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Force Control for Grasping Soft Tissue

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***Abstract* – Tissue grasping is a crucial component of surgical procedures that involves simultaneously satisfying two competing criteria – maintaining grasp stability while avoiding damage due to excessive grip force. Automation of grasp force control thus requires a controller to apply grasping forces just sufficient to maintain grasp stability. This task is complicated by the serially connected dynamics of grasp friction and tissue relaxation. This paper presents a preliminary experimental investigation of a simple model-independent approach to grasp control based on (i) measurement of total tangential grasp force and (ii) discrimination of relaxation and friction forces by imposing a limited basis set of grasper motions.** †

Index Terms – grasping; soft tissue; robotics; surgery

I. Introduction

Grasping in surgical procedures makes possible such standard manipulation tasks as stabilizing, separating, moving, and suturing tissue. The grasping task itself consists of imparting specified displacements to particular regions of tissue. If the tissue slips in the grasper during crucial parts of a surgical task, substantial damage can occur. To avoid this, novice surgeons sometimes employ a "death grip," resulting in unnecessary damage to the tissue being grasped. With experience, surgeons learn to employ smaller grasp forces using tactile and visual cues to control grasping forces.

The tissue grasp force control problem can be defined as one of applying the minimum grasp force to resist external forces on the grasped tissue, such as from tissue elasticity, physiologic motion, and other manipulations proximal to the grasp location.

Fig. 1 shows an idealized schematic of a grasp in which the tissue is modelled as viscoelastic using the Voight-Kelvin model [1]. The grasper applies both a compression force (grasping force) and a lateral displacement x to a small area of grasped tissue. The free tissue generates an external force on the grasped tissue in response to the grasper displacement and rigid boundary condition.

As the grasper applies a grasp force, an area of contact develops between the grasped tissue and the grasping fingers. Since the contact pressure between arbitrarily shaped objects is generally unevenly distributed, shear slip will not occur evenly over the surface, but rather will propagate from regions of lower to pressure to those of higher pressure until the entire interface is slipping. This process is known as incipient slip [2].

For tissue manipulation, a grasp can be defined as stable if, given an infinitesimal displacement of the grasper, δx, there exists a region of zero slip in the contact area between the grasped tissue and the grasping fingers.

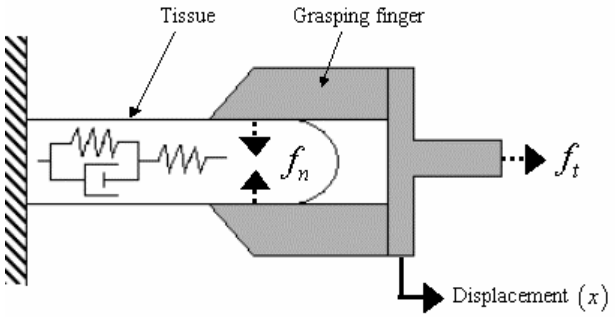

Fig. 1. Pinch grasp of tissue flap.

In this context, grasp force control involves applying the minimum force to maintain grasp stability and so calls for operating near or within the regime of incipient slip.

II. Related Work

Tissue grasping and grasping instrument design have been addressed in several prior studies. A number of innovative grasping instruments have been reported. Notable among them are those that provide haptic feedback of grasping force [3] and those that include tactile sensors to measure force distributions on the grasping fingers [4].

Grasp stability has also been well studied. However, few papers consider stability with deformable objects. A system identification and grasp control law for manipulating deformable objects with deformable fingers based on a lumped-element model is presented in [5]. In addition, computer-learning methods for stably lifting deformable objects with unknown properties are presented in [6].

Finally, a number of investigators have also considered grasp force control in the regime of incipient slip. Two methods of detecting incipient slip exist. The first is through measurement of the integrated forces over the contact area and the second is through measurement of the distribution of force in the contact area. In the first case, an accelerometer embedded in a deformable finger pad is used to detect incipient slip [7]. It shows that slip can be both detected via integrated forces and avoided via model independent controllers. In the second case, direct vision through a transparent finger is used to detect areas of slip within the contact region [8]. Although these specific examples are not applicable to grasping of soft tissue, because surgical grasper fingers are rigid and small, they do suggest that soft tissue grasp controllers can be designed based on monitoring of incipient slip.

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III. Minimum Force Grasping

To avoid the complexity of distributed sensing within the grasp contact area, this paper investigates the feasibility of detecting incipient slip in a grasp of soft tissue using integrated tangential force.

The incipient slip regime represents the transition between the tangential grasp stiffness being dominated by tissue deformation forces to being dominated by grasper-tissue friction forces. Fig. 2 depicts this transition for the case of steadily increasing tangential displacement. Since the tangential friction forces, f_t, decrease during slip, incipient slip is characterized by a decreasing tangential stiffness,

$$d^2 f_t / dx^2 < 0. \quad (1)$$

Assuming that friction force is independent of displacement during slip, tangential stiffness eventually goes to zero.

Using (1) as an indicator of incipient slip is complicated by three factors. First, maintaining a reasonable signal to noise ratio can be difficult when computing derivatives of force. Since stiffness during slip goes to zero, however, inequality (1) can be employed to detect incipient slip as long as tissue stiffness is measurably different than zero and the transition to slip does not occur too rapidly. Second, since tissue is viscoelastic it exhibits stress relaxation, in which its stiffness decreases to a steady-state value under constant load. For arbitrary grasper and tissue motions, relaxation can occur concurrently with incipient slip. Models of tissue viscoelastic and friction properties along with their parameter values would likely allow the two effects to be differentiated. These models, however, are currently unavailable. A third complication can arise from variations in external forces that dominate independent of grasper motion.

This paper presents a preliminary experimental investigation addressing the following two questions:

1. Can change in stiffness be sensed adequately to be used as a detector of incipient slip, and
2. Can a grasper motion basis set be used as a model-independent means to disambiguate tissue relaxation and incipient slip?

It is assumed here that external force variations do not dominate (1). The remainder of the paper describes the experiments and results. Conclusions and future directions are described in the final section of the paper.

IV. Experiments

The experimental apparatus of Fig. 3 was designed to simulate the grasp shown in Fig. 1 with two simplifications. First, the grasping fingers are replaced with smooth, 5 mm diameter cylindrical contact surfaces to emphasize friction forces and avoid pressure concentrations. Second, the apparatus is designed such that contact forces are measured only on one side of a particular piece of tissue, since opposing sides often have different properties.

The apparatus consists of a flat plastic tissue fixation frame mounted on top of a 6-axis force/torque transducer sampling at 1kHz. The force torque transducer is mounted on a crossed roller bearing slide, which is actuated by a ball screw linear actuator under PD control. The linear actuator includes an optical encoder providing linear position measurement at 3 μm resolution. The tissue is held on the fixation frame by two parallel rows of pins 15 mm apart and is free to move between them.

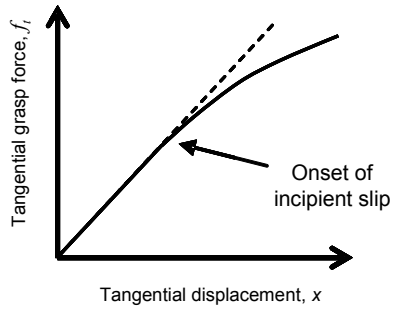

Fig. 2. Transition from tissue model to friction model.

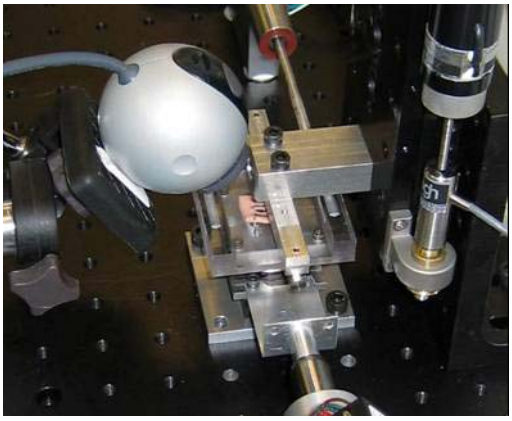

Fig. 3. Experimental apparatus

In forming a grasp, a smooth cylindrical indenter is pressed into the tissue, parallel to the axis of displacement, between the two rows of pins. The indenter extends beyond the edges of the tissue so that when slip occurs, the contact geometry remains constant. A motorized micrometer and a piezoelectric stack actuator are used in series to apply force to the indenter. The piezoelectric stack is controlled at 1kHz with proportional and derivative gains based on the grasp force error.

Tissue displacement is estimated with a camera mounted at approximately 45° from horizontal, running at 10-30 fps. Tissue deformation in the contact area is estimated by comparing the displacement of points at the edge of the contact region to the displacement of the tissue fixation slide.

A. Experiment 1 – Characterization of incipient slip

The first experiment studied the transition of the grasp from stability to instability. Tests were performed on excised samples of porcine aorta wall. All samples were preserved in a bath of modified Krebs-Henseleit solution.

In each test, the tissue was first cleaned of its loose adventitial layer, cut to a width of 10 – 12 mm, and mounted on the tissue fixation frame with the intima facing upwards. A specified load was then applied to the sample by the indenter and held constant throughout the test. After 5

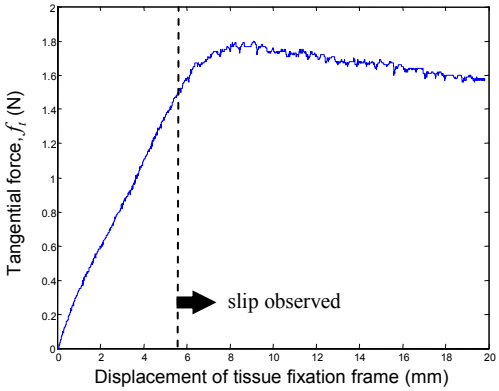

Fig. 4. Tangential force vs. displacement.

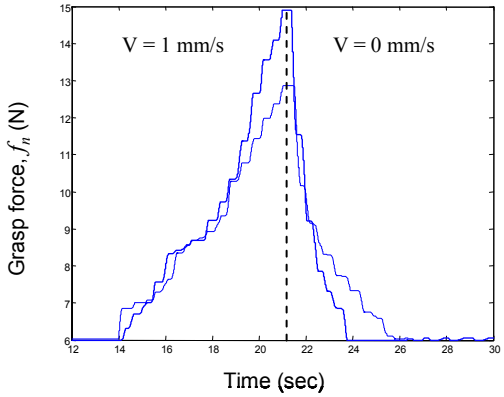

Fig. 5. Commanded compression force vs. time.

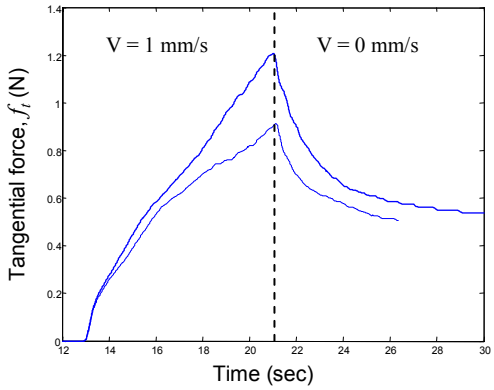

Fig. 6. Tangential force vs. time.

seconds of compression with zero displacement, the frame was displaced at a specified constant velocity over a distance of 20 mm.

Fig. 4 shows a representative plot of shear force versus displacement of the tissue fixture frame. Compression force was 12 N and grasper velocity was 1 mm/s. Tissue stiffness is approximately 0.25 N/mm and incipient slip evolves between ~6 mm and ~8 mm with a substantial number of data points recorded at the 1 kHz sampling rate. Tissue slip was confirmed via image measurement. This suggests that grasp force control based on change in stiffness may be possible, at least for the conditions tested.

B. Experiment 2 - Grasp force control

A simple approach to disambiguating tissue relaxation and incipient slip is to consider a basis set for grasper trajectories consisting of constant velocity segments of duration much longer than the time constant of the tissue's stress relaxation as well as zero velocity segments. For constant velocity segments, tangential stiffness evolves to depend only on incipient slip. Since velocity is constant, (1) can be replaced by

$$d^2 f_t / dt^2 < 0 . \qquad (2)$$

Zero velocity segments following constant velocity segments experience tissue relaxation and in these situations, the grasp force can be reduced. A simple control law considering nonzero and zero velocity segments is given by

$$\frac{df_n}{dt} = \begin{cases} -kd^2 f_t / dt^2, & \operatorname{sgn}\left(\frac{d^2 f_t}{dt^2}\right) = -\operatorname{sgn}\left(\frac{df_t}{dt}\right) \\ 0, & otherwise \end{cases} . \qquad (3)$$

Tests of this control law were performed on unpreserved porcine aorta wall. In each test, a minimum load of 6 N was applied to the sample by the indenter. After 7 seconds of compression, the force controller was turned on and the frame was first displaced at 1 mm/s over a distance of 8 mm and then held at 8 mm for 5-10 seconds.

Results for controller gains of 6 and 8 are depicted in Figs. 5-6 showing the controller first increasing grasp force to prevent slip and then decreasing grasp force during zero-velocity tissue relaxation. Note that some slip can be seen for both trials in Fig. 6.

V. Conclusion

This paper investigates the control of tissue grasp force using changes in shear force as an indicator of incipient slip. Preliminary experiments suggest that under some conditions this approach may prove practical. Furthermore, the concept of a grasper trajectory basis set was proposed as a means of distinguishing tissue relaxation and incipient slip.

Current work includes modeling and parameter estimation of both tissue relaxation and grasper-tissue friction as a means to formally address the questions posed by the paper.

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