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Haptic display able to replicate the rheological behaviour of surgical tissues

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Abstract

Minimally invasive surgery exhibits many advantages, but still suffers from loss of the perception of rheological properties of manipulated tissues. This problem is tackled at first by realizing a sensorized surgical tool and visualizing on a monitor the compliance parameter of manipulated tissues, but the only visual feedback was however not completely satisfactory. Afterwards, we realized a tactile display returning the kinesthetic (force-position) sensation of the stiffness and damping of manipulated tissues. Finally, here we discuss the behaviour of a haptic display where the tactile information is integrated with kinesthetic sensation. The haptic display is associated with a sensory system specially designed, but here we also propose the solution of using the already sensorized laparoscopic forceps, by processing the acquired signals applying the Hertz theory.

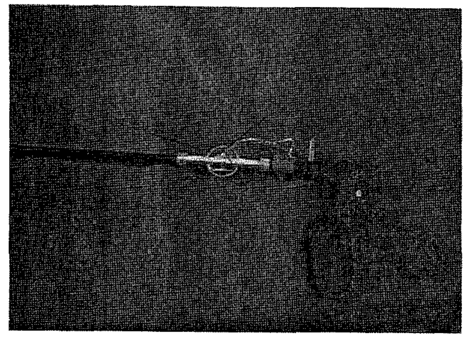

Figure 1: Sensorized surgical tool.

1 Introduction

Minimally invasive surgery is an innovative technique developed to reduce the traumatic effect of some surgical operation on the patient. It requires the introduction in the patient abdomen of some surgical elongated tools via small incisions. In recent years many surgeons undertook this technique promoting its rapid increase [1]. In effect, this technique minimizes trauma to surrounding tissues reducing risks, costs, and recovery time. [2]. The price of these advantages is the surgeon loss of both tactile and kinesthetic sensibility due to the trasmission mechanism of the elongated tools. In addition, there is no a direct vision to the working area, but the abdominal environment is visualized on a monitor and it produces a lack of visual workspace reference frames, getting worse the touch feeling. This restricts the application of this technique only to some specific fields. These effects are so important that it can be very difficult to discriminate the anatomical nature of the manipulated tissue [3]. This is true, in particular, if the camera images are partially occluded. In such cases, losses on perception may cause important lesions.

2 Haptic sensation

The human method to discriminate the softness of an object with the hand is to sqeeze or indent it with the fingerpads. The force exerted on the object causes local deformation in the contact region, as well as on the fingerpad, directly depending on the compliance of the manipulated object. The object-finger interaction provides two kinds of information: tactile information, referring to distributed skin sensation of a surface deformation perceived by mechanoreceptors innervating the fingerpad and kineshetic information, referring to kinematics parameters of limbs, position and motion, mediated by a sensory receptor in the skin, joints, and muscles.

The matching of these information convey the haptic sensation enabling the softness discrimination. The tactile perception always occurs within the context of a particular static posture and depends upon what that posture

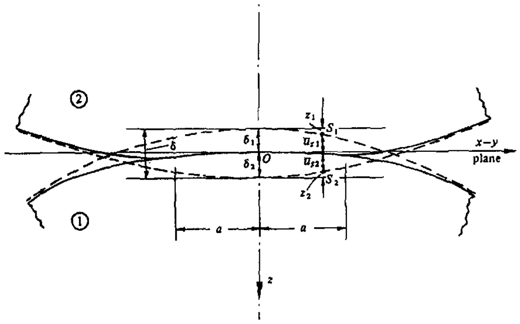

Figure 2: Behaviour in the region of contact of two bodies.

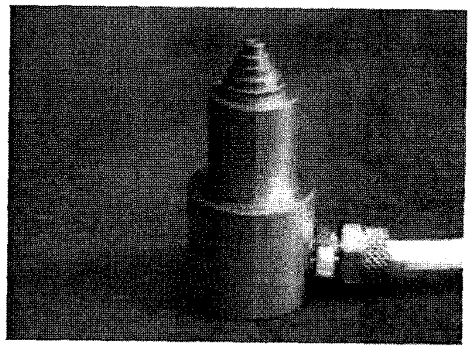

Figure 3: The physical setup of the haptic display.

is; if the posture remains constant the variations in stimulation that control tactile perception are solely cutaneos. The kinesthetic perception, such as documented in literature by several experiments where cutaneos sensibility has been completely eliminated by anesthesia, convey spatial information on the basis of resistance to limb movement alone. To realize artificially recognizing function of softness similar to human hand above-described, the kinesthetic (force-position) sensing alone is insufficient, but is necessary to include tactile feedback.

3 Previous work

We planned our work trying to replicate at first the kinesthetic sensation and then we added the tactile information. A first approach to problem was a realization of a sensory system applied to passive laparoscopic forceps able to realize real time data acquisition and analysis [4]. To measure the applied force and the position of the jaws, we employed strain gauges and an optical position sensor device (see Figure 1). Afterwards we interfaced the sensorized laparoscopic tool with an actuator, designed to provide the surgeon with a kinesthetic sensation of the compliance of manipulated tissues[5]. Although the performances of the kinesthetic display are good and the experimental results encouraging, according to the work of Srinivasan and LaMotte[6], both tactile and kinesthetic information are necessary for discriminating the softness of materials. Motivated by this we designed a sensory and actuatory system able to replicate a haptic sensation.

4 Display system

Aware of difficulties to realize a matrix system we concentrated our efforts to realize a single element sensor and actuator. Our design was inspired by the mechanism of tactile perception, where the human finger exerting an increasing force on manipulated objects, the contact area between the object and the fingerpad grows in size in relation to compliance of the object. Our goal was to replicate this behaviour designing and realizing a display, associated with a suitable sensory system, able to provide it.

4.1 Sensory system

As our goal is to known how the size of contact area grows with increasing load we adopted optoelectronic technology in order to measure the contact area and we employed a load cell in order to evaluate the applied force. By using a data acquisition card we acquired in real time these signals and sent them to a PC where a graphic Force versus Area was shown. But for the sake of simplicity, we studied the possibility of using the sensorized laparoscopic forceps to make an indirect measure of Force versus Area. To make this we can resort to Hertz theory[7], but the following condition must be satisfied:

materials involved in contact mechanism must be homogeneous, isotropic, and elastic within range of experimental interest, and their dimensions must be significantly bigger than contact area.

Under this condition we can consider the simpler case of Hertz theory of solids of revolution. The contact area is circular, having a radius a and the equation describing the displacements of points of objects within the contact area is

$$\overline{u}_{z1} + \overline{u}_{z2} = \delta - \frac{r^2}{2R} \quad (1)$$

where $\delta = \delta_1 + \delta_2$ is the relative displacement of two bodies, $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$ is the relative curvature, r is the radial distance from the center of contact ($r \leq a$) (see Figure 2). A distribution of pressure on the contact area proposed by Hertz is

$$p(r) = p_0 \left[1 - \left(\frac{r}{a}\right)^2\right]^{\frac{1}{2}} \quad (2)$$

and the relative deflection within the loaded area is

$$\overline{u}_z = \frac{1-\nu^2}{E}\frac{\pi p_0}{4a}(2a^2 - r^2); r \leq a \quad (3)$$

By substituting the expressions for $\overline{u}_{z_1}$ and $\overline{u}_{z_2}$ into equation 1 we get

$$\frac{\pi p_0}{4aE^\star}(2a^2 - r^2) = \delta - \frac{r^2}{2R} \tag{4}$$

where $\frac{1}{E^\star} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$ and in general is nonlinear. From Eq. 4 we can obtain the radius of the contact circle

$$a = \frac{\pi p_0 R}{2E^\star} \tag{5}$$

and the mutual approach of distant points in the two solids is given by

$$\delta = \frac{\pi a p_0}{2E^\star}.$$

The total force compressing the bodies is related to the pressure by

$$F = \int_0^a p(r) 2\pi r dr = \frac{2}{3} p_0 \pi a^2 \tag{6}$$

Using equation 5 in 6 we can relate the radius to force F

$$a = \left(\frac{3FR}{4E^\star}\right)^{\frac{1}{3}}$$

from which the area is obtained as

$$A = \pi a^2 = \pi \left(\frac{3FR}{4E^\star}\right)^{\frac{2}{3}}. \tag{7}$$

If one body is rigid then

$$R_2 \to \infty \qquad E_2 \to \infty$$
$$\frac{1}{R} = \frac{1}{R_1} \qquad \frac{1}{E^\star} = \frac{1-\nu_1^2}{E_1}$$

and all expressions are simplified. By means the sensorized forceps we can acquire the force exerted on manipulated materials and the deformation inducted; so we can evaluate the stress-strain relationship, from which we can calculate the Young's modulus that generally has nonlinear behaviour and by substituting it into equation 7, the curve F versus Area is easily derived.

4.2 Haptic display

The display is comprised of a linear concentric cylinders able to run one inside the other, like a telescope (see Figure 3). By lowering the central cylinder, having an area A_0 down to Δh the finger of the user encounters a surface $A_1 = A_0 \Delta A$; and by pushing down again, after Δh the finger interacts with a surface increased $A_2 = A_1 \Delta A$ and so on. If we impose a constant pressure p_0, the display opposes to user's finger a force $F_0 = p_0 A_0$ at first step and $F_i = p_0 A_i$ at next steps. In Figure 4 you can see the characterization of the display experimentally identified. So by controlling the pressure with a pneumatic servo valve we can replicate the behaviour Force versus Area of manipulated tissues evaluated early.

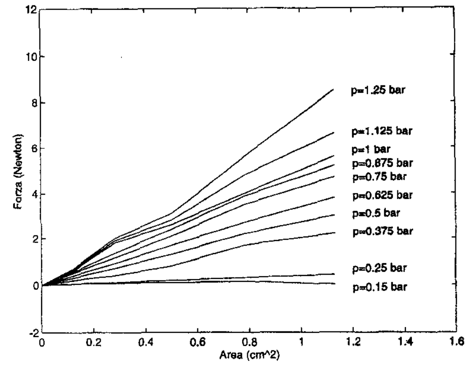

Figure 4: Characterization of the haptic display.

4.3 Experimental results

Before of using the indirect method to evaluate the behaviour Force versus Area by means the sensorized laparoscopic forceps we validated this approach to problem. We chose several specimens of material and we observed how the size of contact area grows with increasing load using the area sensor and the load cell. We acquired these signals and sent them to a PC where a graphic Force versus Area is shown. Then we manipulated same materials with sensorized laparoscopic forceps and we applied the Hertz theory. In Figure 5 we show the graphic Force versus Area, for a given material, acquired by sensor area and load cell comparised with that one obtained with sensorized forceps and using the Hertz theory. So we controlled the display by supplying a suitable pressure in order to replicate the behaviour Force versus Area. Several psychophysical tests are realized to assess the performances of display and validate its capacity to provide both tactile and kinesthetic information, i.e. if the display can be denoted as haptic display. At present the tests are only qualitative, but in next developments a suitable psychophysical theory will be studied in order to support quantitatively this method.

5 Conclusions

We described some preliminary work on the construction, identification and control of a display for replicating the rheological properties of materials for application to minimally invasive surgery. Although our results are encouraging, much work has to be done in order to extend the range of materials to be tested. Also, the haptic display will be sensorized and controlled in closed loop and the physical size of the display will be miniaturized in order to be integrated with the sensorized laparascopic forceps. Finally, a psychophysical theory will be studied to support

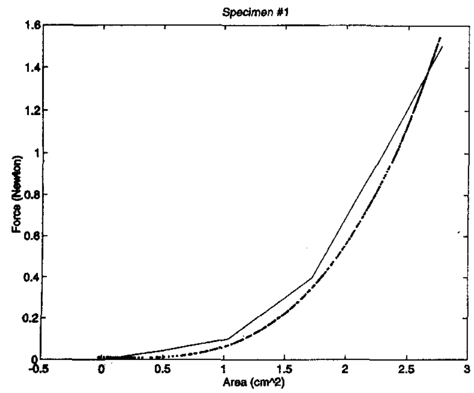

Figure 5: Force versus Area obtained by measuring directly with an area sensor and load cell (continuous curve) comparised with that one calculated using the sensorized surgical tool (dotted curve).

our qualitative tests with a quantitative method.

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