Mechanics of Needle Insertion in Soft Tissues

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Introduction: Percutaneous needle insertion has become a standard procedure in open surgery, notably for biopsies of abdominal tumors, breast cancer, and prostate cancer [1]. However, the needle insertion into a target is difficult because it can be deflected easily due to the design of the needle tip. This deflection can cause the needle to miss its target, and the insertion procedure might need to be repeated, leading to adverse damage to the tissue. Therefore, it is crucial to predict the needle steering behavior during the insertion into soft tissues. This work proposes an analytical approach for computing the needle-tissue interaction forces and modeling the needle deflection to estimate needle steering behavior inside the soft tissues. This model in predicting the needle deflection is based on preoperatively obtained data, and does not require real-time feedback of measured system states for updating the model parameters. The analytical model uses computing software, e.g., MATLAB, to estimate the needle deflection, which requires less computational time than the Finite Element methods.

Materials and Methods: The needle-tissue interaction forces when a bevel-tip surgical needle is fully inserted into a soft tissue can be characterized into three groups [2], shown in Fig 1, the cutting force Fc, The friction force Ff and the tissue deformation force Fs. The needle was assumed to be a cantilever beam resting on an elastic foundation. The Euler-Bernoulli Beam governing equation [3] $\frac{\partial^2}{\partial x^2} \mathrm{EI} \left(\frac{\partial^2 \mathrm{w(x)}}{\partial x^2}\right) + \mathrm{kw(x)} = \mathrm{q}$ was utilized to create the analytical model of needle deflection under the external needle-tissue interaction forces mentioned previously. This analytical deflection model can be extended to calculate the needle deflection in multilayer tissues by adjusting each layer's elastic property and length. Experimental insertions into PVC Tissue-mimicking materials were performed to validate the accuracy of the needle analytical deflection model. A force measurement setup consisting of a linear actuator, a force sensor Nano17®, and a data acquisition software program, LabVIEW, was employed to perform needle insertions and extractions in 5, 20, 30, and 40 kPa elastic modulus phantom tissues to estimate the needle-tissue interaction forces.

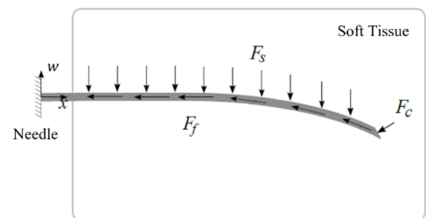

Fig. 1 A bevel-tip needle being inserted into soft tissue

Results and Discussion: The performance of the proposed analytical deflection model was evaluated by conducting needle insertion experiments into multilayer phantom tissue. The multilayer phantom block was a four-layer tissue consisting of 40, 30, 20, and 5 kPa. The number of insertion tests for deflection experiments was three, with an insertion distance of 100 mm and an insertion velocity of 5 mm/s. In Fig 2, the experimental needle deflection was estimated using the image processing program ImageJ, and the error bars show the standard deviations. The vertical dark line indicates the separation surface between the different layers. The needle's analytical and experimental deflections were plotted using MATLAB and were utilized to compare the analytical deflection and experimental data.

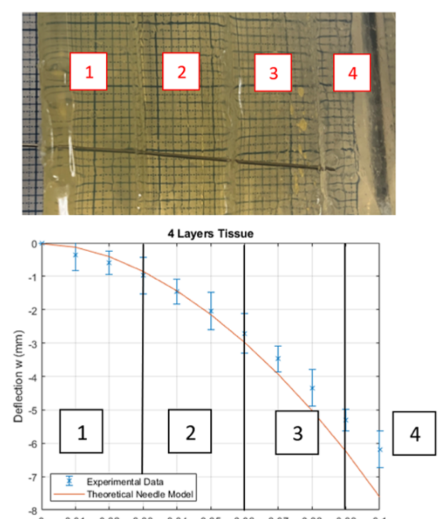

Fig. 1 Comparisons between the analytical deflection model predictions and experimental deflection estimations

Conclusions: 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 21% modeling error.

References:

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