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Trajectory Generation for Robotic Needle Insertion in Soft Tissue

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Abstract—**Accurate needle insertion in soft, inhomogeneous tissue has been a major concern in several recent studies involving robot-assisted percutaneous therapies. In procedures that involve multiple needle insertions such as transrectal ultrasound guided prostate brachytherapy, it is important to reduce tissue deformation before puncture and during insertion. In order to reduce this deformation, we have studied the effect of different trajectories for a 2-DOF robot performing needle insertion in soft tissue. We have compared tissue deformation and infinitesimal force per tissue displacement for different trajectories. According to the results of our experiments, infinitesimal force per displacement is a useful parameter for online trajectory update. Our proposed position/force controller is shown to provide considerable improvement in performance with regard to tissue deformation before puncture.**

Keywords— **Tissue indentation, Robotic needle insertion, Force, Prostate brachytherapy**

I. Introduction

Accurate needle insertion in soft, inhomogeneous tissue and less tissue deformation during needle insertion have been of practical interest in recent studies because of their importance in percutaneous ("through the skin") local therapies. We are studying this effect in procedures that require initial setup of the imaging system such as transrectal ultrasound (TRUS) guided prostate brachytherapy (see Fig 1). In such procedures, less tissue deformation (movement) before puncture and during needle insertion results in less movement of the prostate and therefore requires less frequent re-setting of the TRUS probe to provide good imaging of the area.

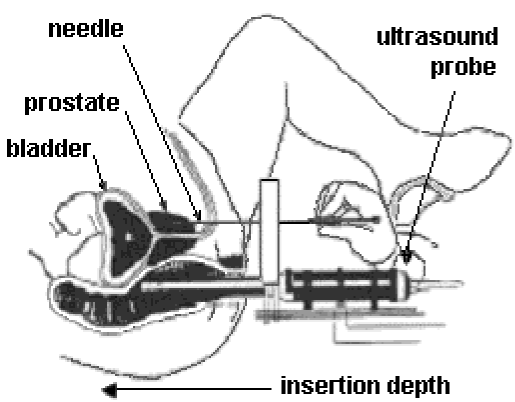

Fig. 1. Prior to needle insertion, the ultrasound probe is inserted into the rectum and locked in position [1,2].

During the needle insertion procedure, the needle exerts force on the tissue at the needle tip, which results in tissue being displaced and eventually punctured [3]. An additional force at the needle tip is required when puncturing tissues with greater stiffness such as skin [1,4,5]. Therefore it is required to adjust the force at the needle tip during robotic needle insertion according to the stiffness of each tissue layer, which also varies from patient to patient. Several studies have been carried out by researchers to learn about the relation between forces at the needle tip and tissue deformation. Kataoka et al. [6] use a physical quantity called infinitesimal force per unit length in order to find the relation between tissue deformation and needle deflection. They adopt this quantity instead of traction because of the long thin shape of the needle. DiMaio experimented insertions at constant velocity and found a relationship between insertion velocity and shaft force "density" (force per unit length behind the force peak at the needle tip) during penetration in a phantom made of PVC [7,8]. In this paper we study different types of needle motions and their effects on the tissue indentation prior to puncture. We compare the magnitudes of the infinitesimal force per tissue displacement prior to puncture and tissue indentation associated with different types of motions (different trajectories). We also use the results to generate trajectories for translational motion of the robot as well as updating those trajectories online.

II. Methodology

A test-bed was set up in our laboratory for studying needle insertion in soft tissue (see Fig. 2). This provides needle motion with two degrees of freedom (DOF) – translation in one (horizontal) direction and rotation about the translational axis. The needle insertion was performed using the translational motion. In the test-bed, the speed and force of insertion can be controlled as well as the speed and rotational direction of the needle. A 6-DOF force/torque sensor is attached to the needle holder in order to measure the forces and torques acting on the needle. A multi-threaded application for trajectory generation, position/force control, and data acquisition has been written using Visual C++. The application is written such that force readings are obtained at the rate of 1 KHz, and the control thread uses a servo rate of 25Hz. The application interface allows defining a trajectory by selecting its type to be constant velocity, constant acceleration or variable acceleration. It also allows

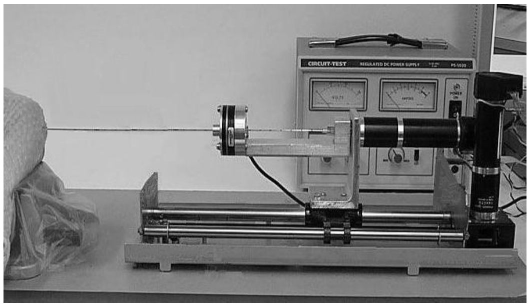

Fig. 2. Needle insertion setup

us to specify the final needle position, the needle velocity and acceleration for both degrees of freedom [9].

Experiments were carried out using several multi-layer phantoms. In our experiments, the needle was moved toward the tissue until the force sensor gave a non-zero force reading in the insertion direction. This denotes the point where the needle touches the tissue. Then a desired trajectory according to the user's settings for translational and rotational motions was generated and the needle motion was controlled to track the trajectory. A proportional-integral-derivative (PID) control scheme was used to track the specified trajectories during needle insertion.

Fig. 3 shows how the tissue indentation was measured. The zero position in Fig. 3 denotes the skin contact position and the force peaks are when the skin puncture occurs. Since we are measuring the position from the time that the needle touches the skin, the position of the tissue puncture is the amount of indentation of the tissue.

Also it should be mentioned that we adopted $K_e = \lim_{\Delta x \to 0} (\Delta f / \Delta x)$ to be the infinitesimal tissue force per tissue displacement in the insertion direction before puncture. In a simple mass-spring model of tissue, K_e is actually considered to be tissue stiffness. Due to the polynomial stiffness model of skin tissue, this quantity is not a constant [10]. It reaches its maximum at the point of puncture. This physical quantity was used in the trajectory update method.

III. Results

Experiments were carried out on two-layer phantoms of turkey tissue with its skin intact. The visco-elasticity properties of this tissue made it better suited for our experiments than artificial phantoms such as silicon materials. In our experiments, we used an 18Ga needle with a beveled tip.

Needle insertion data was logged for about 25 insertions for each type of motion. Each insertion was done at a new location of the phantom in order to avoid the artifact caused by the holes created during previous insertions. However, each set of insertions was made in a close neighborhood to have consistent tissue behavior for the set.

During the experiments, we noted that the orientation of the beveled edge of the needle had an effect on the amount of bending in the needle. Therefore for uniformity, we did all our experiments with the same upward orientation of the needle bevel at the skin contact point.

Different types of insertion are categorized below:

A. Trajectory with Constant Velocity (no rotation)

Trajectories with constant velocity for translational motion with no rotational motion were generated. Translational velocities varied form 1 mm/s to 20 mm/s. The result for this method showed that increase of velocity reduces tissue indentation but there was not a dramatic difference in the amount of tissue indentation among high translational velocities. Table I summarizes the results of tissue indentation for needle insertions with different translational velocities. We considered translational velocity of 10 mm/s without rotation as the standard for comparing other types of trajectories.

B. Trajectory with Acceleration (no rotation)

Trajectories with constant acceleration for translational motion with no rotational motion were generated. We used the following accelerations: 3 mm/s^2, 7 mm/s^2, and 10 mm/s^2. All trajectories had zero initial velocity. The result for this method had no consistency. It also did not show any consistent improvement over the standard trajectory (i.e. constant velocity of 10 mm/s).

Also a quintic polynomial trajectory (i.e. variable acceleration) for translational motion with no rotational motion was generated. The coefficients for the quintic polynomial were set such that it would not saturate the input voltage and the maximum velocity did not exceed 23 mm/s.

The result for this method also had no consistency. It also did not show any consistent improvement over the standard trajectory (i.e. constant velocity of 10 mm/s).

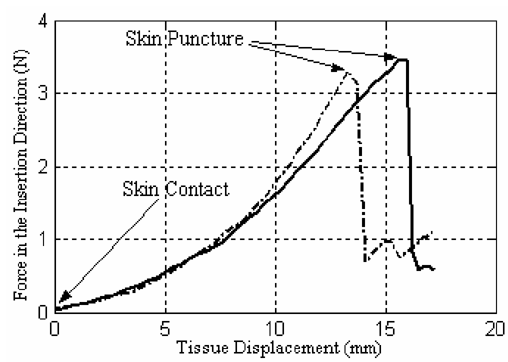

Fig. 3 Tissue indentation measurement
solid line: insertion with constant velocity of 1 mm/s,
dashed line: insertion with constant velocity of 15 mm/s

TABLE I
SUMMARY OF THE EXPERIMENTAL RESULTS FOR THE EFFECT OF DIFFERENT TRANSLATIONAL VELOCITIES ON TISSUE INDENATION

Velocity (mm/s)	Avg. Tissue Indentation (mm)	Standard Deviation
1	15.7971	1.89
5	13.2743	1.89
10	12.4414	1.87
15	13.0271	1.64
20	13.3100	1.76

C. Trajectory with Constant Velocity (with rotation)

Trajectories with constant velocity for rotational motion were generated while 10 mm/s constant velocity for translational motion was maintained. Rotational velocities varied form 1 rpm to 25 rpm. The result for this method showed that having rotational motion for the needle during insertion definitely reduces tissue indentation and the required force for puncture in the insertion direction. However, it was found that the speed of rotation did not have much effect on these values. The results showed that high-speed rotations such as 15 rpm and higher did not reduce the indentation any more than 5 rpm. The same was found with velocities below 3 rpm. The best domain was found to be 3 to 7 rpm. The effects of different methods of rotational motions can be found in [11].

D. Trajectory with online update

In order to find the desired value of the infinitesimal force per tissue displacement to be used in our trajectory update routine, we made several insertions. We noted that in each insertion, K_e increases until it reaches the value needed to puncture the skin (see Fig. 4). The faster that value of K_e was reached during insertion, the less was the tissue indentation. The K_e value is different for different tissue types because of the difference in the mechanical properties of the tissues. The small changes in the value of K_e at the point of puncture in our phantom were due to the inhomogeneity of the tissue layers behind the skin and the skin itself. The average infinitesimal force per tissue displacement at the point of tissue puncture for our phantom was found to be 0.4 N/mm with standard deviation of 0.13. In the trajectory update approach, we chose a constant desired K_e, which was the average infinitesimal force per tissue displacement at the point of puncture obtained from the first insertion. Then in subsequent insertions, we increased the velocity of our translational motion in order to achieve the desired K_e faster.

To elaborate on this approach, the first insertion with the standard trajectory was made in order to find the desired value of K_e. From the position/force data logged during this

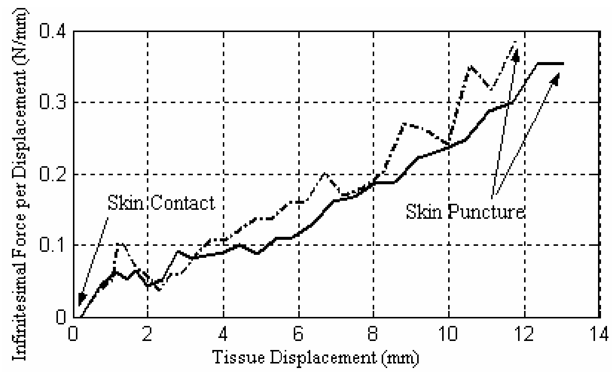

Fig. 4. Infinitesimal force per tissue displacement prior to puncture solid line: insertion with constant velocity of 10 mm/s, dashed line: insertion with constant velocity of 15 mm/s

insertion, the desired value of K_e was calculated using

$$K_e = \frac{\sum_{j=i-n+1}^{i} \left(\frac{f_j - f_{j-1}}{x_j - x_{j-1}} \right)}{n} \quad (1)$$

where f_j and x_j are the amount of force in the insertion direction and tissue indentation respectively at the j^{th} time step, i is the time step of the force peak (tissue puncture), and n is the number of time steps prior to puncture to be used for finding the average of K_e.

Thereafter, in each insertion, initially a trajectory with constant velocity of 10 mm/s for translational motion was generated. During the insertion in every time step, the controller determined the error between the infinitesimal force per tissue displacement and its desired value. This error increased the velocity of the translational trajectory with a gain factor and continued to track the new trajectory. Each insertion was continued until a sharp drop was found in the amount of force in the insertion direction. The insertion was then stopped since we only wanted to measure the tissue indentation.

Twenty sets of experiments were carried out on turkey phantoms. In each set, we made one insertion with the standard trajectory (i.e. constant velocity of 10 mm/s) and 3 insertions using the trajectory update method. The results of all the experiments were consistent and showed less tissue indentation for the trajectory update method than for the standard trajectory. We also used this method incorporating rotational motion with a constant rotational velocity of 5 rpm. The results of our experiments are summarized in Table II.

IV. DISCUSSION

This research was carried out to develop a scheme for trajectory generation for needle insertion in soft tissue,

TABLE II
COMPARISON BETWEEN THREE DIFFERENT TRAJECTORIES

Trajectory Type	Avg. Tissue Indentation (mm)	Standard Deviation	Improvement to the Standard
Standard	14.09	2.49	-
Online Update without Rotational Motion	12.14	1.87	12% to 19%
Online Update with Rotational Motion	11.97	0.45	14% to 20%

specifically for procedures that require several insertions and initial setup of the imaging system.

From the results of the online trajectory update method, we found that a linear increase in the velocity of translational motion occurs after 10mm/s initial velocity is reached (see Fig. 5). This increase of velocity during insertion represents acceleration in the motion due to an additional force exerted at the needle tip during insertion.

Comparing the results from all the different types of translational motions, we observed that the initial velocity and the amount of acceleration are important factors to be considered in trajectory generation for needle insertion in soft tissue.

V. CONCLUSION

Tissue indentation and forces during needle insertion in turkey tissue were measured. Different types of translational motion and rotational motion were compared. It was found that increasing the velocity of translational motion as well as having rotational motion during insertion reduces the amount of indentation. A trajectory update routine for translational motion was developed which updates the velocity of insertion online according to the desired value of infinitesimal force per tissue displacement. This routine was combined with rotational motion to yield a 2-DOF online trajectory generation scheme that gave the best results among all trajectories considered in this paper. This method is particularly suitable for situations where needle insertion is to be performed using a robotic system such as in robot-assisted prostate brachytherapy for which a system is currently under development in our laboratory.

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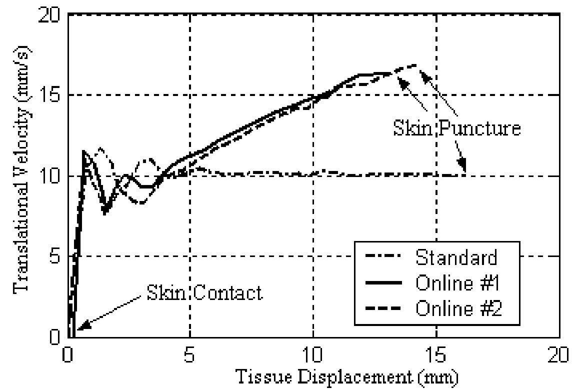

Fig. 5. Translational velocity in the standard trajectory and online trajectory update method

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