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STUDY OF NEEDLE INSERTION FORCES

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Abstract

"A biopsy is the removal of a sample of tissue from the body for examination" [1]. Research on the subject indicates that needle insertion forces during the procedure cause significant deformation of the tissue causing the target tissue to deform. This can lead to positional errors during the procedure. Hence, an understanding of the forces that play an important role in the process of needle insertion is of great importance for improving the efficacy of biopsies. This research project will examine the work done in this field in order to provide an overview of the subject.

1. Introduction

During a biopsy procedure, a needle is inserted into the soft tissue to reach the target in order to extract a sample for further analysis. Needle insertion procedures are widespread in traditional and relatively new percutaneous medical treatments. To perform these procedures successfully the physician requires both visual and tactile feedback. Hence, an understanding of the forces involved in needle insertion in soft tissue is vital for developing force feedback systems that mimic the tactile feedback that a physician gets during a biopsy procedure. These systems can be used for training new practitioners as well as for developing robot assisted needle delivery systems. This research project aims to give a brief review of the forces involved in needle insertions into soft tissues and an overview of the research that has been carried out in this field.

1.1 Outline of the Paper

The paper first deals with the problems associated with needle insertion procedures to acquaint the reader with the purpose of the studies being carried out. Then a brief mechanical analysis of the problem is presented followed by an introduction to material issues. Related work done in the field, some open issues and other relevant topics of interest will be discussed subsequently.

2. Problems Related To Needle Insertion Forces

For the accurate insertion of a needle it is vital to locate the proper insertion point based on the position of the target from the surface of the skin. This can possibly be achieved by pre-operative scan data. During the procedure, the surgeon has both visual and tactile source of feedback. The visual feedback is derived form the part of the needle remaining outside the body, the insertion point and inter-operative non invasive scanning methods. The tactile feedback is of great importance as the needle insertion force varies with depth of penetration and the type of tissue which is being penetrated. Thus it can help the practitioner accurately judge needle position inside the body. Unfortunately, this judgment can only be achieved through *in vivo* (on patient) experience. This proves to be a great problem with the training of new physicians.

Another challenge in this field is the lack of representative materials for accurate prediction of needle insertion forces. That is to say in experiments conducted to study or model needle insertion forces cannot be carried out on patients. These have been carried out on porcine and bovine samples as well as fixed cadavers. In vivo experiments have also been carried out on anesthetized pigs. However, differences in the thoughness and deformation properties of soft tissues exist between cadavers and live patients. These can be attributed to the cool tissue temperature in cadavers, effects of past rigor and the introduction of formaldehyde [10]. Thus, these techniques can only provide approximations of the forces that the practitioner experiences when working with patients.

Another problem that plagues biopsy procedures results from the soft tissue deformation due to needle insertion forces. Pre-operative scan images are often used for location of needle insertion point with respect to a tissue target. However, during the procedure the soft tissue surrounding the target and the target itself are deformed due to needle insertion forces [2]. The figure below illustrates this issue.

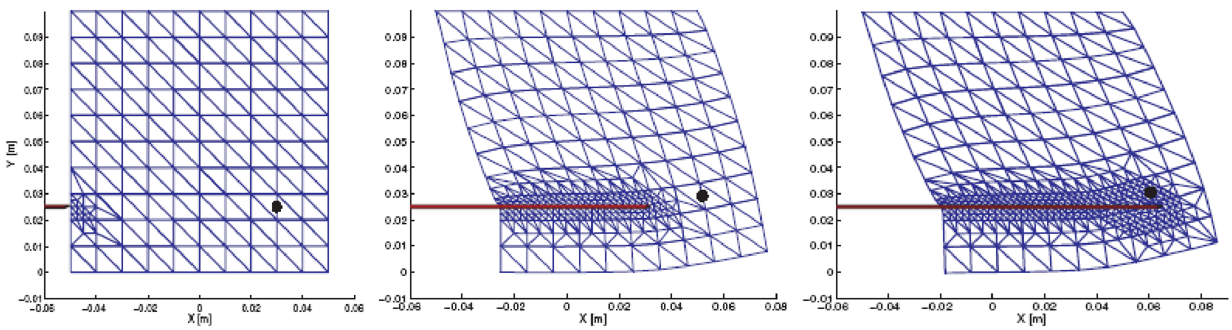

Fig. 1. Simulated intercept of a small target embedded within elastic tissue [3]

3. Analysis of Needle Penetration Process

Needle insertion and extraction at a constant velocity can be broadly classified under the following four phases [4]:

- **Deformation Phase**

  In this phase the needle tip is in contact with the tissue causing deformation, however it does not puncture the tissue. It ends when tissue is penetrated.

- **Penetration Phase**

  This phase begins with tissue penetration and continues till the needle stops. The insertion force increases with the depth of insertion.

- **Relaxation Phase**

  This phase occurs after the needle stops due to the viscoelastic properties of the material.

- **Extraction Phase**

  This is the last phase and is a result of friction and release of elastic strain energy.

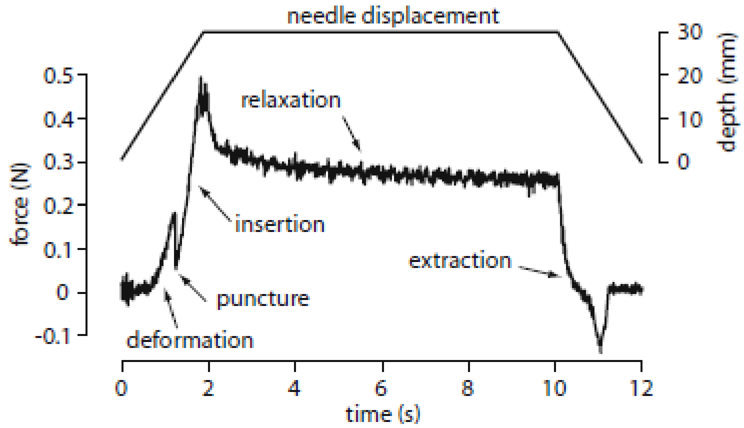

Fig. 2. Phases of needle insertion [5]

In general models predicting needle insertion forces can be classified under two broad categories. The first category views needle penetration as the deformation of tissues caused by the forces at the interaction and uses stiffness-like functions to fit the experimentally obtained data [4]. The second category uses energy methods to model the needle insertion process. A brief overview of the deformation model is given subsequently owing to its simplicity.

3.1 Deformation Method

Based on the work of C. Simone *et al* [11] the total force is considered to be a summation of stiffness, friction, and cutting forces, as shown in equation 1. The stiffness force is pre puncture while the friction and cutting forces are post puncture with the cutting force including the plastic deformation due to cutting and the needle tip stiffness force.

$$f_{needle}(x) = f_{stiffness}(x) + f_{friction}(x) + f_{cutting}(x) \tag{1}$$

The figure below gives the positions of the tissue surface during the different stages of needle insertion.

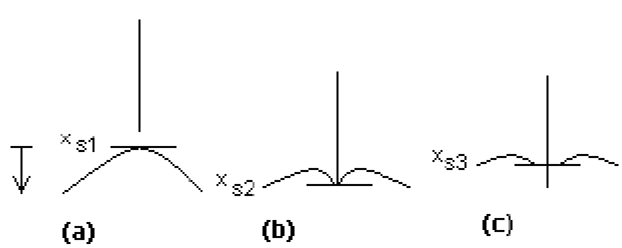

Fig. 3. Locations of the tissue surface at different stages of needle insertion. (a) pre-puncture (b) puncture (c) post-puncture. [11]

- **Stiffness Force**

The stiffness force due to the elastic properties of the organ and its capsule, and it is given by the following relation:

$$f_{stiffness} = \begin{cases} 0 & x_{tip} < x_{s1} \\ f(x) & x_{s1} \le x_{tip} \le x_{s2} \\ 0 & x_{tip} > x_{s3} \end{cases}, \tag{2}$$

Where, x_{tip} = position of needle tip

xs_1, xs_2, x_{s3} = positions of tissue surface relative to fixed coordinate system

$f(x)$ = one – dimensional quasi static stiffness model given by:

$$f(x) = a_1 x + a_2 x^2 \tag{3}$$

Where, a_1 and a_2 are nonlinear stiffness parameters which are determined experimentally.

- **Friction Force**

The friction force occurs due along the length of the needle due to the tissue adhesion and clamping, and is given by the following relation:

$$F_{friction}(\dot{x}, F_a) = \begin{cases} C_n \operatorname{sgn}(\dot{x}) + b_n \dot{x} & \dot{x} \le -\Delta v/2 \\ \max(D_n, F_a) & -\Delta v/2 < \dot{x} \le 0 \\ \min(D_p, F_a) & 0 < \dot{x} < \Delta v/2 \\ C_p \operatorname{sgn}(\dot{x}) + b_p \dot{x} & \dot{x} \ge \Delta v/2 \end{cases} \tag{4}$$

Where, C_n and C_p are negative and positive dynamic friction values

b_n and b_p are negative and positive damping coefficients

D_n and D_p are negative and positive static friction

$\dot{x}$ = relative velocity of needle and tissue
F_a = sum of non frictional forces applied to the system

- **Cutting Forces:**

  Cutting forces represent forces necessary to slice through the tissue, and are given by the equation:

$$f_{cutting} = \begin{cases} 0 & x_{tip} \leq x_{s2}, t < t_p \\ f_{cutting} & x_{tip} > x_{s3}, t \geq t_p \end{cases} \tag{5}$$

t = time
t_p = time of puncture
$f_{cutting}$ is a constant and is obtained by subtracting the friction force from the total force after puncture.

The friction force in this case is given by,

$$f_{frcition} = b_p l v_{needle} \tag{6}$$

l = length of needle in tissue
v_{needle} = velocity of needle tip

4. Material Issues

The materials which significantly affect the needle insertion forces are the tissue samples as the biopsy needle materials (usually stainless steel) remain constant. However, biological tissues have a variety of forms, each having different mechanical properties. Porcine and bovine tissue samples are widely used for studies regarding needle insertion forces with human cadavers also being used on occasion.

5. Related Work

To date many researchers have investigated ways to improve the physician's skill in needle biopsy procedures. Most of these focus on the simulation of tissue deformation, modeling of needle insertion forces and design of haptic simulators.

A design for a experimental force simulator for tactile feedback is presented by P. N. Brett *et al* [10]. This design combines experimentally measured data to derive the force resisting the needle progress. B. Maurin *et al* [5] have presented a study of needle insertion forces using *in vivo* porcine data to accurately predict needle insertion forces using a robotic delivery system. Another experiment involves the modeling of needle insertion forces for developing a robot assisted needle delivery system by C. Simone *et al* [11]. Such systems have the advantage of both human and computer control simultaneously thus improving the accuracy, consistency, therapy delivery speed and possibly reduction of patient discomfort [11].

A model for interactive simulation of needle insertion during percutaneous procedures based on Finite Element Methods is presented by S. P. DiMaio and S. E. Salcudean [3]. Another important work in the estimation of fracture toughness of tissue based on energy methods is carried out by Toufic Azar and Vincent Hayward [4].

In the field of tissue deformation modeling, a simulation of mechanical compression of volumetric breast data using Finite Element Methods has been presented by Albert L. Kellener *et al* [6].

6. Open Issues

The issue of positional error due to needle insertion forces continues to be an unsolved problem in the area of needle biopsies. As stated earlier in Section 2, there is a difference in the position of the tissue target prior to a biopsy procedure and during the procedure, when a biopsy needle is inserted through the surrounding tissue. An important source of this error is the soft tissue deformation due to the biopsy needle insertion forces [2]. Therefore, it can be hypothesized that, if the needle insertion force is reduced, the soft tissue deformation will be decreased and the accuracy of the procedure will improve.

As discussed in Section 5, the majority of research conducted in this field involves modeling of needle insertion forces and accurate simulation of tissue deformation to better aid in the training of physicians. However, research in the reduction of needle insertion forces remains scant.

One such study presented by Andreas Schneider *et al* [8] looks at biomimetic microtexturing for neurosurgical probe surfaces. Their design based on an insect's ovipositor indicates that for certain surface geometries it is possible to move forward with minimum force when using a reciprocating actuation.

7. Other Related Topics of Interest

Another innovative idea in the field of needle biopsy is introduced by Stacy Figueredo *et al* [9] with the introduction of endoscopic biopsy needles with flexural members. Their design aims to improve upon the limitation of current biopsy needles which in general do not preserve tissue histology. Biopsy needles can in general be classified as end cut and side cut depending on the method employed to cut tissue. The design presented by Stacy Figueredo *et al* [9] studies 10x scaled prototypes of an end cut biopsy needle with flexural members of different geometries. The figure below illustrates the design.

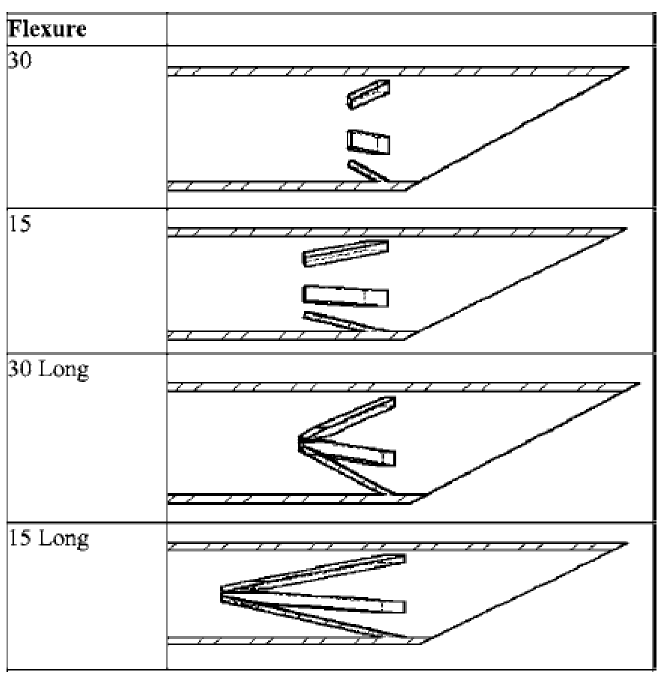

Fig. x. Needle Prototype Cross Sections [9]

Such design shows evidence that for certain geometries of the flexural members the average mass of the sample collected was 1.1 g ($\sigma = 0.21$) as compared to 0.78 g ($\sigma = 0.19$) for existing wedge design and 0.71 g ($\sigma = 0.09$) for existing extended wedge design. This indicates that using a flexural design would have the added advantage of greater sample mass collection.

References

[1] http://www.netdoctor.co.uk/health_advice/examinations/biopsy.htm

[2] Jessica R. Crouch, Chad M. Schneider, Josh Wainer, Allison M. Okamura: Needle Insertion with Tissue Relaxation: MICCAI (2) 2005: 624-632

[3] S.P. DiMaio and S.E. Salcudean: Needle Insertion Modelling for the Interactive Simulation of Percutaneous Procedures: MICCAI 2002

[4] Toufic Azar and Vincent Hayward: Estimation of the Fracture Toughness of Soft Tissue from Needle Insertion: ISBMS 2008: 166-175

[5] Maurin, B., Barbe, L., Bayle, B., Zanne, P., Gangloff, J., Mathelin, M., Gangi, A., Soler, L., Forgione, A.: In Vivo Study of Forces during Needle Insertions. In: Perspective in Image-guided Surgery: Proceedings of the Scientific Workshop on Medical Robotics, Navigation, and Visualization (MRNV 2004), pp. 415–422 (2004)

[6] Albert L. Kellner, Thomas R. Nelson, Laura I. Cerviño, John M. Boone: Simulation of Mechanical Compression of Breast Tissue: IEEE transactions on bio-medical engineering 2007;54(10):1885-91.

[7] Joseph J. O’Hagan, Abbas Samani: Measurement of the Hyperelastic Properties of Tissue Slices with Tumor Inclusion: Physics in Medicine and Biology, Vol. 53, No. 24., pp. 7087-7106.

[8] Andreas Schneider, Luca Frasson, Tassanai Parittotokkaporn, Ferdinando M. Rodriguez y Baena, Brian L. Davies, S. Ejaz Huq: Biomimetic Microtexturing for Neurosurgical Probe Surfaces to Influence Tribological Characteristics During Tissue Penetration: Microelectronic Engineering, Volume 86, Issues 4-6, April-June 2009, Pages 1515-1517 MNE ’08 - The 34th International Conference on Micro- and Nano-Engineering (MNE)

[9] Stacy L. Figueredo, William R. Brugge, Alexander H. Slocum: Design of an Endoscopic Biopsy Needle With Flexural Members: J. Med. Devices 1, 62 (2007)

[10] Brett PN, Parker TJ, Harrison AJ, Thomas TA, Carr A.: Simulation of Resistance Forces Acting on Surgical Needles: Proc Inst Mech Eng H. 1997;211(4):335-47.

[11] Simone, C., Okamura, A.M.: Modeling of needle insertion forces for robot-assisted percutaneous therapy: IEEE International Conference on Robotics and Automation, 2002. Proceedings. ICRA '02.

[12] Oliver A. Shergold and Norman A. Fleck: Experimental Investigation Into the Deep Penetration of Soft Solids by Sharp and Blunt Punches, With Application to the Piercing of

Skin: J. Biomech. Eng. -- October 2005 -- Volume 127, Issue 5, 838 (11 pages)
doi:10.1115/1.1992528