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Optical Measurement of Tissue Deformation in Needle Insertion

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Abstract

This study develops an optical measurement method to investigate the tissue deformation in needle insertion. Accurate needle insertion with sub-mm accuracy to the target position is desired in various clinical procedures but challenging in practice. One of the main challenges is tissue deformation caused by needle insertion force, introducing the undesired target movements. The double-layered tissue phantom is explored to enable the optical measurement of tissue deformation. Images of tissue deformation were analysed by Kanade–Lucas–Tomasi feature tracking algorithm and digital image correlation technique to measure tissue movement and strain, respectively. This method was further utilized to compare the tissue deformation under different needle insertion speeds. Results show that higher insertion speed increases the tissue deformation due to the increased friction force while reducing the strain perpendicular to the insertion direction near the needle tip. The findings offer insights on tissue deformation and needle-tissue interaction. This study demonstrates the potential of this method to evaluate tissue deformation for various needle designs and insertion motions.

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Keywords: Needle insertion; Tissue deformation; Optical Measurement; FeatureTracking; Digitial Image Correlation

1. Introduction

Needle insertion is a common medical procedure for minimally invasive access in various clinical procedures such as tissue biopsy, regional anesthesia and medication delivery. The diagnostic accuracy and treatment effectiveness in the aforementioned procedures highly depend on the accuracy of needle placement [1]. The sub-mm accuracy is desired but clinically and technically challenging. In the procedure, the needle insertion force deforms and moves the soft organ which is weakly supported by the surrounding soft tissues. Another challenge is that the needle bends during insertion, making the tissue deformation more prominent. The needle bending and tissue deformation often lead to the misplacement of needle tip, introducing difficulties to achieve the desired targeting accuracy [1].

To overcome this clinical challenge of precision needle insertion, a method to quantify the tissue deformation during needle insertion is important to understand the needle-tissue interaction and assist clinicians and medical robots to improve the targeting accuracy. Finite element method (FEM) are widely utilized to predict the tissue deformation. Misra et al. [2] summarized that the realistic tissue properties, nonlinear elasticity or viscoelasticity, are necessary for high fidelity FEM modeling. Yamaguchi et al. [3] applied the arbitrary Lagrangian-Eulerian (ALE) method to develop a FEM tissue model for dynamic analysis of needle insertion and demonstrated a good match on the insertion force between modeling and experimental results. Liang et al. [4] integrated a needle deflection model into the FEM simulation for the prostate deformation and showed about 80% accuracy in a 40-mm insertion. Despite the feasibility of FEM to study tissue deformation, the complexity of needle-tissue interaction leads to high computational costs and limits the model fidelity.

Experimental approaches have been developed to measure tissue deformation in needle insertion to provide more insights on needle-tissue interaction. Dimaio et al. [5] conducted the needle insertion into a thin tissue phantom with a grid of black dots on the top. The dot movements were tracked by image processing to quantify and validate the tissue deformation

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from the tissue FEM model. Kerdok et al. [6] fabricated a silicone rubber phantom with embedded fiducial markers (Teflon spheres) to establish a physical standard for tissue simulation using computer tomography (CT) images of the deformed phantom. Oldfield et al. [7] used the tissue phantom embedded with aluminum oxide particles and the laser illumination system to light the needle cutting plane. An adapted digital image correlation (DIC) technique to track the particles and quantify the mechanical behavior of tissue in the needle insertion was developed. Leibinger et al. [8] adopted a laser-based correlation technique to measure the deformation of the tissue phantom with the embedded fluorescent microbeads and compare the properties of different phantom materials. Based on this survey, there are still few studies on the realistic needle-tissue interaction, which may be underestimated without measuring the maximal tissue deformation around the needle cutting regions. Also, advancements of optical imaging devices and transparent tissue-mimicking phantom materials have opened opportunities to acquire images and analyze the tissue deformation on the needle cutting plane.

This study develops an optical measurement method by using a CCD camera to capture the deformation of tissue phantom in the needle insertion. The tissue phantom is made of polyvinyl chloride (PVC), a transparent tissue-mimicking material [9]. A unique double-layered structure with transparent and particle-embedded layers are fabricated in this study. This double-layered structure is aimed to visualize the deformation around the needle cutting region. Two main measurements are: 1) the tissue movement by tracking the particles embedded in the phantom and 2) the tissue strain by applying the DIC technique on the captured images. Different needle insertion speeds are tested to evaluate the speed effects on tissue deformation. Details of this approach and results are presented in the following sections.

2. Materials and Methods

2.1. Tissue Phantom Fabrication

The PVC tissue-mimicking phantom material in this study has the mechanical and needle insertion properties similar to the soft tissues. The ratio of the PVC polymer solution, the softener and the mineral oil was adjusted to achieve the desired material hardness [9]. The elastic modulus 18.5 kPa was achieved using ratio 1:3 of softener to PVC polymer solution and 5% mineral oil of total weight. In fabrication, the heated and transparent PVC liquid mixture was poured into the acrylic phantom holder with length 100 mm, width 30 mm and height 80 mm as shown in Fig. 1(a). Before it completely cured, the particle-embedded PVC (the same PVC mixture as the transparent PVC) was then poured to form the double-layered structure as shown in Fig. 1(b). The needle was inserted in between these two layers of the phantom as shown in Fig. 1(c). The embedded particles were the fine ground pepper powder which is easily accessible while with the suitable particle size for image tracking purpose.

This unique double-layered tissue phantom enabled the camera to easily focus on the needle cutting region to capture the maximal tissue deformation in the 2D space during needle insertion. The transparent layer ensured that the needle and surrounding tissues with embedded particles were in focus by the camera. The particles far from the needle cutting regions were not in focus and cannot be measured.

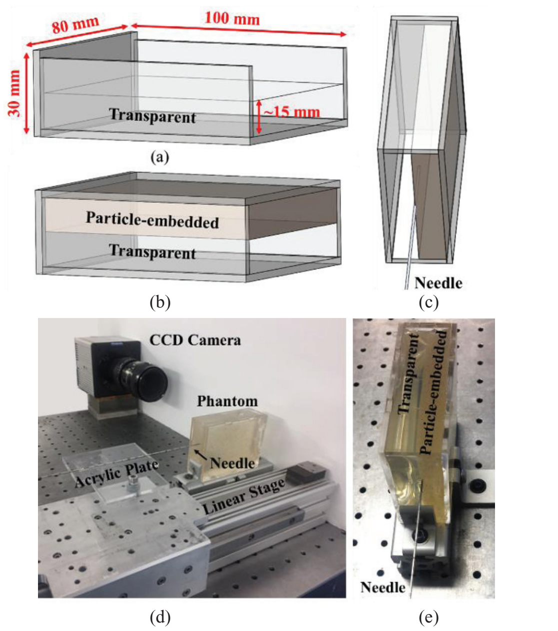

Fig. 1. (a) The acrylic phantom holder and the transparent layer, (b) a double-layered PVC tissue phantom after adding the particle-embedded layers, (c) the needle insertion to the double-layered structure, (d) the needle insertion experimental setup with actuator and high speed camera, and (e) a close-up view of the needle and the double-layered phantom in needle insertion.

2.2. Experimental Setup

The experimental setup is shown in Fig. 1(d). The whole needle insertion process was recorded by a camera (Model 100K by Photron) using 1024 × 1024 pixel resolution and 60 fps setups. A linear stage (Model HLD 60 by Moog Animatics) inserted an 18-gauge needle with a 22° bevel angle (Pro-Mag Ultra Biopsy Needle by Argon Medical Devices) by an insertion length 30 mm.

This study focused on evaluating the tissue deformation caused by the friction under different insertion speeds. Two experiments with the needle insertion speed, 5 mm/s and 10 mm/s, were performed to compare the deformation results and study effects of the needle insertion speed on friction force [10]. Two experiments were conducted along the same insertion path. In the second path, the cutting effect was eliminated and friction force can be determined [11].

2.3. Particle Tracking for Tissue Movement

This study applied the Kanade-Lucas-Tomasi (KLT) feature tracking algorithm [12] in Matlab (by MathWorks) to quantify the tissue movement during the needle insertion by tracking movements of the embedded particles. Fig. 2(a) shows an image of the video before the needle insertion. The