Force Prediction of Composite-coated Needle Moving Inside Tissues

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Abstract

This research investigates the effectiveness of a composite coating consisting of Polydopamine (PDA), Polytetrafluoroethylene (PTFE), and Activated Carbon (C) to mitigate the potentially harmful effects of needle insertion forces. By evaluating the forces at the interface between the needle and tissue, this study aims to develop a model incorporating experimental and numerical approaches to better understand the mechanics of interfacial forces during coated needle insertion. The proposed model is divided into two components: frictional forces on the needle shaft, modeled using a modified Karnopp model with an elastic force component and cutting forces on the needle tip, modeled using a constant cutting coefficient for a given tissue and insertion speed. Upon testing the model on bovine kidney tissue with a 35mm insertion depth, the results demonstrate that the difference between experimental and modeled insertion forces is in the range of 6.5-17.1% for bare and coated needle. Notably, this difference in the insertion force model is expected when working with real tissues, which possess highly complex structures.

Introduction

- Percutaneous procedures like biopsy, thermal ablation, and drug delivery use surgical needles for diagnosis and treatment of diseases.
- Insertion force during these procedures can cause tissue damage and deflections, mainly due to friction force at the needle-tissue interface and cutting force at the needle tip.
- A composite coating of PDA-PTFE and C [1-3] has been developed for needles to reduce these effects and enhance target-reaching accuracy during insertion.
- Coating is the best approach compared to other force reduction methods because it does not change the needle design and geometry; it only enhances its surface properties [1-3].
- An insertion force model has been proposed to get a deeper understanding of the mechanics behind the reduced insertion force of coated needles.
- The model includes several force parameters such as Coulomb friction, static friction, viscous, elastic, and cutting forces, extracted from experimental data using the least square regression method.
- The insertion force model can predict force parameters in real-time, thereby enhancing surgical procedures and robot-assisted medical interventions.
- The paper outlines a coating technique and an insertion force model to reduce tissue damage during needle insertion through experimental and numerical methods.
- The model can also provide crucial information on the needle's location within the body and variations in tissue stiffness, improving the accuracy of medical procedures and ultimately leading to better patient outcomes.

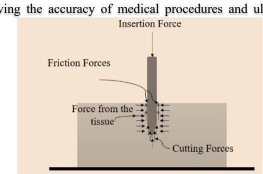

Figure 1: Forces acting between needle and tissue

Model and Methods

The insertion force model is described in the form of equation below.

$$F_I = [F_{CO} + Vb + kX]h + C_c V \tag{1}$$

- F_I and F_{CO} are the insertion and Coulomb friction force, b and h are the velocity and insertion depth, b and X are the viscous coefficient and tissue deflection vertical distance, k and C_c are elastic coefficient and the cutting coefficient.
- For friction force modeling the least square regression method and experiments were used. For LSQR method the equation (2) and (3) are used with sinusoidal insertion-extraction (Figure 2).

$$\begin{bmatrix} F_{friction_1} \\ F_{friction_2} \\ \vdots \\ F_{friction_N} \end{bmatrix} = \begin{bmatrix} sgn(V_{P1}) & V_{P1} & sgn(V_{N1}) & V_{N1} & x_{p1} & x_{N1} \\ sgn(V_{P2}) & V_{P2} & sgn(V_{N2}) & V_{N2} & x_{p2} & x_{N2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ sgn(V_{PN}) & V_{PN} & sgn(V_{NN}) & V_{NN} & x_{pN} & x_{NN} \end{bmatrix} \begin{bmatrix} F_{COP} \\ b_P \\ F_{CON} \\ b_N \\ k_p \\ k_N \end{bmatrix} h \quad \text{Or} \quad F_{friction} = A\,B \tag{2}$$

- V_P, b_P, F_{COP}, x_p and k_p are positive velocities, viscous coefficient, Coulomb friction force, deflection distance, and elastic coefficient, respectively; V_N, b_N, F_{CON}, x_n and k_n are their negative counterparts.

$$B = (A^T A)^{-1} (A)^T F_{friction} \tag{3}$$

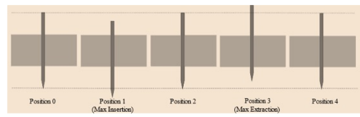

Figure 2: Sinusoidal insertion and extraction of the needle with positions (No tip contact with the tissue).

- To determine the cutting force, Equation 4 was utilized along with the experimental setup illustrated in Figure 3. The experimental setup has been specially designed with a collet that measures only the cutting force using a force sensor.

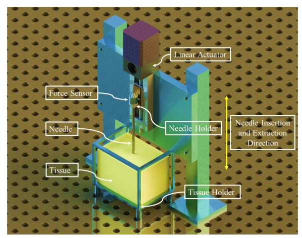

Figure 3: Test setup for cutting force measurement

Results

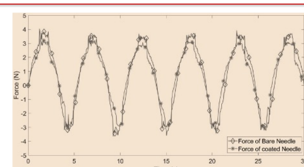

Figure 3: Friction force measured for insertion-extraction for coated and bare needle inside beef kidney.

Parameters	Coated Needle	Bare Needle
Coulomb friction force (F_{COP})	22.86 N/m	27.49 N/m
Viscous Coefficient (b_P)	968.64 Ns/m^2	1105.68 Ns/m^2
Elastic Coefficient (k_p)	8969.36 N/m^2	6416.74 N/m^2

Table 1: Force parameters during Insertion for coated and bare needle inside a beef kidney.

Results

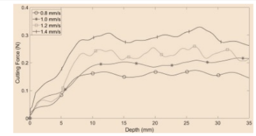

Figure 4: The cutting force vs. insertion length graph into beef kidney; 0.0089 ≤S0.8≤ 0.0653, 0.0129 ≤S1.0≤ 0.0764, 0.0271 ≤S1.2≤ 0.0375, 0.0099 ≤S1.4≤ 0.0415.

Velocities (mm/s)	Average Cutting Forces (N)	Cutting Coefficient (Ns/m)
0.8	0.17	212.25
1.0	0.20	200.00
1.2	0.25	208.33
1.4	0.30	214.28

Table 2:The cutting forces and cutting coefficients for beef kidney.

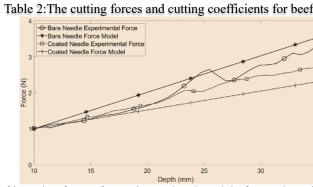

Figure 5 : Comparison of insertion force of experimental and model of coated needle and bare needle inside the beef kidney. Experimental insertion force bare 0.080 ≤ SD ≤ to 0.048.; Experimental insertion force coated 0.041 ≤ SD ≤ to 0.052.

Conclusions

The Coulomb friction force is found to be a significant factor in reducing the insertion forces. This finding is crucial in understanding the needle-tissue interaction mechanisms of coated needles with lubricants. To test the effectiveness of the model, experimental data for both bare and coated needles were collected for a bovine kidney with a 35mm insertion depth. The results showed that the experimental and model data for the insertion force of a bare needle had a discrepancy of 6.5%. On the other hand, the experimental and model data for a coated needle had a larger disparity of 17.1%. These results demonstrate the potential of the model to accurately predict the insertion forces for coated needles. Despite its limitations, the insertion force model proposed in this study can still be applied in haptic medical devices where independent cutting, Coulomb friction, viscous, and elastic data are required. The model can provide medical professionals with valuable insights into the needle's location within the body and variations in tissue stiffness, helping to improve the accuracy of medical procedures and ultimately leading to better patient outcomes.

Acknowledgement

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References

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