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Interaction Model between Elastic Objects for Accurate Haptic Display

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Abstract

The simulation of organ-organ interaction is indispensable for practical and advanced medical VR simulator such as open surgery and indirect palpation. This paper gives a method to represent interaction between elastic objects i.e. organs in medical VR simulation. The proposed model defines displacements of colliding elements based on temporary surface forces caused by temporary displacements, so that the model produces accurate deformation and force feedback considering collisions of objects as well as prevents unrealistic overlap of objects. A prototype simulator of rectal palpation is constructed with the proposed model. The results of experiments confirmed the method expresses organ-organ interaction in real time and produces realistic and perceivable force feedback.

Key words: Haptic display, Interaction, Elastic Objects, Medical simulation

1. Introduction

Recently, medicine is much focused on as one of the most practical applications of virtual reality techniques. Virtual human (or digital human), which is a human model represented in virtual environment, has various kinds of abilities of applications for medical education, procedural training and surgical planning [1]. Several simulators have been matured and some have been already commercialised, such as planning simulators for facial surgery [2] and training simulators of suturing [3], which require less real-time simulation or less realistic haptic sensation.

Although most current simulators have dealt with a single organ object, more practical and advanced simulators like open surgery and indirect palpation require real-time and accurate haptic display with handling organ-organ interaction. Open surgery is a conventional operation style in surgery where surgeons cut chest or abdomen large and push away organs in approaching the tissue of interest. Several kinds of palpation like breast palpation or rectal palpation require indirect palpation, in which doctor palpate the tissue of interest indirectly by touching interposing tissue.

Interaction model between elastic objects needs to fulfil the following requirements.

1. Real-time computation allowing interactive manipulation
2. Taking into account of physical properties of colliding objects
3. Adequate visual reality resulted from interaction between multiple organs

First, interactive manipulation of doctors and surgeons require real-time computation of deformation and haptic feedback. Refresh rate of haptic display should be quite high. Second, the interaction between a soft object and a hard object causes the deformation that the soft object deforms larger than the hard object as shown in Fig.1. Such an interaction results in accurate reaction forces considering physical properties, e.g., stiffness of colliding objects. Last, adequate visual reality is important for realistic simulation as well.

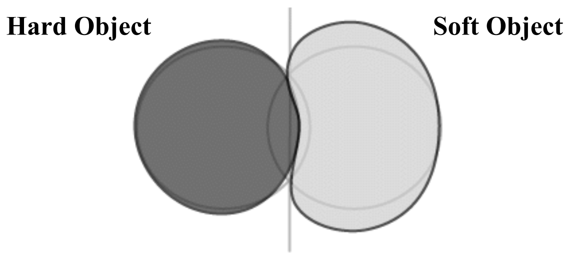


Figure 1. Deformation caused by collision of elastic objects that have different stiffness

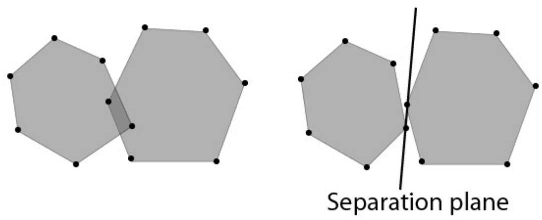
We propose an interaction model between elastic objects that satisfies above requirements and develop a rectal palpation simulator to evaluate the proposed model.

2. Related Works

Modelling of soft tissue has been much studied in Biomechanics [4]. Deformation based on finite element method (FEM) is proper for the simulator that requires accurate haptic force. To achieve real-time simulation, it is effective to apply several techniques like condensation [5] and Hirota's method [6].

As shown in Fig.2, Sibille solves interaction between elastic objects by projecting colliding nodes to the plane that is passing a barycenter of colliding nodes and perpendicular to the average normal vector of colliding nodes [7]. Although the method avoids invasion of colliding objects, deformation and haptic force never take into account of physical properties of colliding objects because of geometrical interaction. The existing methods have no adequate answers to fulfil the above requirements.

On the other hand, until now, several rectal palpation simulators have been developed. However, the simulator ignored the existence of rectum and the accuracy of deformation and haptic forces was inadequate [8].



(a) Before collision **(b) After collision**

Figure 2. Geometrical interaction model by Sibille [7]

3.Methodology

3.1 Problems using a single elastic object

Before explanation of the proposed model, we describe problems of single elastic object representing multiple organs. Several simulators [9, 10] are dealing with multiple organs as single elastic object. The methods filling finite elements into a gap between elastic objects are improper in a situation where contact regions are changeful. Other solution is to combine colliding nodes. If contact regions of organs are changed, topology of an object is changed and global stiffness matrix needs to be reassembled. In addition, re-computation in pre-processing procedures is necessary. Since the limit of haptic refresh rate is quite high, i.e. 250Hz [11], re-computation in real-time is difficult. In the light of storage volume, it is improper that all possible models are pre-computed and stored. In consequence, multiple organs must be modelled as multiple independent objects due to abilities of representation and computer resources.

3.2 Interaction Model between Elastic Objects

Interaction is modelled as giving displacements, which is based on surface forces caused by temporary displacements of colliding elements, to the colliding elements. Fig. 3 illustrates the outline of the proposed model. First, object A is regarded as rigid body and surface forces $\vec{b}$ is calculated on object B (see Fig. 3-a). Next, the object B is regarded as a rigid body and surface forces $\vec{a}$ is calculated on the object A as well (see Fig. 3-b). Finally, since surface forces indicate the degree of resistance to invasion of colliding objects, actual displacements of colliding elements of the object A, B are calculated as $|\vec{b}| : |\vec{a}|$.

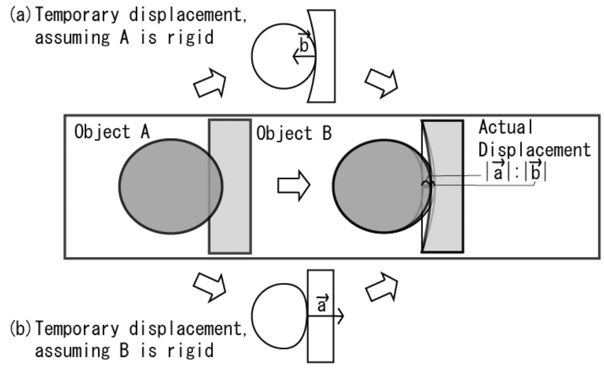


Figure 3. Interaction model between elastic objects

3.3 Calculation of interaction

Calculation of interaction consists of the following procedures.

1. Detection of colliding elements
2. Calculation of temporary displacements
3. Temporary deformation
4. Calculation of temporary surface forces
5. Calculation of actual displacements

Temporary deformation and calculation of temporary surface forces are calculated based on FEM. Detection of colliding elements depends on collision detection algorithm.

- Detection of colliding elements

Colliding elements are detected by the external collision detection method to detect collision of polygon and node. If both polygons are colliding, the following procedures are carried out.

- Calculation of temporary displacements

If a node of object A is colliding to polygon S of object B, S is displaced perpendicularly as shown in Fig.4. Since forces taking into account of stiffness are derived from a result of perpendicular interaction, displacements are perpendicular against a polygon S.

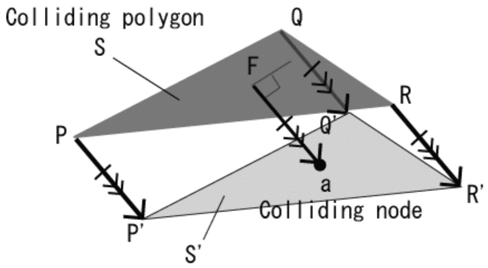


Figure 4. Interim displacement of the surface

The vector of temporary displacement $\overrightarrow{u_{temp\_B}}$ is

$$\overrightarrow{u_{temp\_B}} = \overrightarrow{Fa} \tag{1}$$

where F is foot of perpendicular of the node a to S.

Displacements of nodes, P, Q, R are as follows.

$$\begin{aligned} \overrightarrow{P'} &= \overrightarrow{P} + \overrightarrow{u_{temp\_B}} \\ \overrightarrow{Q'} &= \overrightarrow{Q} + \overrightarrow{u_{temp\_B}} \\ \overrightarrow{R'} &= \overrightarrow{R} + \overrightarrow{u_{temp\_B}} \end{aligned} \tag{2}$$

In the same way, a temporary displacement $\overrightarrow{u_{temp\_A}} = \overrightarrow{Fb}$ is given to colliding polygon of object A, to which a node of object B is colliding.

- Temporary deformation

Calculation of deformation is carried out with temporary displacements.

- Calculation of temporary surface forces

A vector of temporary surface forces $\overrightarrow{f}$ arising on S is defined as an average force vector on P', Q', R' projected onto a normal vector of S.

- Calculation of actual displacements

Since actual displacements of colliding polygons must depend on resistance against invasion to the other colliding polygon, the ratio of actual displacements of colliding polygons is defined as $\left|\overrightarrow{f_B}\right| : \left|\overrightarrow{f_A}\right|$.

In order to reduce computation, only the adjacent polygon that has large magnitude of the vector is displaced and only the colliding node of the other side is displaced. The following is the description about the case of force vector of the object B being larger. The displacement $\overrightarrow{u_A}, \overrightarrow{u_B}$, which are the colliding nodes of the object A and the adjacent polygon of the object B, are as follows.

$$\overrightarrow{u_A} = -\frac{\left|\overrightarrow{f_B}\right|}{\left|\overrightarrow{f_A}\right| + \left|\overrightarrow{f_B}\right|} \overrightarrow{u_{temp\_B}} \tag{3}$$

$$\overrightarrow{u_B} = \frac{\left|\overrightarrow{f_A}\right|}{\left|\overrightarrow{f_A}\right| + \left|\overrightarrow{f_B}\right|} \overrightarrow{u_{temp\_B}} \tag{4}$$

where $\overrightarrow{u_{temp\_B}}$ is the vector of a temporary displacement, $\overrightarrow{f_A}$ and $\overrightarrow{f_B}$ are the vectors of surface forces on the adjacent polygons of the object A and B respectively.

4. Calculation time

We examined calculation time when a sphere-shaped object A and cubic object B collide. Both objects are in contact and a moving point pushes a point of object A from the opposite side of contact region into the colliding direction. Calculation time of deformation, interaction and total computation of one cycle are shown in Fig. 5. The horizontal axis indicates the number of component nodes of both objects A and B. The vertical axis indicates the calculation time (msec). Data processing machine is a general computer with dual Pentium III 933 MHz CPU, 1 GB main memory. It is cleared that total calculation time reaches to 4 msec, which is the limit for haptic loop, when the number of component nodes is approximately 200. On the other hand, it is possible to simulate collisions of two objects that have more than 200 nodes by omitting calculation for the region where the effect of deformation is trivial.

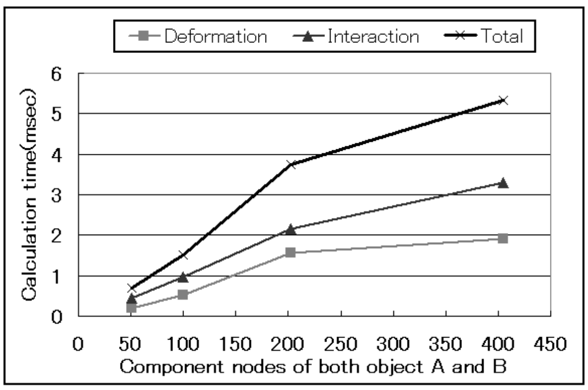


Figure 5. Calculation time of deformation, interaction and total computation

5.Evaluation of haptic display

5.1 Rectal Palpation Simulator

We developed a rectal palpation simulator as an example of indirect palpation and evaluated the proposed model using the simulator. In rectal palpation, medical doctors insert their index fingers into an anus and palpate prostate through rectal wall indirectly and make a diagnosis of prostate.

Figure 6 illustrates the structure of the system consisting graphic part, haptic part, and data processing part. The system consists of a general computer with dual Pentium III 933 MHz CPU, 1 GB main memory and a haptic device, PHANToM Premium 1.0A haptic device (SensAble Inc., Woburn, MA).

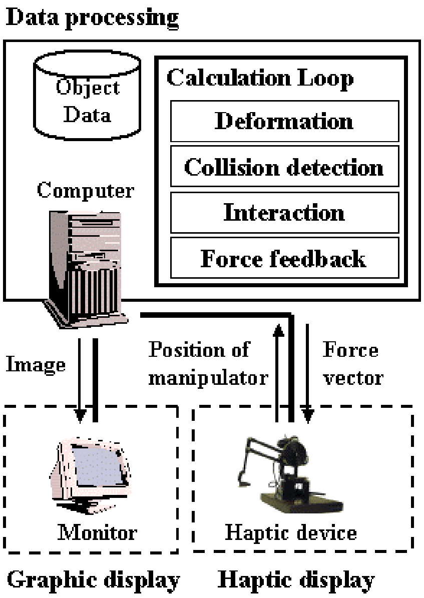


Figure 6. Structure of rectal palpation simulator

A rectum object is re-constructed from the RGB data of Visible Human Dataset [12]. On the other hand, a prostate object is piled cross-sectional image of prostate. The components of the objects are shown in Table 1. Free surface node means non-fixed node that is located on the surface.

Table 1. Components of objects

Model	Total nodes (Free surface nodes)	Tetrahedron
Rectum	282(207)	889
Prostate	360(110)	1312

As Poisson ratio, 0.40 is given to both objects. As Young modulus, 1.0 MPa is given to rectum object and 1.0 and 5.0 MPa are given to two types of prostate objects.

Calculation time of deformation, interaction and total computation in the rectal palpation simulator are 1.17, 1.62 and 2.88 msec respectively.

5.2 Evaluation of haptic display in indirect palpation

We conducted objective and subjective evaluation of haptic display in indirect palpation.

The experiment for objective evaluation verifies that stiffness of a neighboring object has effect on the value of reaction force. Figure 7 shows the view of simulation.

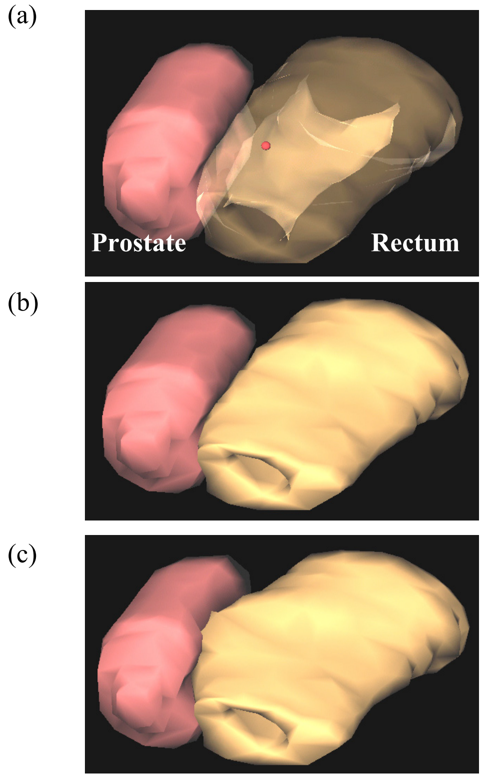


Figure 7. View of rectal palpation simulation. (a) Rectum object is displayed transparently and a manipulating point is located in initial position. (b) Initial position. (c) A manipulating point is pushing rectal wall towards prostate object and both objects are deformed.

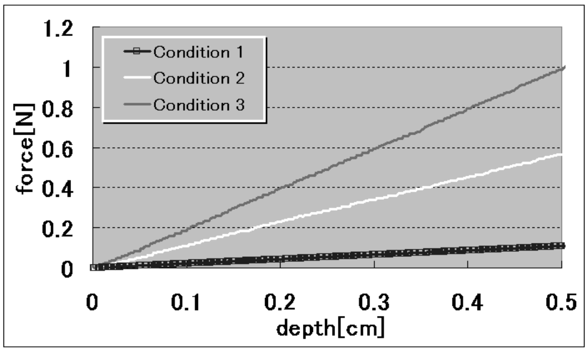
In the experiment, manipulating point is moving from the initial position towards prostate object until 0.5 cm depth and the value of reaction force on manipulating point is calculated. The simulation is carried out under the following three conditions of prostate.

Condition1: No prostate object is set.

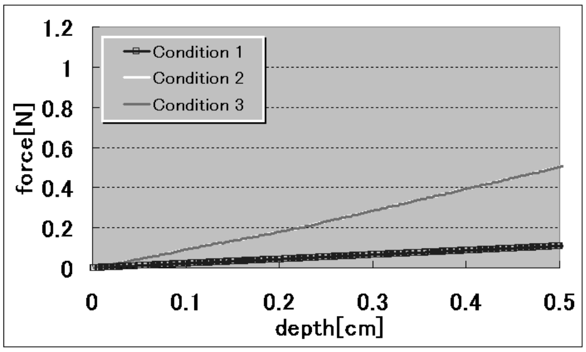
Condition2: Soft prostate object
(1.0 MPa young modulus) is set.

Condition3: Hard prostate object
(5.0 MPa young modulus) is set.

Soft and hard prostate objects are assumed as regular prostate and hardened one due to cancer. Figure 9 shows the value of haptic forces. The horizontal and vertical axes mean the depth (cm) of pushing the rectum object and the haptic force (N), respectively.



(a)



(b)

Figure 8. Reaction forces produced by (a) the proposed model (b) Sibille's model.

In Fig.8-a, the forces are different between condition 2 and 3 in the case of the proposed model. On the other hand, Fig.8-b shows that the forces of both cases have no difference, where forces of condition 2 and 3 are almost same. In consequence, the lines of forces are overlapped in Fig.8-b. It was founded that the proposed model produces the haptic force taking into account of the stiffness of a neighbouring prostate object.

The subjective experiment validates that the difference of stiffness of a neighbouring object is perceivable by human being. 15 examinees perform four tests, in which they touch prostate objects indirectly under condition 2 and 3. An examinee answers the condition, in which the examinee feels harder than in another condition. We compare both interaction models: the proposed model and the existing model by Sibille [7]. In order to avoid the influence of manipulating way and position of an examinee's hand, bottom of a dominant hand is fixed on a desk and a forefinger is moving in left or right direction.

Results of the experiment are shown in Fig. 9. Results were tested by pair test at $\alpha < 0.05$. The number of correct answer in the case of the proposed model was over critical value, 37, while the existing model resulted in under the critical value. Hence, the proposed interaction model enables a user to perceive difference of stiffness of a neighbouring object.

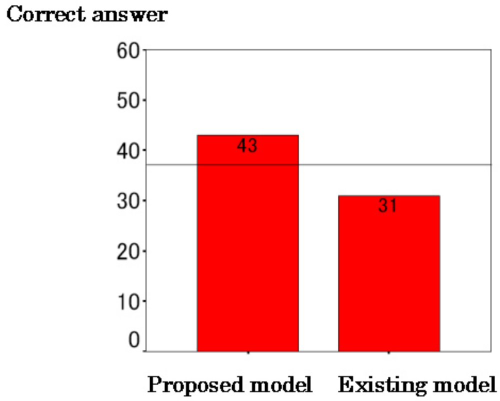


Figure 9. Results of subjective evaluation

5.4 Evaluation by a medical doctor

A paper reported that most cardiovascular surgeons memorize definitely the stiffness of normal and hardened aorta [13]. We assume that medical doctors in urology memorize definitely the feeling when pushing prostate as well as cardiovascular surgeons and we let a urological doctor evaluate the feeling that the simulator displays. As a result, the feeling when pushing prostate object is roughly similar to the real one. The doctor gave the other comment that improvement of the feeling when stroking rectal was possible. Since the comment is probably derived from low resolution of rectum object, development of methods enabling real-time simulation with high resoluted object is a subject in future.

6. Discussions

The proposed model produces accurate haptic display with handling interaction between elastic objects in real-time. It will be necessary to be able to handle larger size of objects in real time for realistic open surgery simulator. Simulation of slip between elastic objects is a future work by modelling horizontal interaction.

7. Conclusion

This paper proposed the interaction model between elastic objects to produce haptic force considering stiffness of a neighbouring organ for accurate haptic display. The proposed model gives displacement based on surface forces caused by temporary displacements to colliding elements. Interactive simulation with two 200-noded objects is possible on a current general PC. Subjective evaluation using rectal palpation simulator cleared that the proposed method could express differences of stiffness of an elastic object hidden another elastic object perceivably for haptic sensation of human being.

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