacial surgery. *World Journal of Surgery*, 14:725–732, 1990.

[MVK85] J. Marsh, M. Vannier, and R. Knapp. Computer assisted surface imaging for cranofacial deformities. In M. Hebal, editor, *Advances in Plastic and Reconstructive Surgery*. Year Book Medical Publishers, 1985.

[SCKF92] Jun Satoh, Hiroaki Chiyokura, Masahiro Kobayashi, and Toyomi Fujino. Simulation of surgical operations based on solid modeling. In Tosiyasu L. Kunii, editor, *Visual Computing. Integration Computer Graphics with Computer Vision*, pages 907–916, Tokyo (Japan), 1992. Computer Graphics Society, Springer Verlag.

[Tay92] H. Taylor, R. Augmentation of human precision in computer-integrated surgery. In *Innovation et Technologie en Biologie et Medecine*, 1992.

[TG92] J-P. Thirion and A. Gourdon. The 3d marching lines algorithm and its application to crest lines extraction. *rapport de recherche INRIA*, (1672), May 1992.

[Thi93] J-P Thirion. New feature points based on geometric invariants for 3d image registration. Technical Report 1901, I.N.R.I.A., April 1993.

[TMS+92] J-P Thirion, O. Monga, Benayoun S., Gueziec A., and Ayache N. Automatic registration of 3d images using surface curvature. In *IEEE Int. Symp. on Optical Applied Science and Engineering*, San-Diego, July 1992.

[TW90] D. Terzopoulos and Keith Waters. Physically-based facial modelling, analysis, and animation. *The Journal of Visualization and Computer Animation*, 1:73–80, March 1990.

[Via92] M.L. Viaud. *Animation Faciale avec Rides d'expression*. PhD thesis, Universite Paris VI, 1992.

[Wat87] Keith Waters. A muscle model for animating three-dimensional facial expression. *Computer Graphics*, 21(4), July 1987.

[Wat92] K. Waters. A physical model of facial tissue and muscle articulation derived from computer tomography data. In *Visualization in Biomedical Computing*, pages 574–583. SPIE, 1992.

[YHYT90] Takami Yasuda, Yasuhiro Hashimoto, Shigeki Yokoi, and Jun-Ichiro Toriwaki. Computer system for craniofacial surgical planning based on ct images. *IEEE Transactions on Medical Imaging*, 9(3):270–280, September 1990.

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