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Effects of Velocity Modulation during Surgical Needle Insertion

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Abstract– **Precise interstitial intervention is essential for many medical diagnostic and therapeutic procedures. But accurate insertion and placement of surgical needle in soft tissue is quite challenging. The understanding of the interaction between surgical needle and soft tissue is very important to develop new devices and systems to achieve better accuracy and to deliver quality treatment. In this paper we present the effects of velocity (linear, rotational, and oscillatory) modulation on needle force and target deflection. We have experimentally verified our hypothesis that needle insertion with continuous rotation reduces target movement and needle force significantly. We have observed little changes in force and target deflection in rotational oscillation (at least at lower frequency) of the needle.**

I. Introduction

Percutaneous intervention is an essential part of many medical diagnostic and therapeutic procedures including biopsy, brachytherapy, anesthesia, cryo-ablation, thermo-ablation, etc. Accurate needle insertion for these procedures is very important. But accurate steering and placement of surgical needles in soft tissues are challenging because of several reasons such as tissue heterogeneity, anisotropy, and elastic stiffness, unfavorable anatomic structures, needle bending, inadequate sensing, tissue/organ deformation and movement, and poor maneuverability. Therefore, understanding of the complex mechanism of needle interaction with soft tissue is an area of active research.

Several research groups have been working on needle force measurement, modeling of soft tissue and its interaction with needle [1-10]. However, most of the researchers agree that a complete model of the force experienced during needle insertion into soft tissues requires a combination of empirical and analytical modeling. They have emphasized on thorough testing and in-depth analysis, development of new testing and modeling methodologies, and multiple model (e.g. deformation, friction, and optimal speed) integration for better understanding and re-generating the complex *in vivo* soft tissue environment during various percutaneous interventions. Target movement due to organ deformation is critical in percutaneous procedures. Recently, a group of researchers have reported significant reduction of target movement using linear oscillations (at 2kHz & 20kHz) during needle insertion in soft material phantoms [10]. But compact system that can generate high linear oscillations and can be incorporated in different medical devices is not yet readily available.

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Therefore, here in the present work we have investigated alternative methods to reduce target deflection during needle insertion in soft materials or tissues. In this paper, we present efficacy of velocity modulation during surgical needle insertion in soft materials. We have verified our hypotheses of needle insertion force reduction and the target movement minimization by performing experiments with various insertion speeds along with needle oscillations (rotational) as well as full rotations. The experimental setup, material & method, and experimental results & discussions are presented in Section II, and Section III, respectively. We have made some concluding remarks and pointed out future research directions in the Section IV.

II. Experimental Setup

A. Experimental setup

We have designed and fabricated a 6 DOF (degree-of-freedom) robotic system for *in vitro* needle insertion experiments (Figure 1). All the motions of the robot are actuated by stepper motors. Two linear optical encoders which allow 10μm resolution are mounted on x, and y-axes. A rotary optical encoder with 5μm resolution is fitted on z-axis. The rotational positions about x-axis and y-axis are also monitored by optical encoders with 5μm resolutions.

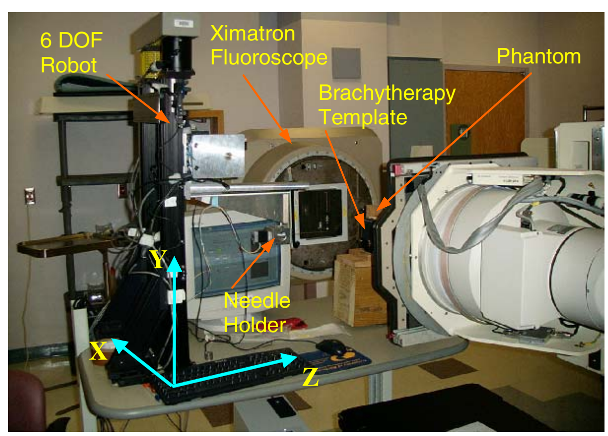

Fig. 1: The 6 DOF robotic system and the Ximatron® fluoroscopy machine.

A 6 DOF force/torque (F/T) sensor, (Nano25-SI-125-3® from ATI), is mounted aligning its z-axis parallel to the

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robot's z-axis. The robotic system is kinematically controlled; commands are sent using LabVIEW™ (version 7.1 from National Instruments). The software is executed on Windows XP in a Pentium® 4, 1.6GHz computer with graphical user interface (GUI), which we have developed. The fluoroscope used for our experiments is the Ximatron® C-series Radiotherapy Simulator, (manufactured by Varian Oncology Systems, Salt Lake City, UT) having a maximum field size of 40cmx40cm. The voltage and current settings for image acquisition during our experiment were 75kV at 4mA, respectively. Normal settings during actual patient film acquisition range from 60kV–129kV at 200mA, with a rate range of 20mAs–200mAs.

B. Material and method

We performed experiments with insertion/linear velocities at 5mm/s, 10mm/s, 50mm/s and 200mm/s; needle oscillations at 1Hz, 2.5Hz, and 5Hz; and needle rotations at 60rpm, 300rpm, and 600rpm. We used 18-gauge commonly used diamond tip prostate brachytherapy needle; the force/torque data were acquired using the 6 DOF F/T sensor; the needle travel was measured using motor encoders. We have used fluoroscopy (X-ray) to assess the target deflection in phantom at different speeds and modes of needle insertion. Soft material phantoms were prepared from polyvinylchloride (PVC) – a liquid plasticizer and a softener (Super Soft Liquid Plastic, from M-F Manufacturer, TX); all the phantoms were 7.5cm in diameter and 15.5cm in length with both ends open; needles were penetrated about 12cm into the phantoms. Two small pieces of a highly flexible radio-opaque wire of 0.2mm diameter were placed approximately at 1.5cm and 6.5cm in each of the phantoms (prior to solidification of PVC) for evaluating target movement using fluoroscopy. We measured the movements of the target wires relative to the cross-wire of the fluoroscopy and the reference wires fixed outside the phantom cylinder. Note that force/torque and target movement data (when needle was rotated) could not be collected simultaneously because of hardware limitations; the wirings of the F/T sensor would wrap around the rotating shaft. However, the experiments were done identically with same composition and time elapse of the phantom materials.

III. Result and Discussion

We have performed three sets of experiments with robotic needle insertion into PVC phantoms with different insertion/linear velocity (*Experiment 1*), oscillatory velocity (*Experiment 2*) and full rotational velocity (*Experiment 3*). In all the needle insertion and retraction experiments, we used trapezoidal velocity profile. Both the acceleration and deceleration for the needle motion were 508mm/s^2. The needle was retracted to the initial position following the trapezoidal velocity profile same as during penetration. The force-torque and position data were recorded at a sampling frequency of 100Hz. The F/T data is smoothed using a running average of 50 point-window.

A. Experiment 1: Effects of lineal velocity

In this experiment we investigate how the forces (axial and transverse), torques (about x, y, & z axes), and target movement varies when the insertion/linear speeds of the needle are changed. The main portion of the needle motion, i.e. the cruising velocity, was 5mm/s, 10mm/s, 50 mm/s, and 200mm/s.

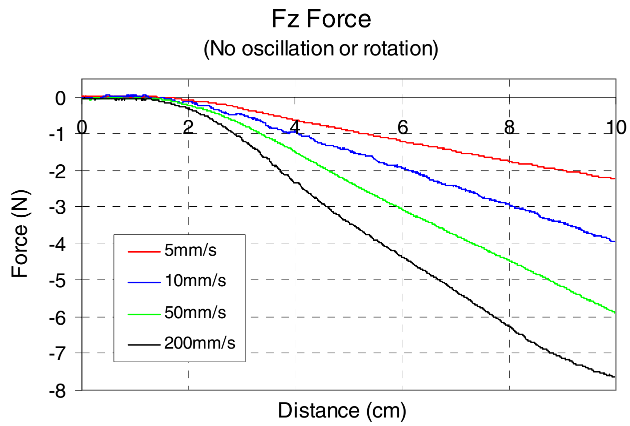

Fig. 2: F_z (main penetration) forces at different linear velocity without needle rotation or oscillation.

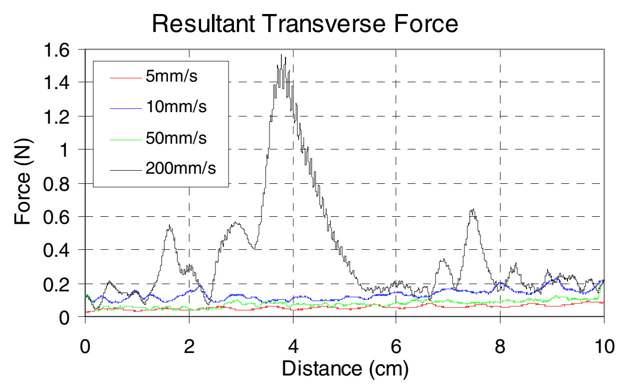

Fig. 3: F_{rt} (resultant transverse) forces at different linear velocity without needle rotation or oscillation.

The results from the experiments are presented in Figures 2-3 (forces), Table I (torques), and Figure 11 (target movement). From the plots in Figure 2, it is observed that the main insertion force, i.e. z-force (F_z) increases with increase in insertion/linear velocity. We have increased the insertion speeds in the ratio of 2, 5 & 4; but the changes in force appear to be in different ratio, i.e. 1.8, 1.5 & 1.3; maximum change occurred between 5mm/s and 10mm/s. The trends in resultant transverse force (F_{rt}, which is the resultant of F_x & F_y) is quite different (Figure 3); F_{rt} for 5mm/s, 10mm/s, and 50mm/s are within 0.2N; but that for 200mm/s is significantly higher, a part of which is attributed to some hardware mounting issues. Maximum torques about three axes at 5mm/s, 50mm/s, and 200mm/s insertion speeds are presented in Table I. We observed very small torques, in the order of 10^{-3} N.m about x & y axes, and 10^{-4} N.m about z axis. The target movement is shown in Figure 11 (first four bars, at 0rpm rotational speed). The target deflection increases with the increase in insertion speed. We can correlate this pattern with the change in axial force with increase in insertion speed (Figure 2). Thus, we can infer that techniques for force reduction will definitely reduce target movement.

B. Experiment 2: Effects of needle oscillation

To investigate the effects of needle oscillations, we have inserted the needle at 1Hz, 2.5Hz, and 5Hz rotational oscillation with total angular displacement of 20^0 and 90^0. We did not notice appreciable difference by change the angular travel distances. Needles were inserted at 5mm/s, 50mm/s, and 200mm/s. Experimental results are presented in Figure 4 through Figure 10, and in Table I.

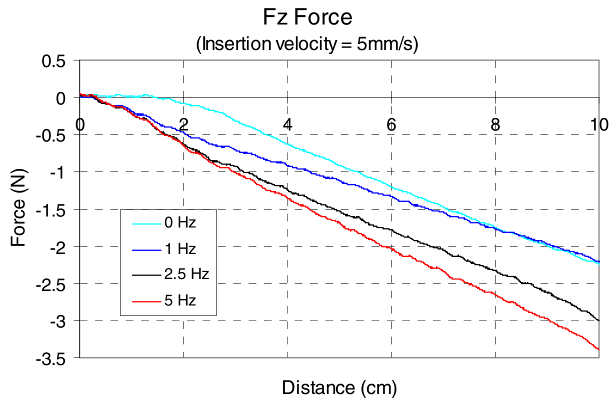

Fig. 4: F_z forces at 5mm/s insertion velocity with needle oscillation at 0Hz, 1Hz, 2.5Hz, and 5Hz.

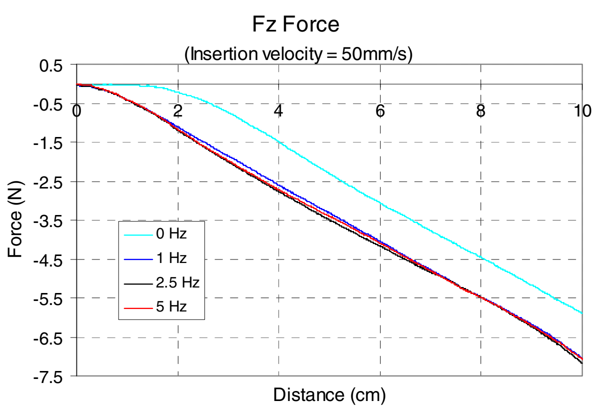

Fig. 5: F_z forces at 50mm/s insertion velocity with needle oscillation at 0Hz, 1Hz, 2.5Hz, and 5Hz.

The F_z force graphs in Figures 4 & 6 show an increase in forces with increase in oscillation. However, at 50mm/s insertion speed for all the oscillation frequencies the increased F_z forces lie almost along on the same line (Figure 5). This suggests that the 50mm/s insertion velocity may be a threshold upon which oscillation, in general, will only produce a maximum level of improvement. In all the cases minimum F_z forces are observed without oscillation. The aforementioned point is corroborated as we closely look at the 200mm/s insertion velocity graphs in Figure 6. From the plots it is noticed that more improvement is achieved at 2.5Hz & 5Hz oscillations, while again the 0Hz case shows the least force. The 2.5Hz and 5Hz cases show definite improvement over the 1Hz case, both are approaching the 0Hz force. This could imply that a larger oscillation frequency may show better performance than the no oscillation case.

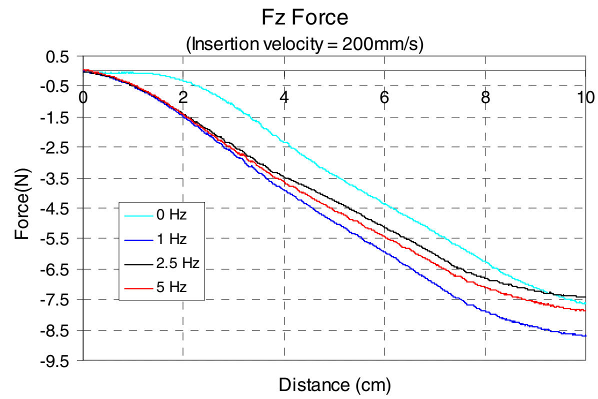

Fig. 6: F_z forces at 200mm/s insertion velocity with needle oscillation at 0Hz, 1Hz, 2.5Hz, and 5Hz.

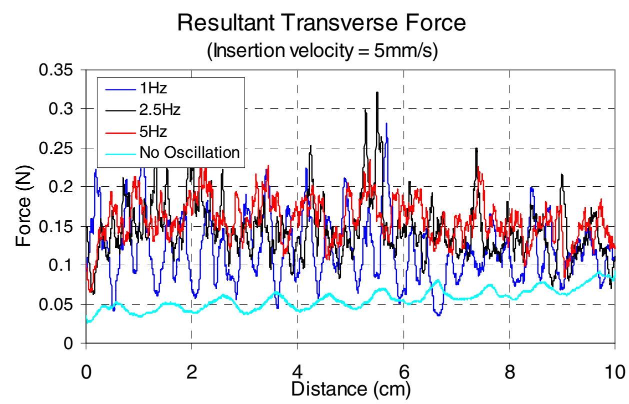

Fig. 7: F_{rt} forces at 5mm/s insertion velocity with needle oscillation at 0Hz, 1Hz, 2.5Hz, and 5Hz.

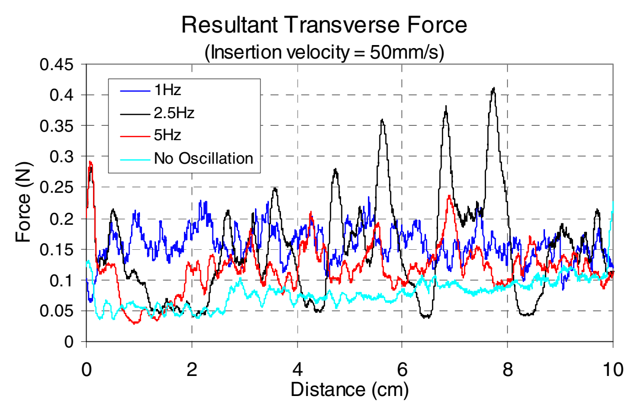

Fig. 8: F_{rt} forces at 50mm/s insertion velocity with needle oscillation at 0Hz, 1Hz, 2.5Hz, and 5Hz.

The resultant transverse forces (F_{rt}s) at different oscillations at 5mm/s, 50mm/s, and 200mm/s insertion velocities are presented in Figure 7 through Figure 9. For 5mm/s insertion speed the profiles of F_{rt}s are similar at 1Hz, 2.5Hz and 5Hz oscillations; minimum F_{rt} is observed at no oscillation (Figure 7). But in case of 50mm/s insertion speed some increase in F_{rt} is noticed at 2.5Hz oscillation

(Figure 8). For 200mm/s insertion we observe a high peak at 0Hz, which is not intuitive; however for all other oscillations the resultant transverse forces are quite small and they exhibit similar profiles. It appears that oscillation increases transverse force as well.

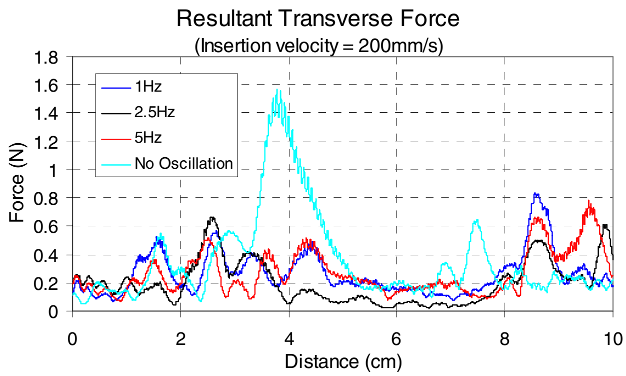

Fig. 9: F_{rt} forces at 200mm/s insertion velocity with needle oscillation at 0Hz, 1Hz, 2.5Hz, and 5Hz.

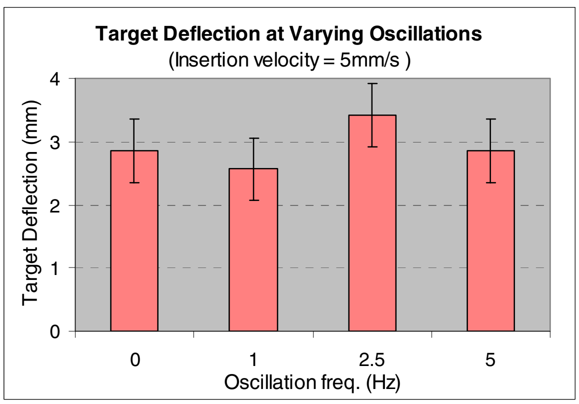

Fig. 10: PVC phantom deformation at 5mm/s insertion speed and different oscillations of needle.

TABLE I
MAXIMUM TORQUES AT DIFFERENT INSERTION VELOCITIES AND ROTATIONAL OSCILLATIONS

Insertion Velocity	Oscillation Freq.	Torque-x (N.m)	Torque-y (N.m)	Torque-z (N.m)
5mm/s	0Hz	-0.00012	-0.00294	-0.00017
	1Hz	-0.00761	-0.00272	-0.00041
	2.5Hz	-0.0064	-0.00456	-0.00155
	5Hz	-0.00661	-0.00189	0.001489
50mm/s	0Hz	0.001305	-0.00469	0.000474
	1Hz	-0.00574	-0.00442	0.000376
	2.5Hz	-0.00584	-0.00693	0.00042
	5Hz	-0.00689	-0.00447	0.000395
200mm/s	0Hz	0.007078	-0.00129	0.000432
	1Hz	-0.00618	-0.00648	0.000328
	2.5Hz	-0.00517	-0.0055	0.000593
	5Hz	-0.0059	-0.00486	0.000378

Maximum torques at different velocities and oscillations are presented in Table I; here we observe some increase in torque produced by oscillation, at least at low frequency. However, the amount of increase in torque is relatively insignificant. Very high frequency oscillation may decrease torques, this aspect needs further investigation. In Figure 10 we observe inconsistent target deflection at different oscillations at 5mm/s insertion seed. It appears that low frequency oscillations cannot reduce target deflection; however high frequency oscillation may be more effective. Because of the hardware limitations we could not oscillate the needle at higher frequency.

C. *Experiment 3: Effects of rotational velocity*

In this experiment the needle was rotated at 60rpm, 300rpm and 600rpm while inserted at 5mm/s, 50mm/s, 100mm/s and 200mm/s. Movement of the target, i.e. the radio-opaque wire embedded in PVC, was observed under fluoroscopy; no force/torque sensor was attached to the needle because of cable/wire winding-up problem. Both the cannula and the trocar of the needle were rotated together. From the experimental result it is observed that at 5mm/s, the increased rotational speed has very positive effect on target movement; there is significant decrease in target deflection (Figure 11).

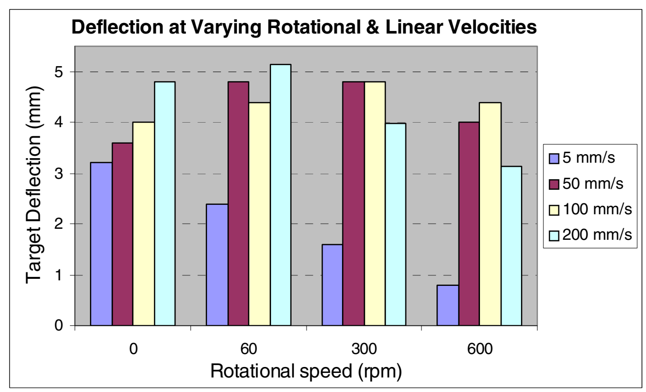

Fig. 11: PVC phantom deformation at different insertion speeds and rotational speeds of needle.

The target deflection decreases with increase in rotation; about 25% reduction at 60rpm, 50% reduction at 300rpm, and 75% reduction at 600rpm at 5mm/s insertion speed. However, as the insertion velocity increases, the amount of target deflection increases. Interestingly, for 50mm/s, 100mm/s, and 200mm/s insertion speeds the target movement increases at 60rpm and 300rpm, but decreases at 600rpm. The results suggest different thresholds, i.e. where the deflection begins to reduce from a maximum, for different insertion speeds; at 50mm/s and 100mm/s the thresholds appear to be between 300rpm and 600rpm, and that is for 200mm/s seems to be between 60rpm and 300rpm. These results reveal that reduction in deflection or deformation of target in soft material or tissue can be achieved by rotating the needle at higher speeds. The maximum rotational speed of the needle for our experiments was limited to 600rpm because of the capacity of currently used motor.

IV. Conclusion and Future Work

In this research work we have investigated the efficacy of velocity modulation during surgical needle insertion in soft materials. We have chosen homogeneous (or near homogeneous) PVC as phantom material because soft tissue is heterogeneous and anisotropic in nature; thus it could be difficult or inconsistent in evaluating the effectiveness of the proposed techniques. We have investigated the effects of modulation of insertion/linear velocity, rotational oscillation, and full rotation of 18G diamond tip needle (cannula plus trocar) that is commonly used for prostate brachytherapy procedures.

From the experimental results, we observed steady increase in main axial force on the needle as the insertion speed increases; however change in resultant transverse force and torques are not very significant. With increase in insertion speed, we noticed increase in target movement. Thus, it appears that for precise placement of surgical needle in soft tissue, one needs to find out optimal insertion speed that will minimize tissue or organ deformation or deflection. The experimental results also reveal that the rotational oscillation, at least low frequency oscillations, makes little difference; in fact it increases the forces and thereby increases the target deflection. However, the data does suggest a possible threshold at about 50mm/s insertion speed for the particular phantom composition used in the experiments; this demands further investigations. It appears that the needle rotation will decrease organ/tissue deformation/deflection as long as we can achieve a high enough rotational speed to counteract the deformation created by the higher insertion speeds. Further experimentation is needed to quantify where said threshold lies, and also if there is a point where the rotational speed reaches a maximum beyond which no further improvement can be achieved. When taken in context with the other data shown, it is a safe hypothesis that higher rotational speeds will reduce the amount of deformation seen in the phantom and thereby the organ. Because of the hardware limitations, we could not collect force-torque data during needle rotation; in future we will modify our hardware so that both the target deflection and the corresponding force-torque data can be acquired concurrently. We are redesigning some of the hardware to achieve higher rotational speed and oscillation of the needle to eliminate some of the drawbacks as mentioned above.

Acknowledgements

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