An Elastic Organ Model for Force Feedback Manipulation and Real-time Surgical Simulation

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1. Introduction

In recent years, there have been rapid advances in the application of surgical simulators to virtual reality (VR) techniques and their use in various field of medicine, and we have been developing a 3D surgical simulation system for surgical planning using virtual reality. This simulation system allows us to incise skin and organs as elastic objects in real-time on CRT and to visualize their internal structures, such as blood vessels and lesions. By using these surgical simulators, surgeons are able to go through various approaches to urgent operations and carefully plan the procedures beforehand. It is very useful, especially for experiencing operations for defomities or with some expected difficulties. And medical students are able to train for surgical operations again and again. This should greatly reduce operating time and unexpected problems during actual operations. However, there are some problems with the present simulator. In general, it is difficult to manipulate, deform and incise volumetric organ models as elastic objects in real-time, and surgeons require more realistic simulation involving the sense of touch. Thus, the purpose of our study was to construct an elastic organ model for real-time simulation. Furthermore, by connection to a force feedback device we are attempting to add a feedback function that responds to the pressure of operator's hand. In short, we are trying to provide for manipulation of elastic organ models with a sense of touch or sense of force. In this study, we focus on model deformation in response to application of force at a single point, such as by pushing, and at two points, such as by pinching.

2. Methods

There are certain requirements of our VR system : (1) Reality, to accurately represent the shape of an individual patient's organ in detail, and to be able to deform the organ according to physical, anatomical and pathological information; (2) real-time simulation, to handle the volumetric organ model in real-time; (3) performance of quantitative deformation; (4) representation of an organ's internal structures, such as blood vessels; (5) various manipulation, to push, pick, pinch, incise, excise, and so on, the organ model by hand or with surgical tools, such as scalpels, in the virtual space; (6) easy connection to the force feedback device and easy calculation and handling of certain values for force feedback.

Many researchers often use the finite element method for model deformation. However, with the finite element method it is generally difficult to construct the model and divide model structures into finite elements automatically, because the organ model for surgical simulation is very complicated, and its actual shape in each patient is required. Moreover, it is difficult to manipulate the complicated organ model in real-time. Therefore, to prepare a real-time simulation and a force feedback function we developed an elastic organ model, tentatively called the ***"sphere-filled model "***. This organ model consists of a group of small spheres inside and polyhedrons at the surface.

The model is a volumetric model and comparatively well suited to quantitative deformation and high-speed operation. The system is composed of a graphics workstation (Onyx RE2 : SGI) and the force feedback device. We use MRI or CT data sets obtained from the patient. The model is reconstructed as follows. First, the contours of the organ specified are manually extracted from medical images - MRI or CT data sets. Second, the inside of the organ is semi-automatically filled with some element spheres. The organ model can be almost completely filled with spheres automatically, but sometimes, automatic filling is not performed perfectly. The problem is that some spheres do not exist inside the organ model, or that they exist outside the organ model because of the complicated shape of the organ. Under such conditions, we can fill necessary spheres or remove unnecessary spheres manually by using a "mouse" device. All the sphere elements have the same radius. This time, the element spheres are placed at face-centered cubic lattices. Finally, the surface organ model filled with spheres is constructed by triangulation.

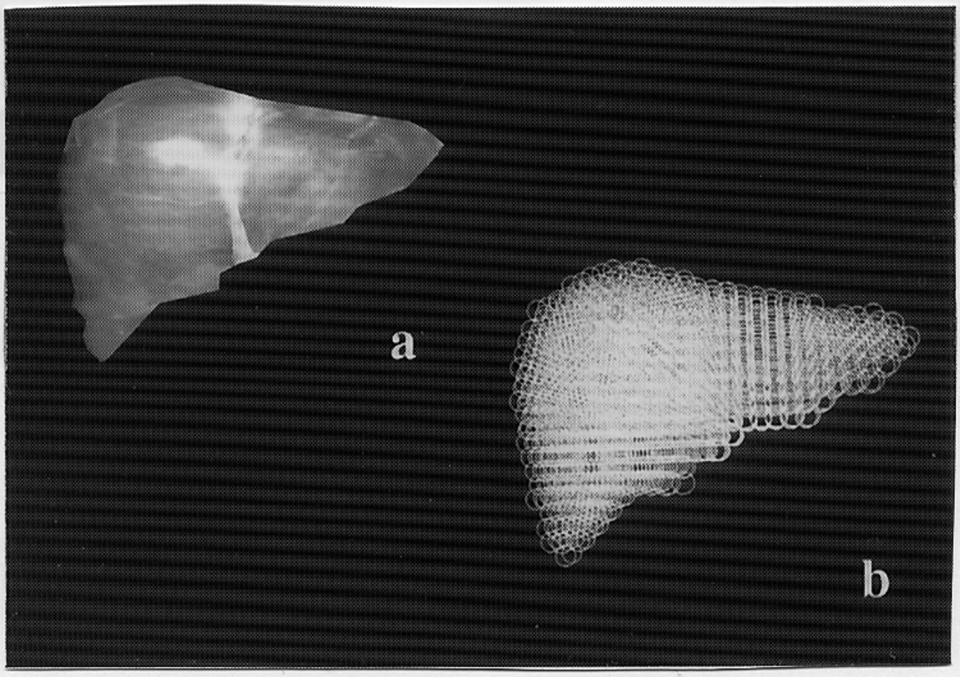

Fig.1 The structure of an elastic organ model of the liver. Fig.1a is a surface model of the liver with texture constructed by the sphere-filled model. Fig.1b represents the inner structure of this sphere-filled model of the liver. This liver model consists of 1861 spheres.

If external force is applied to this elastic organ model, it is deformed by the movement of each element sphere. Each element sphere is pressed and moved in turn by measuring its distance from the neighboring element spheres. In short, none of element sphere overlaps, and ultimately the entire shape of the organ model is deformed.

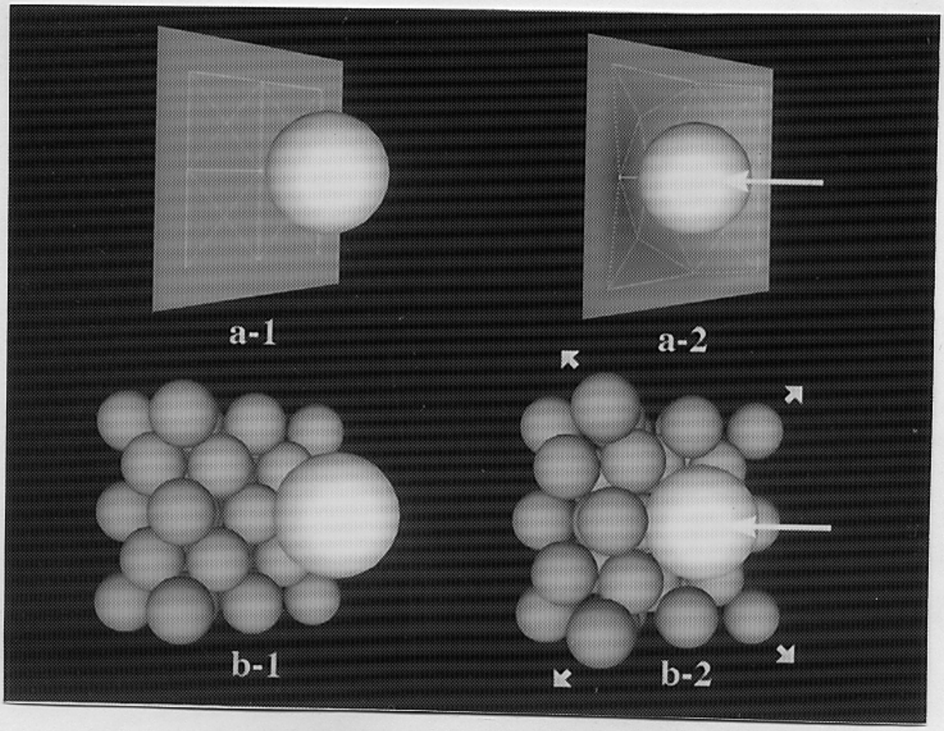

Fig.2 The basic behavior of model deformation. If external force is applied to the model, it is deformed by the movement of each element sphere

In addition, certain force feedback values, such as the direction and the strength of force, are calculated. In our surgical simulation system, the position of external force on CRT is controlled by the force feedback device, and certain values calculated according to the model deformation are sent to the force feedback device system from the graphics workstation, and the force feedback device then produces mechanical resistance to the finger of the operator.

3. Results

Fig.1 shows the structure of an elastic organ model of the liver. Fig.1a is a surface model of the liver with texture constructed by the sphere-filled model, and Fig.1b shows the inner structure of this sphere-filled model of the liver. The liver contours were obtained from the MRI data set with 4-mm intervals. This liver model consists of 1088 polyhedrons at the surface and 1861 element spheres. If necessary, we can map the texture of the surface of livers removed from cadavers in order to perform more realistic simulation. In this simulation, it is easy to convert the surface texture to color code.

Fig.2 shows the basic behavior of model deformation. If external force is applied to the object, each element sphere is pressed and moved in turn (Fig.2b-2). The entire object is deformed (Fig.2a-2).

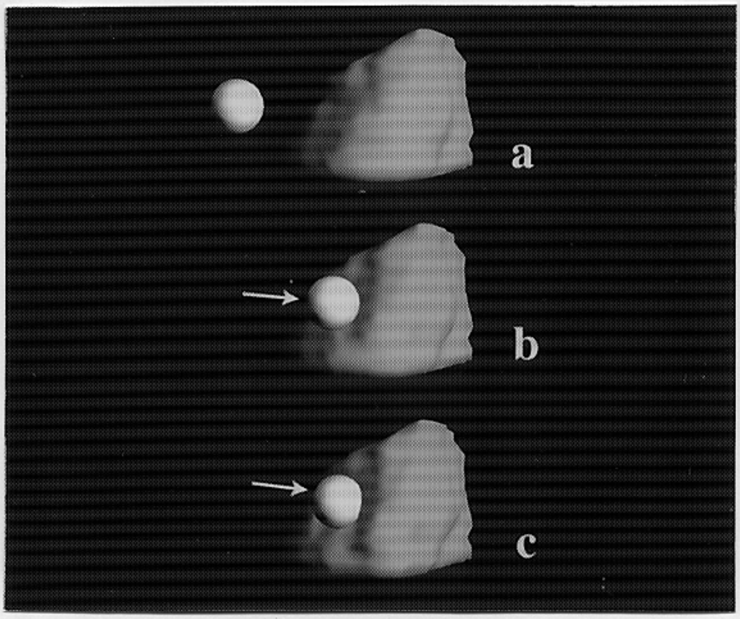

Fig.3 Serial images of model deformation of the partial organ surface

Fig.3 shows serial images of model deformation. These images represent the partial organ surface deformed by external force and show a good response of deformation to external force. These images were displayed at 15-20 frames/s.

Fig.4 shows deformation simulation of the liver with texture constructed by the sphere-filled model. These images were displayed at 10-12 frames/s. Errors of volume in deformation are under 8 %. Fig.4a shows the performance of the model when pushed with a finger or surgical tool at a single point. Fig.4b shows the performance of the model when pinched with the operator's fingers at two points.

Fig.5 shows a scene of an operation using a force feedback device. It is possible to control the external force indicated by the white ball and push the deformable model.

Fig.6 shows the appearance of the force feedback system with three controlled manipulators. A surgeon attached his right arm to the device. The operator's thumb, forefinger and middle finger are attached to the distal part of the motion controlled manipulators.

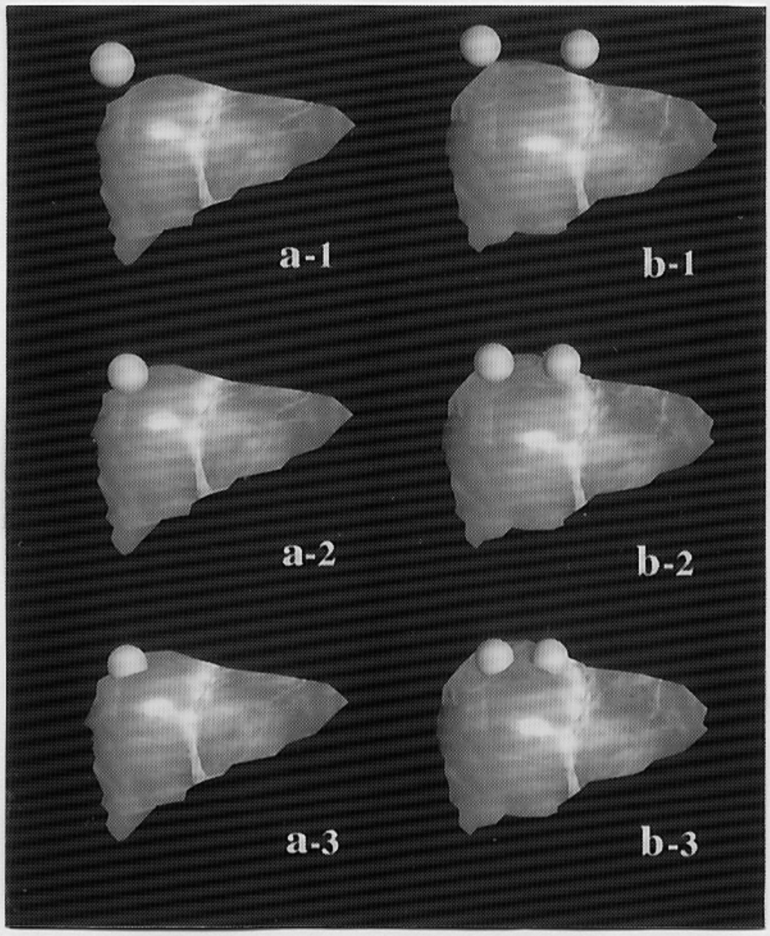

Fig.4 Deformation simulation of the liver with texture by the sphere-filled model.

4. Conclusion

By filling the model with element spheres, a new elastic organ model, a volumetric deformable model, containing a relatively small number of data for controlling deformation was achieved. The features of this model can be summarized as follows. (1) It is suitable for real-time simulation and quantitative deformation. (2) The organ model can be constructed by the same procedures no matter how complicated the shape of the organ of interest may be. It is relatively easy to divide the model into some elements, and the model can be constructed automatically or semi-automatically. (3) We are currently trying to provide for manipulation of this model with a sense of touch and a sense of force by connecting it to the force feedback device. It is easy to calculate the values for force feedback, such as strength and direction. In the future, we will study the feasibility of applying this model to our VR system based on the results of simulated deformation, and will make the behavior of our model more realistic and sensitive. In addition, we will attempt to apply this model to incision and excision and to represent the internal structures of organs, such as blood vessels.

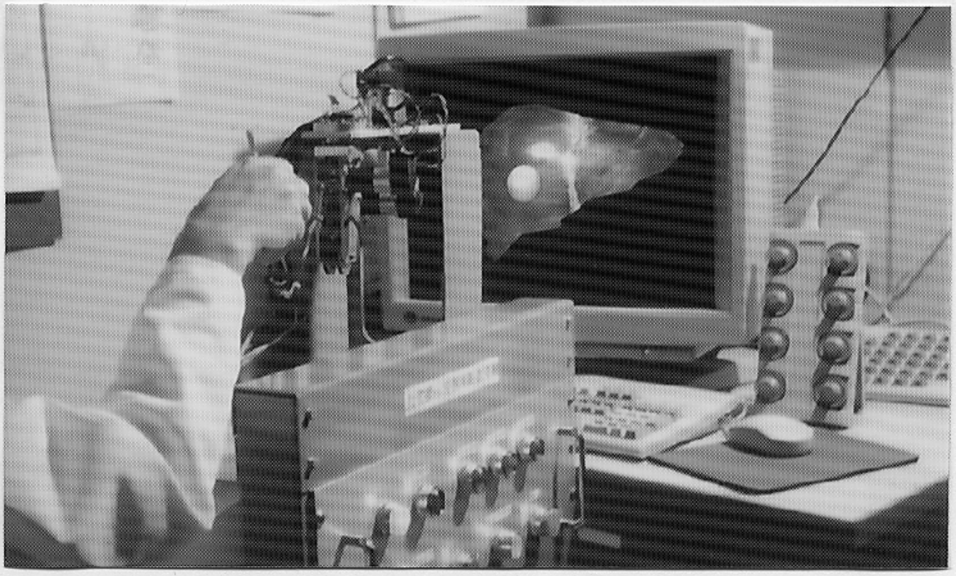

Fig.5 A scene of an operation using a force feedback device.

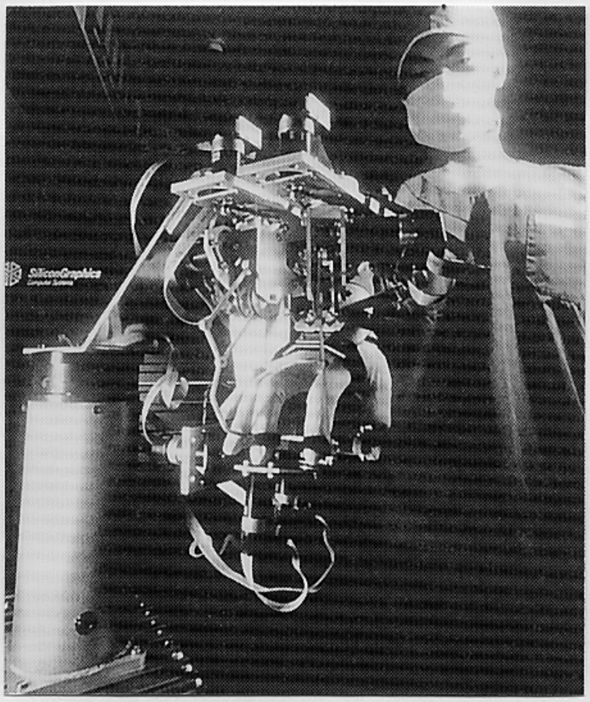

Fig.6 The appearance of the force feedback system with three controlled manipulators. The operator's thumb, forefinger and middle finger are attached to the distal part of the motion controlled manipulators.

5. References

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