Predicting Needle Deflection in Soft Tissue: An Investigation of Interfacial Mechanics and Tissue Deformation

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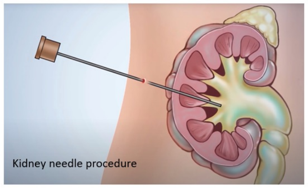
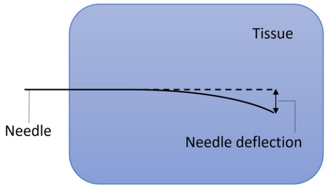
Introduction

Percutaneous needle insertion has become a standard procedure in the region of open surgery, notably for biopsies of abdominal tumors, breast cancer, and prostate cancer [1]. In many cases, achieving high needle targeting accuracy is difficult due to the complexity of the human body tissues. Therefore, it is essential to study and model the steering behavior of a needle inserted into multi-layered tissues to plan for the optimal path of the needle during the insertion. The procedure during which the needle must pass through multi-layer tissues requires professional skills due to complex deflections. Therefore, it is essential to create realistic simulators for surgeons and nurses, to practice their clinical skills [2].A model based on a Euler-Bernoulli beam deflecting under static force distribution profiles was developed to simulate needle insertion [3]. A needle was modeled as a cantilever beam supported by a series of nonlinear springs [4].

Objective

This work utilizes the Euler-Bernoulli beam elastic foundation theory to model the needle insertion process in multi-layered tissues where the needle is considered as a cantilever beam undergoing various external loads resulting from the needle-tissue interaction. This Euler-Bernoulli model uses preoperative tissue-specific parameters and geometric needle properties to predict the needle deflection, which can be used later to improve the accuracy of the needle path planning in robotic assistance and training systems





Materials and Methods

The modified dynamic Euler-Bernoulli beam theory for needle insertion is based on the Euler-Bernoulli beam theory [5,6]. Define the geometry and material properties of the needle. The needle is modeled as a thin, slender beam with a circular cross-section. The tissue is modeled as a nonlinear, viscoelastic material with a strain-dependent modulus of elasticity and a viscosity coefficient. Euler-Bernoulli beam theory:

$$\rho A\left(\frac{\partial^2 w(x)}{\partial t^2}\right)+EI\left(\frac{\partial^4 w(x)}{\partial x^4}\right)=F_y\left(F_c,F_f,F_s\right)$$

$E,I,\rho,$A are the Young' s modulus, the moment of inertia, the area and density of the needle.

The solution of the governing differential equation:

$$\frac{d^2 w_i}{d\tau^2}=[w_{i-2}-4w_{i-1}+6w_i-4w_{i+1}+w_{i+2}]+\frac{(\Delta x)^2}{EI}\;F(x_i,\tau)$$

The boundary conditions:

$$\mathrm{w}(0)=0,\frac{\partial \mathrm{w}}{\partial \mathrm{x}}(0)=0,\frac{\partial^2 \mathrm{w}}{\partial \mathrm{x}^2}(\mathrm{L})=0,\frac{\partial^3 \mathrm{w}}{\partial \mathrm{x}^3}(\mathrm{L})=0$$

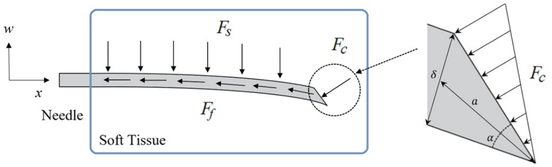


Figure 1. Needle-tissue interaction forces during the insertion of bevel-tip needle into a soft tissue..

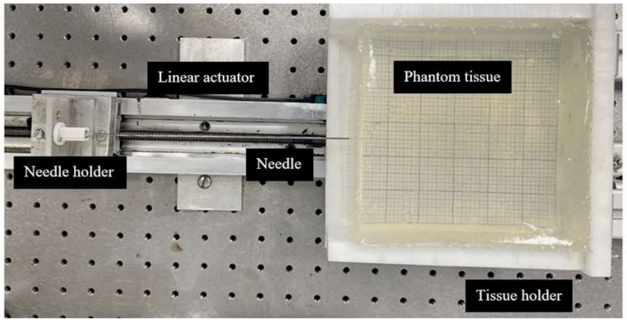


Figure 2. Needle insertion experimental setup.

Results

Experiments were performed on phantom tissue using needle insertion to test the efficacy of the proposed deflection model. The objective was to observe the needle's steering behavior, use an analytical model to predict its deflection, and then compare the results to the actual deflection observed during experiments on both biological and phantom tissues to verify the model's accuracy. The mean values of the experimental needle deflection in both porcine muscle tissue and phantom tissue with an elastic modulus of 10 kPa, along with the analytical deflection prediction, were recorded. Using ImageJ, the experimental needle deflection was estimated by incorporating preoperative measurements of the layer depth and properties, needle geometry, and material properties. The error bars indicate the standard deviations. The analytical and experimental needle deflections were plotted using MATLAB, and this plot was utilized to compare the analytical and experimental data.

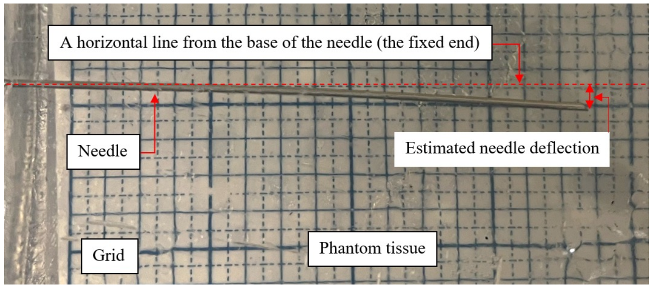


Figure 3. A captured image of a needle inside a tissue during the experimental needle insertion used to estimate the tip deflection.

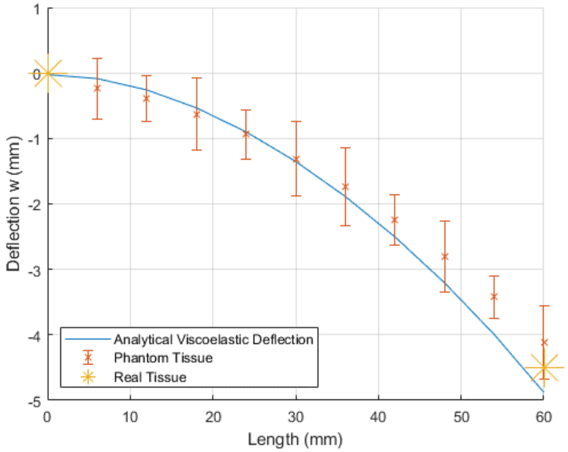


Figure 4 Comparisons between the analytical deflection model predictions and experimental deflection estimations during the insertion into the porcine muscle tissue and a phantom tissue with 10 kPa elastic modulus.

Conclusion

Subcutaneous and percutaneous insertion of needles and catheters require high accuracy to ensure that the needle will not miss the pre-defined target inside the tissue. Our analytical deflection model can plan the needle insertion trajectory in tissues with nonlinear properties reducing the possibility of the needle missing its mark. The experimental data show that this method can predict the needle tip deflection with 10 to 20% modeling error

Acknowledgements

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