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Experimental study of robotic needle insertion in soft tissue

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Abstract. In the procedures that involve needle insertion such as 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 axial rotation of the needle during insertion. Different methods for rotational motion were compared and the results show that axial rotation can reduce frictional forces as well as tissue indentation before puncturing.

Keywords: Needle insertion; Robot; Force and torque; Friction; Tissue indentation

1. Introduction

Accurate needle insertion into soft, inhomogeneous tissue is of practical interest because of its importance in percutaneous ("through the skin") local therapies. We are investigating the problem of needle insertion in prostate brachytherapy. As is well-known, the effectiveness of the treatment depends on the accuracy with which the radioactive seeds can be placed. The major causes of inaccuracy in seed placement are tissue deformation and needle deflection during insertion and retraction procedures [1–4]. It is known that the magnitude of tissue deformation depends on the frictional forces between the needle shaft and the tissue [1,5–7]. In the present work, we have investigated the effect of various motions of a needle during insertion on reducing the frictional forces. We have also compared the magnitudes of the forces required for penetration and tissue indentation associated with different methods of needle rotation during insertion.

2. Methodology

A test-bed was set up in our laboratory for studying needle insertion in soft tissue (see Fig. 1). This provides needle motion with two degrees of freedom (DOF)—

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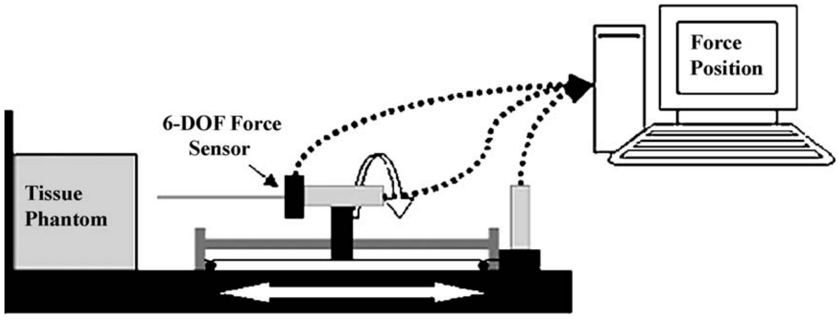

Fig. 1. Schematic diagram of the test-bed.

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 direction of 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 position/velocity control, 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 25 Hz.

Experiments were carried out using several multi-layer phantoms. For each constant velocity along the translational axis, we compared the effect of different rotational motions of the needle. The following were considered: no rotation, continuous rotation with different speeds, partial rotation in two alternating directions with different speeds and degrees, and needle rotation based on control of forces in the X–Y plane (Z-axis being the insertion direction).

In our experiments, the needle was moved toward the tissue until the force sensor gave a non-zero force reading in the Z (insertion) direction. This denotes the point where the needle touches the tissue. Then a desired trajectory with specified velocities for translational and rotational motions was generated and the needle motion was controlled to track the trajectory. The translational velocity was varied from 5 to 20 mm/s and the rotational velocity was varied from 1 to 15 rpm. A proportional-integral-derivative (PID) control scheme was used to maintain the specified velocities during needle insertion.

3. 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. We used an 18-gauge needle with a bevelled tip for our experiments.

Needle insertion data was logged for about 200 insertions. Each insertion was done at a new location of the phantom in order to avoid the holes created during previous insertions; however, each set of insertions was made in a close neighbourhood to have consistent

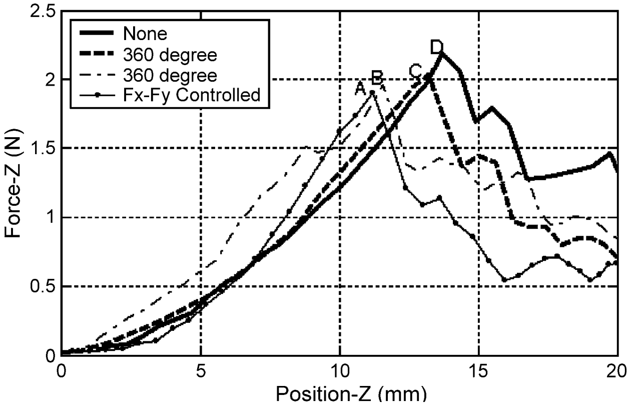

Fig. 2. Comparison of the effects of different rotational motions on tissue indentation (translation velocity for this experiment was set to 10 mm/s and rotation velocity was set to 3 rpm).

tissue behaviour for the set. We found that 10 and 15 mm/s translational velocities were good as the basis for later tests involving different rotational motions.

Each set of tests consisted of the following cases:

- no rotational motion;
- continuous rotational motion in one direction, e.g., rotating the needle with a speed of 3 rpm clockwise;
- 90° rotational motion in each direction about its nominal (zero) position;
- 30° rotational motion in each direction about its nominal (zero) position;
- 10° rotational motion in each direction about its nominal (zero) position;
- rotation with control on forces in the *X* and *Y* direction, e.g., keeping them as close to zero as possible.

The results for the rotational motions showed that they resulted in less tissue damage and indentation before penetration compared to the motions with no rotation. One set of results is shown in Fig. 2. The zero position in Fig. 2 denotes the skin contact position and A, B, C, and D are the points of which tissue punctures occur. Since we are measuring the position from the time that the needle touches the skin, the position of the tissue puncture

Table 1
Summary of the experimental results for the effect of different types of motion on tissue indentation

Type of motion	Average tissue indentation (mm)	Standard deviation
No rotation	16.1312	3.7568
360° Rotation	14.3478	2.3464
90° Rotation	13.6021	1.8051
30° Rotation	13.4545	1.1747
10° Rotation	12.9402	1.6337
Force controlled rotation	13.1634	1.5296

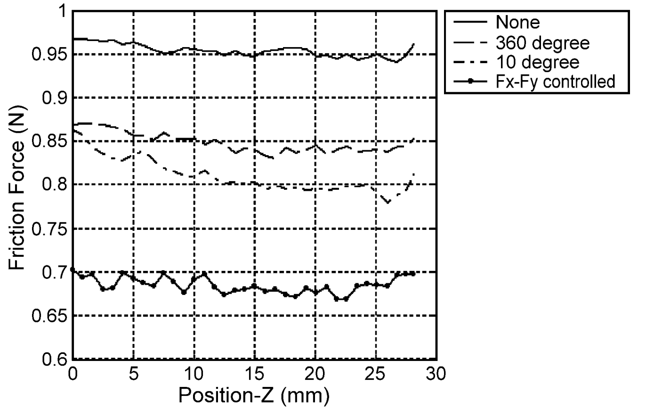

Fig. 3. Comparison of the effects of different rotational motions on friction (translation velocity for this experiment was set to 10 mm/s and rotation velocity was set to 3 rpm).

is the amount of indentation of the tissue. Table 1 summarizes the results for different types of insertions.

In order to measure frictional forces correctly, we moved the needle inside the tissue until the force in the *Z* direction dropped sharply. This was the moment that the tip of the needle came out of the tissue. The thickness of the tissue used for this test was about 4 cm. Then the needle was moved 3 cm more and the force in the *Z* direction was measured (see Fig. 3). With this experiment, the amount of force read by the force/torque sensor is only the friction along the needle shaft because there is no tissue cutting involved. Table 2 summarizes the results for different types of insertions and the corresponding frictional forces.

In general, controlling rotational motion with force control in the *X* and *Y* directions gave the best results in terms of less tissue damage, indentation and frictional forces. Also, the results of these experiments show that although continuous rotational motion of the needle reduces the frictional forces acting on the needle and therefore makes needle insertion easier, it causes more tissue damage and deformation as a result of defects in the shape of the needle, e.g., when the needle is not perfectly straight. This was noticeable by the increase of forces in the *XY* directions (see Fig. 4).

Table 2
Summary of the experimental results for the effect of different types of motions on friction

Type of motion	Average frictional force (N)	Standard deviation
No rotation	0.9693	0.0634
360° Rotation	0.8535	0.0335
90° Rotation	0.7481	0.0471
30° Rotation	0.8224	0.0330
10° Rotation	0.7938	0.0092
Force controlled rotation	0.6827	0.0313

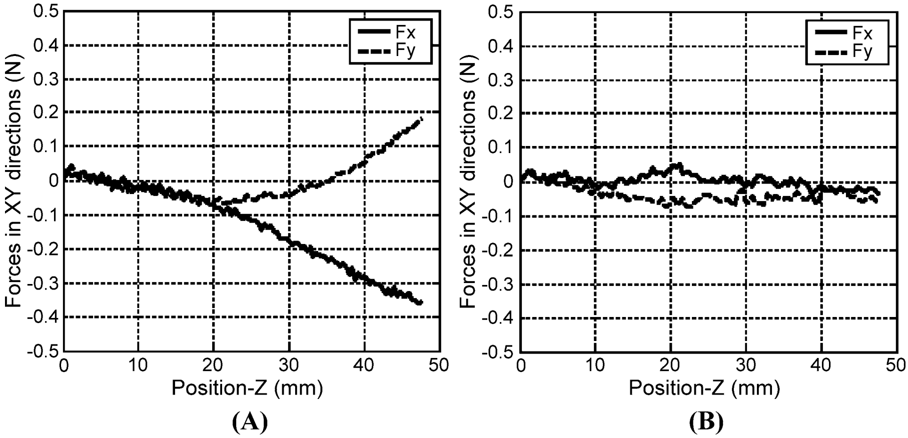

Fig. 4. Comparison of the magnitude of the forces in *XY* directions (A) 360° rotation (B) controlling Fx and Fy to be as close to zero as possible with |0.05| N deadband.

From an applications point of view, in prostate brachytherapy less tissue indentation and lower frictional forces during needle insertion are desirable as they result in less movement of the prostate and therefore require less frequent re-setting of the transrectal ultrasound probe to provide good imaging of the area. The results also show the effects of different translational velocities and needle bevel orientations on tissue deformation. During the experiments, we noted that the orientation of bevelled 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.

4. Concluding remarks

Forces and torques during needle insertion in turkey tissue were measured. The insertion forces did not exceed 3.5 N in all cases when the insertion rate was between 5 and 20 mm/s. Having rotational motion during insertion reduces frictional forces and tissue movement (shift). Therefore, rotational motion should be incorporated in needle insertion procedures such as in prostate brachytherapy. Among different rotational motions, it was found that the best approach was to control the rotational motion of the needle by keeping the forces orthogonal to the insertion direction as close to zero as possible. This is a particularly important result for situations where needle insertion is to be performed using a robotic system such as in robot-assisted prostate brachytherapy.

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