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MOSQUITO-INSPIRED CANNULA TO IMPROVE CONTROL OF ACTIVE SURGICAL NEEDLE IN SOFT TISSUE

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ABSTRACT

Active needles obtain more significant tip deflection and improved accuracy over passive needles for percutaneous procedures. However, their ability to navigate through tissues to reach targets depends upon the actuation mechanism, the tip shape, and the surface geometry of the shaft. In this study, we investigate the benefits of changing the surface geometry of the active needle shaft in a) needle tip deflection and b) trajectory tracking during tissue insertion. The modifications in passive needle surface geometry have been proven to reduce friction force, tissue displacement, and tissue damage. This study incorporates the effect of modifying the regular smooth cannula with a mosquito proboscis-inspired design in the active needles. The changes in insertion force, tip deflection, and trajectory tracking control during insertion into a prostate-mimicking phantom are measured. Results show that insertion force is reduced by up to 10.65% in passive bevel-tip needles. In active needles, tip deflection increased by 12.52% at 150mm when the cannula is modified. The bioinspired cannula improved trajectory tracking error in the active needle by 39% while utilizing up to 17.65% lower control duty cycle. Improving tip deflection and tracking control would lead to better patient outcomes and reduced risk of complications during percutaneous procedures.

Keywords: mosquito inspired, cannula, insertion force, tip deflection, tracking, control

1. INTRODUCTION

This study proposes a mosquito proboscis-inspired cannula for active steerable needles to increase needle tip deflection and reduce trajectory tracking errors during tissue insertion. The active needle is designed for percutaneous procedures like biopsy and brachytherapy to reach a desired target in tissues like the liver, prostate, or kidneys. Active needles can produce large tip deflection and controlled path tracking inside tissues, which are considered limitations in a conventional passive bevel tip

needle. The commonly used bevel-tip needles deflect due to reaction force at the asymmetric tip, which also deforms the tissue undermining the needle placement accuracy and reducing the efficacy of the needle-based procedures. A tip-actuating active needle can react to uncontrolled needle bending and tissue deformation, thus guiding the needle toward the desired path inside tissues. However, these uncertainties diminish the capability of the active needle to obtain accurate needle placement [1]. We propose a mosquito proboscis-inspired design on the needle shaft to facilitate desirable needle-tissue interaction.

Ma et al. [2] have categorized bioinspired needles based on five objectives: 1) minimizing insertion force, 2) reducing tissue deformation, 3) increasing the needle's maneuverability, 4) enhancing the needle's adhesion ability, and 5) other applications. In this study, we aim to modify the active needle's design with bioinspired features from a mosquito proboscis to achieve increased maneuverability. The mosquito-inspired feature would reduce the insertion force and tissue deformation leading to desirable large needle tip deflection and accurate trajectory tracking control. Needle insertion force consists of cutting force at the needle tip, friction force at the needle-tissue interface, and tissue stiffness force [3]. The needle insertion force is measured as the axial reaction force at the needle base during insertion. Several studies have been conducted on modifying needle tip geometry to reduce the cutting forces. In this study, we design the active needle with a conical tip (a symmetrical tip) to prevent the needle tip deflection in the absence of actuation. We study the post-puncture insertion, and the conical tip does not produce any deflection that couples with the deflection arising due to active needle actuation. We modify the surface of the needle shaft that interacts with the tissue to reduce the friction force as a measure of reducing the needle insertion force. The reduction in insertion force with a passive needle has been linked to decreased tissue deformation and tissue damage [4]. Gidde et al. [5] performed experiments with a mosquito-inspired passive needle (a 3D printed needle of outer diameter 3mm) prototype

on tissue-mimicking gel and biological tissue and achieved a reduction in insertion force of 38%, tissue deformation reduction of 48%, and tissue damage reduction of 27%. We expect to see similar improvements in the active needle.

In this study, we are modifying the active needle designed by Acharya et al. [6, 7] by adding the mosquito proboscis-inspired feature on the cannula of the needle. The original design consisted of an active stylet, whose tip was deflected by a shape memory alloy (SMA) wire actuator and a compliant cannula. The outer surface of the cannula interacted with the tissue medium during insertion. We are modifying the outer surface of the cannula to accommodate a maxilla shape - a jagged structure found in mosquito proboscis [8]. The maxilla shape is scaled up and applied to the needle cannula. The change in the mosquito-inspired active needle features like insertion force, needle tip deflection, trajectory tracking error, and control effort are measured and compared against the active needle with the regular cannula.

2. MATERIALS AND METHODS

This section has three subsections. The first subsection includes the design of mosquito inspired cannula for the percutaneous needle and its prototype fabrication. The second subsection describes the experimental method to evaluate the change in insertion force and needle tip deflection during tissue insertion due to mosquito-inspired cannula in conventional passive bevel tip needles and in newly designed conical tip active needles. The third subsection explains the change in control parameters like trajectory tracking error and control effort on the active needle due to mosquito-inspired cannula.

2.1. Design and fabrication of mosquito-inspired cannula

A mosquito proboscis-inspired cannula is designed, fabricated, and installed into an SMA-actuated active needle. The 180 mm long mosquito-inspired cannula is fabricated by 3D printing the surface profile on a polymer sheet with dimensions inspired by Gidde et al. [5], such as maxilla angle M_A and maxilla spacing t_h . The thin sheet of rubber-like polymer with a regular smooth surface and mosquito proboscis-inspired barbed surface profile (see Fig. 1a) is 3D printed with Elastico™ material using a Stratasys J35 printer. The printed polymer sheets are rolled on top of thin polytetrafluoroethylene (PTFE) tube (outer diameter of 2.57mm) to create a regular smooth cannula and a mosquito-inspired barbed cannula (Fig. 1b). The final outer diameters of both cannulas are 3.5mm. The SMA-actuated active stylet with a conical tip and a distal bending region (Fig. 1c), developed by Acharya et al. [6], is inserted into the two types of cannula tubes. They are assembled into a robotic needle insertion setup, as shown in Fig. 1d. It consists of a linear stage unislide to insert the needle into phantom tissue along the Z-direction. The SMA actuator is powered with PWM power to control the tip deflection along the XZ plane (horizontal plane).

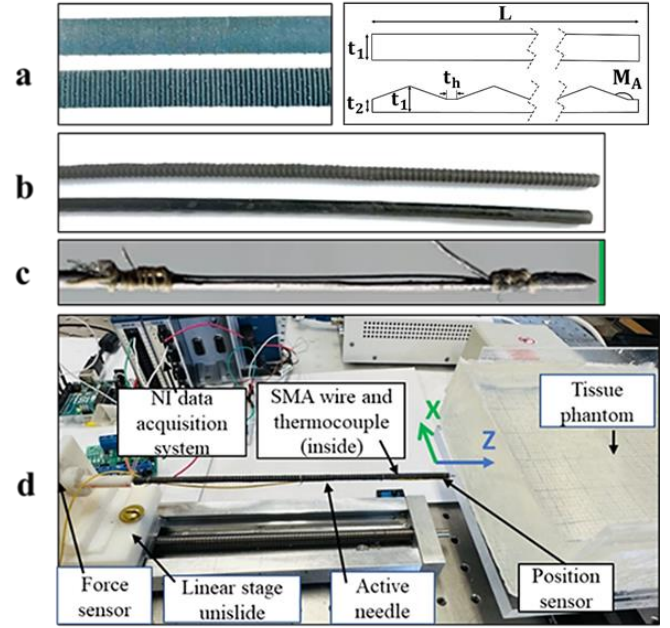


FIGURE 1: (a) 3D printed polymer sheets with the smooth and mosquito-inspired jagged surface (left), cross-section geometry of the sheet with the parameters: maxilla angle (M_A) of 170° , length (L) of 180mm, outer thickness (t_1) of 0.45mm, inner thickness (t_2) of 0.3mm, and maxilla spacing (t_h) of 0.2mm (right), (b) Polymer sheet rolled into a cannula tube (outer diameter: 3.5mm), (c) SMA-actuated needle stylet, (d) Robotic needle insertion test setup.

2.2. Measuring insertion force and deflection in needles with the mosquito-inspired cannula

The effects of the mosquito-inspired cannula on conventional passive bevel tip needles and SMA-actuated active needles are evaluated by measuring the insertion force and needle tip deflection during tissue insertion. The insertion force combines cutting force at the needle tip and friction force on the needle shaft due to interaction with the tissue. The cutting force is considered constant, and friction force grows with insertion depth. During the insertion, the jagged shape reduces the needle tissue contact area compared to the smooth surface, resulting in a lower friction force, thus the lower insertion force [5, 8]. A polyvinyl chloride (PVC) phantom tissue equivalent to 20kPa stiffness resembling a prostate tissue is prepared for needle insertion experiments. The passive bevel tip needles with both types of cannulas are inserted into the tissue phantom along Z-axis (see Fig.1d) up to 150mm insertion depth at a slower velocity of 1mm/s . The active needle is first inserted up to 50mm into the phantom tissue without any SMA actuation and stopped. This is followed by SMA heating to the temperature of 100°C for full actuation, which is then followed by additional 100mm insertion with the fully actuated needle tip. A PID controller is designed to take the temperature feedback from the SMA wire actuator with a 0.003-inch type K thermocouple (Omega, Stanford, CT) and electrically heat the SMA wire with PWM power to the desired temperature. A six-axis force/torque

transducer Nano 17® (ATI Industrial Automation, Apex, NC) is attached to the needle base and connected to a data acquisition system for measuring insertion force. The resulting needle insertion force data are obtained using LabView software (National Instruments Corporation, Austin, TX). The deflection of the needle tip is measured at the end of 150 mm insertion depth using a scaled paper under the transparent phantom as a reference. The resulting insertion force and needle tip deflection due to both types of cannulas in passive and active needles are presented in the Results and Discussion section.

2.3. Testing trajectory tracking control in active needle with the mosquito-inspired cannula

The trajectory tracking control of the active needle with the regular cannula and that with the mosquito-inspired cannula is performed inside the tissue phantom, and a comparison of trajectory tracking error and control effort is made. An electromagnetic position sensor (NDI, Canada) is attached to the tip of the needle such that its position (x, y, z) in the 3D cartesian coordinate space is acquired as feedback. The position feedback is used to actuate the SMA wire to desired strain such that desired planar needle tip deflection is obtained during tissue insertion. The active needle is initially inserted up to 50 mm depth and stopped. For deflection tracking control in prostate phantom, the needle tip deflection reference trajectory along X-axis (see Fig. 1d for axis orientation) is created as Setpoint SP_x . The position sensor measures the process variable PV_x to evaluate the error e_x to be fed into the controller. The needle insertion is performed from 50mm to 100mm insertion depth using linear stage unislide at a velocity of 1mm/s . A PI controller is programmed using LabVIEW to actuate the needle tip deflection $x(t)$ perpendicular to the insertion direction. The PI loop time is set to 0.1sec such that at each loop, a new data point of the deflection trajectory is applied as a setpoint. The control $u_x(t)$ as calculated in (3), is fed as a PWM duty cycle (0% to 100%) to the SMA actuator in the needle. The needle deflection tracking performance is evaluated by measuring root mean squared error (RMSE) using (4).

$$PV_x(t) = \sqrt{(x(t) - x(0))^2} \quad (1)$$

$$e_x(t) = SP_x(t) - PV_x(t) \quad (2)$$

$$u_x(t) = K_c e_x(t) + \frac{K_c}{\tau_i} \int_0^t e_x(\tau) d\tau \quad (3)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_i (e_{x_i})^2} \quad (4)$$

3. RESULTS AND DISCUSSION

The effect of the mosquito-inspired cannula in passive and active needles is shown in Fig. 2. Similarly, tip deflection achieved at 150mm insertion depth inside phantom tissue is presented in Fig. 3. The mosquito-inspired cannula reduced the

insertion force throughout the insertion depth. This is due to the reduction in frictional force between the bioinspired cannula and the tissue phantom interface resulting in the decrease of insertion force from 7.78N to 6.95N (a 10.69% reduction) at 150mm depth. Furthermore, the mosquito-inspired cannula increased the tip deflection of the passive needle from 10.48mm to 14.68mm (a 40.50% increment).

The insertion force in the active needle is initially lower for both types of cannulas, but it increases rapidly and crosses the value of passive needles as tip deflection increases at higher insertion depth (after 9 mm). The insertion force is initially lower for an active needle with mosquito inspired cannula but increases rapidly and crosses the value of a regular cannula active needle at a higher insertion depth (red curve crossing the yellow curve) (see Fig. 2). This is due to the larger tip deflection value obtained by the active needle with mosquito inspired cannula. The tip deflection increases from 26.88mm to 30.35mm (a 12.52% increment) for active needles by modifying the cannula. Even though the friction is reduced, the increased needle tip deflection causes an increase in the insertion force. The mosquito-inspired cannula facilitates higher tip deflection in both active and passive needles, which is desirable for needle steering.

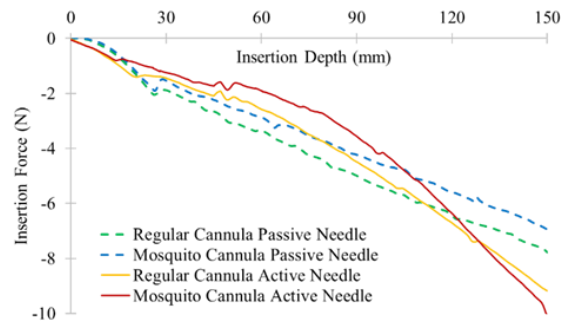


FIGURE 2: Insertion force measured at the needle base during insertion into phantom tissue.

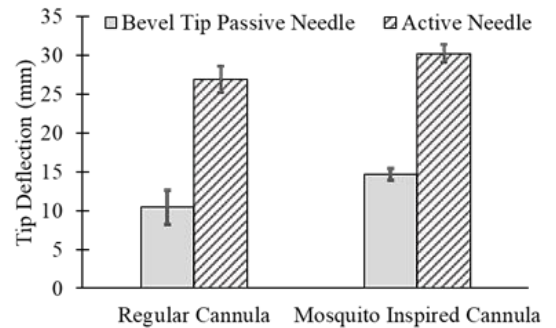


FIGURE 3: Needle tip deflection at 150mm insertion depth in phantom tissue.

The mosquito-inspired cannula improved the needle steering feature by reducing insertion force and increasing needle tip deflection. The proposed cannula achieved a larger deflection for an equal amount of electric power, meaning that

lesser energy is required to achieve the same deflection. Therefore, the increased deflection would also improve the control performance in trajectory tracking of the needle inside the tissue gel. The active needle with two different cannulas is inserted into a prostate-mimicking phantom to follow the reference trajectory. The insertion speed is kept constant, but the deflection of the needle tip is controlled, and the actual needle tip deflection tracking inside the tissue phantom is shown in Fig. 4. The RMSE of deflection tracking for the needle with regular cannula is measured to be 0.55mm and that with regular cannula is measured to be 0.90mm. The average control duty cycle from the PID controller for actuating deflection along the reference path is 51% for the regular cannula needle and 42% for the mosquito-inspired cannula needle.

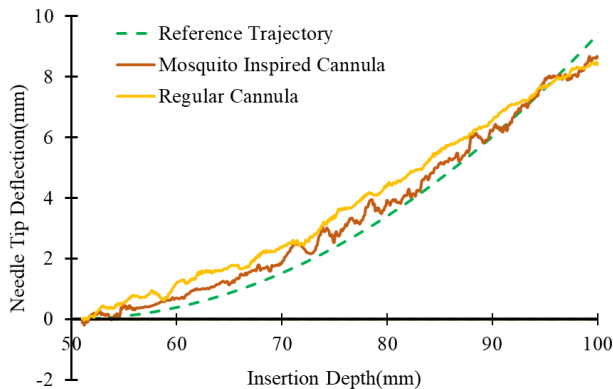


FIGURE 4: Needle tip deflection tracking in phantom tissue for different cannula.

4. CONCLUSION

The mechanics of mosquito proboscis-inspired cannula for active steerable needle insertion into prostate-mimicking phantom are studied. The bioinspired cannula reduced insertion force up to 10.69% in the passive needle. In active needle insertion, force increased at higher depth due to increased tip deflection. Mosquito-inspired cannula improved active needle tracking by reducing RMSE by up to 39% and reducing control effort duty cycle by up to 17.65%. Thus, the mosquito-inspired cannula has the potential to improve needle steering accuracy and reduce control effort in active needles. The future scope of this study involves testing the active needle with the mosquito proboscis-inspired cannula in various biological tissues. A histology study to evaluate tissue damage would also be performed to assess its effectiveness and safety in clinical settings.

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