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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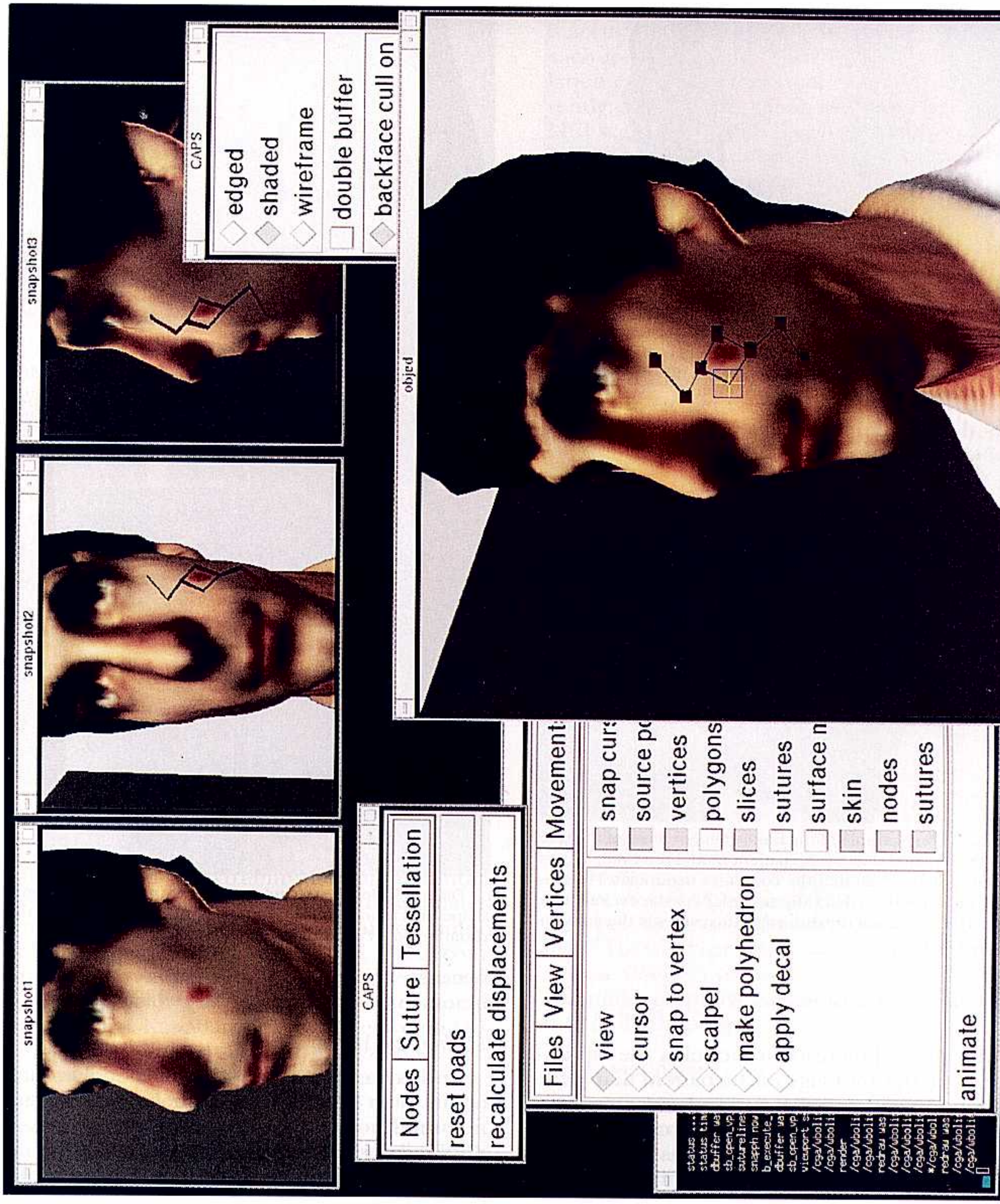

FIG. 1. A screen image of the CAPS program showing a patient model with an interactively defined surgical plan: a rhomboid excision and a double Z-plasty closure.

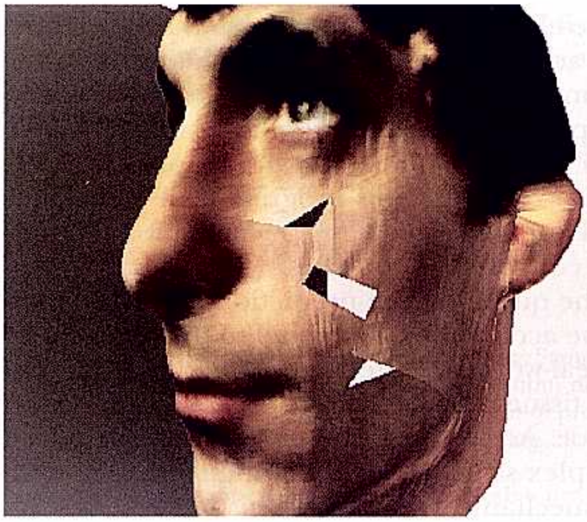

FIG. 6. The flaps of the Z-plasties are shown in the process of being transposed.

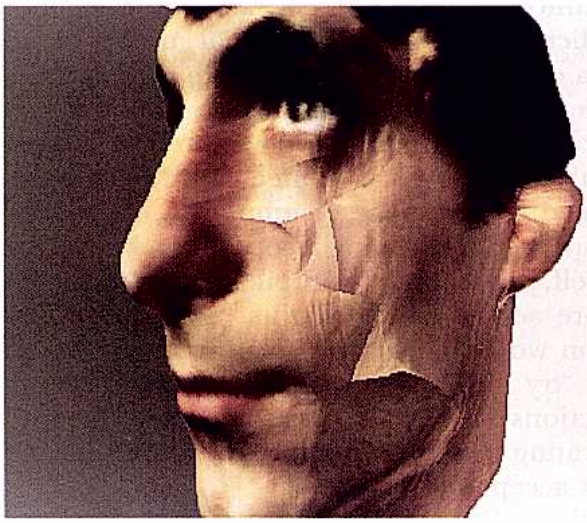

FIG. 7. The results of the double-Z-to-W closure. Note the subtle standing and lying cones generated.

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