A Finite-Element Facial Model for Simulating Plastic Surgery

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CAPS (Computer-Aided Plastic Surgery) is a prototype computer program that uses a three-dimensional graphic model of a human face and incorporates a finite-element mathematical model of the physical properties of the soft tissue. This program can estimate the biomechanic consequences of ablation and rearrangement of tissue. The results of two hypothetical surgeries on the face are presented. A surgeon could use this program as a sketch pad to predict and compare the outcome of facial plastic procedures on a patient-specific model. The relation of this program to previous work is discussed, and directions for research and possible applications are addressed. (*Plast. Reconstr. Surg.* 96: 1100, 1995.)

Planning for facial plastic surgery is aided by physical models of varying complexity, from pen marks on photographs to paper cut-outs to three-dimensional models that are "operated" on to yield predictive results. The computer simply provides a tool that allows a mathematic representation of the patient be the model. Dynamic mathematical models of the mechanical behavior of materials have been used in engineering for many years. Work in computer animation has yielded simulations that behave like human skin. An interactive graphic interface to a skin and soft-tissue computer model would allow a surgeon to plan and simulate the outcome of surgical procedures of these tissues.

Approaches that have been used in the past to employ the computer for surgical planning may be classified in four categories:

1. Two-dimensional geometric
2. Expert systems
3. Three-dimensional geometric
4. Mechanical analysis

Two-Dimensional Geometric

Two-dimensional models are the computer equivalent of pen marks on the preoperative photograph. Computer paint programs and image processors are currently used to design rhinoplasties, midface advancements, and mandibular osteotomies.[1] The computer is used to display two-dimensional images that have been digitally retouched by the operator. They rely solely on the surgeon to create his or her surgical plan, predict the outcome, and then retouch the photograph to create the final image. Caution has been advised in the medicolegal implications of interpreting these images as prediction of outcome.[2]

Expert-Based Systems

Another approach is using the computer to store the experience of experts in the field and their predictions as to surgical outcome based on varying choices made in the surgical plan. The expert system is the equivalent of an algorithm or flowchart summarizing that expert's approach to a certain problem. The computer functions as an interactive textbook for training or decision making. It presents predetermined case histories and images, as well as a menu of possible actions for the user to choose from. The system will then display a prediction of outcome based on the procedures chosen. All possible outcomes are prestored in the simulation system.[3]

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Presented at the Scientific Program of the American Association of Plastic Surgeons 71st Annual Meeting in Vancouver, British Columbia, Canada, May 17–20, 1992.

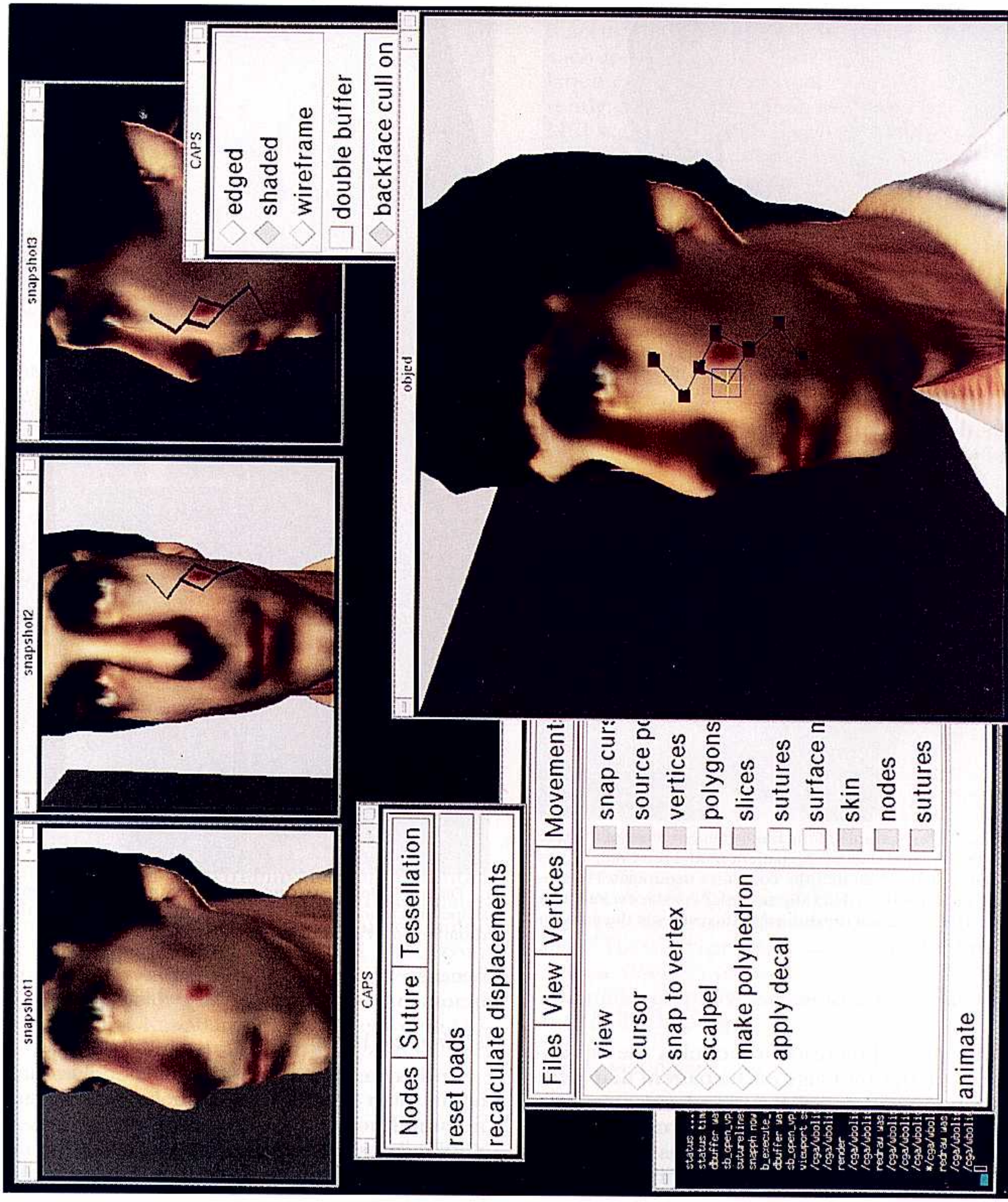

FIG. 1. A screen image of the CAPS program showing a patient model with an interactively defined surgical plan: a rhomboid excision and a double Z-plasty closure.

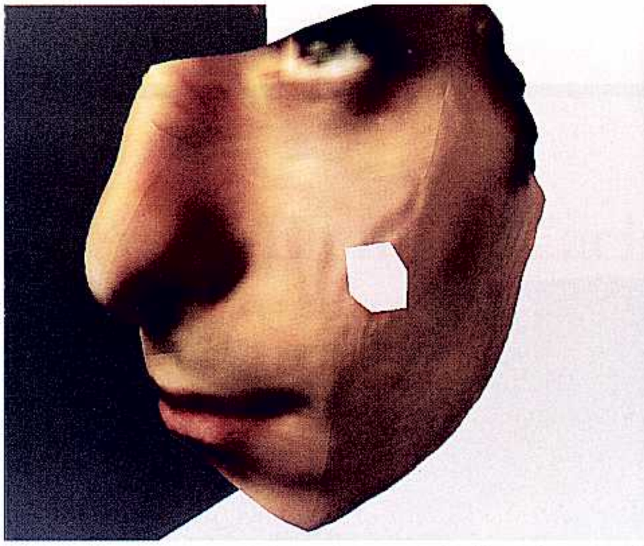

FIG. 2. A close-up of the patient model with an hexagonal approximation of an "elliptical" excision.

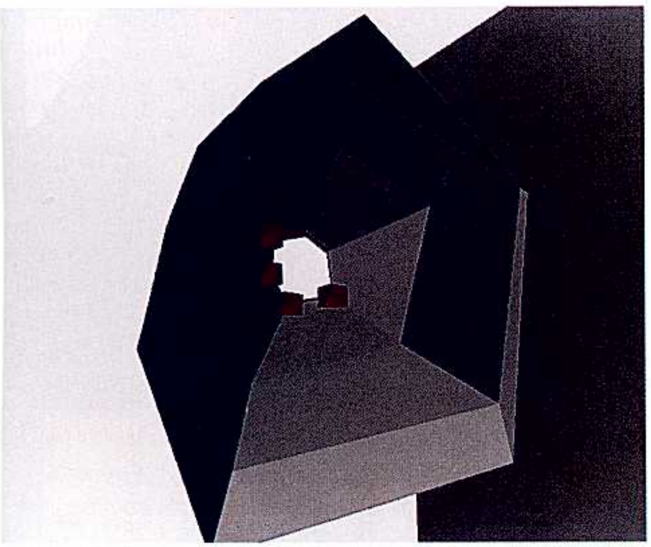

FIG. 3. An example of the finite-element mesh of the face with the detailed data of the patient model removed. This is the polygonal model that the computer manipulates to simulate a closure by making the two edges of the excised area share a border. Then the distortion this causes in the polygon is calculated.

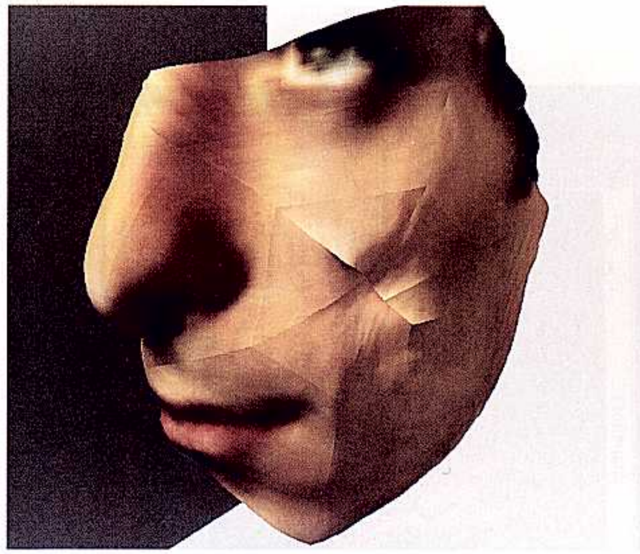

FIG. 4. The results after the detailed facial data are added back to the polygonal model. This simulates a straight-line closure of an "elliptical" excision. Note the two standing cones at the ends and the two lying cones along the middle of the excision.

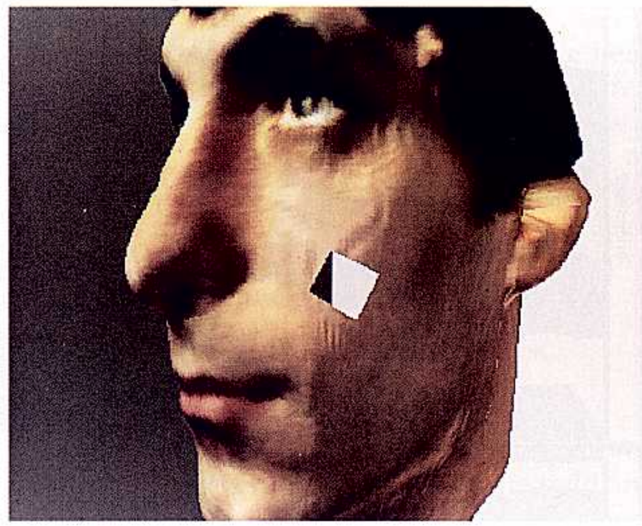

FIG. 5. A close-up of the patient model with a diamond-shaped excision and two Z-plasties planned to perform the rhomboid-to-W closure.

Three-Dimensional Geometric

The three-dimensional model is the equivalent of plaster moulage of the patient that is cut or remodeled to predict surgical outcome. The patient-specific data obtained from radiology studies such as CT and MRI scans can be formatted by computer graphic rendering techniques into visual three-dimensional objects. Surgical simulation systems have been based on segmentation (cutting) and rearrangement of the volume data. This technique is very useful in bone surgery, such as craniofacial surgery,[4,5] because the modeled tissue is rearranged in blocks and is not appreciably elastic.

Mechanical Analysis

In this method, the computer model is analogous to an elastic sheet that behaves in a manner similar to that of skin and soft tissue. A physical description of the patient's tissue is added to the geometric data that are used to analyze relevant mechanical consequences of a proposed surgical procedure. The subject is of intense research at this time, but no system is currently employed in clinical situations. Delp and coworkers[6] constructed a computer simu-

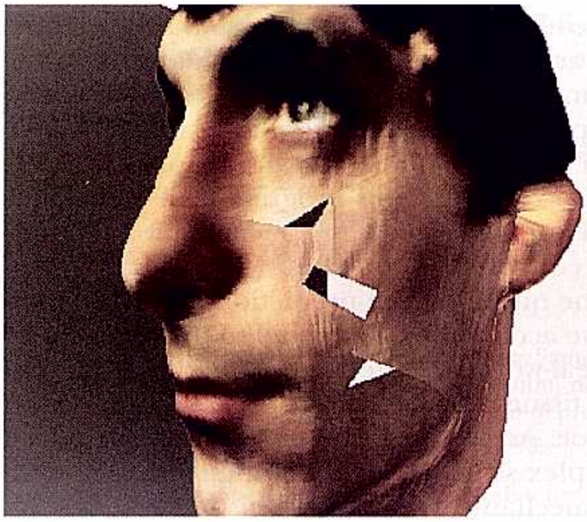

FIG. 6. The flaps of the Z-plasties are shown in the process of being transposed.

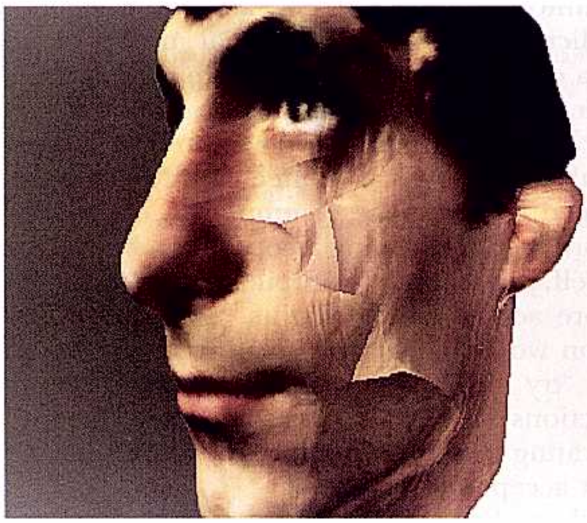

FIG. 7. The results of the double-Z-to-W closure. Note the subtle standing and lying cones generated.

lation of the lower extremity musculotendinous system that can walk in a computer-simulated environment and be used to analyze tendon transfer operations. Larabee and Galt[7] compared a two-dimensional finite-element mesh (FEM; see below) to pigskin to analyze flap advancements. Kawabata et al.[8] used a two-dimensional finite-element mesh to analyze the effect of various Z-plasty parameters. Motoyoshi et al.[9] used a finite-element mesh model of facial soft tissue to predict the outcome of orthognathic surgery. Waters and Terzopolos[10] used a finite-element mesh with overlying detail similar to CAPS to generate computer-synthesized facial expression.

CAPS employs both three-dimensional geometric and mechanical analyses and is an attempt to bring the mechanical study of soft-tissue rearrangement into the complex geometry of the face.

The ultimate goal of the patient model is that it accurately accounts for the patient's tissue at each location of the body for computer simulation. Three-dimensional patient data currently obtained in medicine (e.g., CT scans, MRI scans, PET scans) are encoded volumetrically (i.e., each point in space is defined by an absolute reference frame, which is independent of the patient, and at each of these points, the material is encoded). These data are not immediately amenable to modeling because there is no information as to how each piece of material connects to other pieces of the material. However, there are several algorithms for the construction of finite-element meshes based on data in volume data sets.[11]

A finite-element mesh divides a material with complex geometry into regions (elements) which, taken together, approximate the behavior of the entire material. Each region (element) is defined by the boundaries it shares with other elements. A matrix with the material properties of the elements will predict each element's distortion, given the restriction that it must still share the same borders with the other elements. The essence of the CAPS program is in removing certain elements and then redefining the remaining elements as sharing their (formerly separate) borders, just as a surgeon excises tissue and defines new shared edges with sutures.

METHODS

The Computer

The computer used is a Silicon Graphic Onyx Reality Engine2, a graphics workstation with high-performance three-dimensional rendering.[12] The CAPS program was written by the first author (Pieper) as a part of a Ph.D. thesis in computer graphics at the Massachusetts Institute of Technology.

The Patient Model

A patient model is created from a Cyberware[13] video scan. The scan is performed by rotating a video camera around the subject's face in a cylindrical fashion, roughly centered on the nose. This yields a data set defining the surface of the facial skin in cylindrical coordinates (θ, r, z) and the color of the patient's skin. The data are then reconstructed into a facial surface in rectangular coordinates (x, y, z) so that the computer-reconstructed face can be viewed on the computer monitor from any point chosen by the user.

The User Interface

The program currently functions with a mouse-based graphic interface (similar to Macintosh or Windows interface) in which incisions are defined by connecting points selected on the facial surface by mouse clicks (Fig. 1). Tissue to be excised is determined by causing the incision to complete a closed polygon. Flaps created are assumed by the computer to be undermined.

Computer Data Manipulation

Once the incisions are planned, the face can be segmented into triangular or quadrilateral facets, incorporating the incision as edges (Fig. 3). The detailed contour of the patient's face is handled as a displacement from an idealized polygonal face. These displacements are generated from the Cyberware data and stored as a matrix. Tissue to be excised is removed as a group of triangular segments. The closure is then accomplished by defining new relationships of the edges of the polygonal face's facets. Closure in simple approximation or in a double Z-plasty rhomboid-to-W[14] manner has been preprogrammed and can be selected by the user from a menu. A skin stiffness matrix is used to integrate the strain and distortion this produces throughout the entire network. The details of the altered face model are then reconstructed by means of the displacement data. A prediction of facial distortion resulting from the resection and reconstruction is then displayed.

Results

Two procedures for reconstruction of facial excision are simulated on CAPS: simple straight-line closure (Figs. 2 and 4) and rhomboid-to-W flap (Figs. 5 through 7).

Discussion

Plastic surgery has a long history of employing tools to aid in the planning of surgery; from the leaf template for forehead-flap nasal reconstruction employed by the Indian surgeons to plastic templates milled from CT scan reconstructions, all may be regarded as attempts to "simulate" the operation in a medium other than the patient. The program presented is a small step toward accurate computer simulation of facial plastic surgery. The method of finite-element modeling has been reported before and its results compared with those of physical modeling.[6–8] More work is needed to refine this particular model and validate its results. We have a project under way to compare the predictive results of this program with actual surgical outcomes in cases of facial tumor excision and congenital anomalies.

The quality of the prediction is only as good as the accuracy of the model to the behavior of its real-world counterpart. A model of human soft tissue must assume simplifications of behavior. Actual human tissue is alive and has a complex structure of components with nonlinear mechanical behavior. This model does not currently model the varying thickness of facial soft tissue; the model is of a homogeneous layer of uniform thickness. The analogy is that of predicting the outcome of facial surgery by using a detailed facial model made of uniformly thick foam rubber.

Training is a logical application of a surgery simulator. A surgical trainee could have experienced the outcome of numerous operations before ever performing an operation himself or herself, just as modern jet pilots fly many sorties before actual combat flights.[15] Another application would be surgical planning; a surgeon may "try out" many different possible reconstructions on the patient-specific model prior to operating to determine the procedure with the most acceptable result.

Other changes could make the input and output of the program a more realistic simulation of surgery. The user interface, a mouse-driven graphic interface, was selected because it has already been implemented on the computer. Input devices are being developed that move three-dimensionally and use internal motors to give the user "force-feedback." In other words, the user could move a "scalpel" into the virtual tissue, and he or she could actually "feel" its resistance. Further refinement also could provide more information to the user than simple appearance; e.g., overlays of skin tension lines and underlying anatomic features could be displayed on the screen in a "semitransparent" mode. Once the repair has been performed, the program could provide analytic data such as closing tension and degree of strain of adjacent structures.

In conclusion, the method of finite-element modeling is demonstrated as a means of modeling the physical properties of facial soft tissue in a method with more detail than previously demonstrated.

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