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A Robotic Palpation-Based Needle Insertion Method for Diagnostic Biopsy and Treatment of Breast Cancer

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Abstract— **We describe here a palpation-based needle insertion method for diagnostic biopsy and treatment of breast cancer. The mechanical palpation probe locates cancerous tissue from force information and reduces tissue displacement during needle insertion. We compared palpation-based needle insertion to normal needle insertion by numerical simulation of a breast tissue model and by experiments *in vitro*. The data showed palpation-based needle insertion had a smaller error in both tests. Our findings suggest the procedure is a safe, effective alternative to traditional methods of breast tissue biopsy.**

I. Introduction

A. Needle insertion of breast cancer

Breast cancer accounts for more than a million of the estimated ten million malignancies diagnosed worldwide each year [1]. Breast imaging technologies for early diagnosis of disease are improving along with treatments that may improve the prognosis [2]. Recently, there has been a trend toward minimally invasive procedures such as needle biopsy and radiofrequency ablation (RFA).

RFA therapy uses stereotactic mammography, MRI, or 2D ultrasound imaging to guide insertion of a needle into cancerous tissue. Ultrasound has the advantages of real-time visualization and cost-effectiveness. During such a procedure, the clinician holds an ultrasound probe with one hand and inserts the needle with the other. Then, the needle emits RF energy from microwaves to heat and destroy a cancerous lesion.

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B. Problems

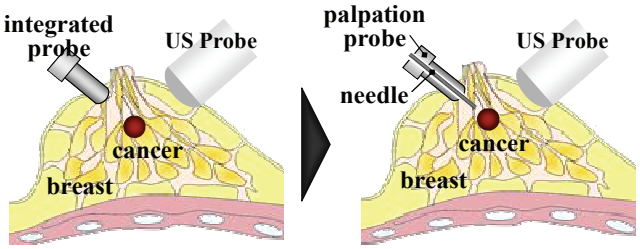
Technical challenges to needle insertion remain, however. Foremost among them are deformation of the soft tissue and displacement of the target lesion. Accurate placement of the needle is especially difficult with small, early breast cancer lesions only a few millimeters in diameter. Accurate needle insertion requires solving the problems of tissue deformation and target displacement.

C. Related work

Current research and development of robots and navigation systems for minimally invasive surgery aim to improve needle insertion and placement [3]-[5]. For example, Vishnu et al. manipulate the position of breast lesions by applying external actuators [6]. Alterovitz et al. simulate steerable insertion for prostate therapy [7-8]. DiMaio et al. measure planar tissue phantom deformation during insertion with a linear elastic material model [9-10]. Dehghan et al. determine the optimal angle of insertion and position with linear and nonlinear models [11]. Daniulaitis et al. use a physics-based model for medical palpation of deformable tissue [12]. Okamura et al. have empirical models for insertion force, tissue stiffness force, friction force, and puncture force [13]. Heverly et al. use the observation that the puncture force depends on the velocity of needle insertion [14].

D. Objective

Here, we report on a palpation-based needle insertion method for diagnostic biopsy and treatment of breast cancer (Fig.1). Our research focuses on improving needle insertion accuracy. We use numerical simulation and experiments *in vitro* to evaluate the effectiveness of robotic-assisted, palpation-based needle insertion of breast cancer.



(a) Palpation phase (b) Needle insertion phase

Fig. 1 The conceptual scheme of "Palpation based needle insertion"

The rest of the paper is organized as follows; Section II presents the method of palpation-based needle insertion. Section III shows our evaluation based on the numerical simulation. Section IV shows our evaluation based on experiments *in vitro*. Finally, section V provides the summary and the future work.

II. CONCEPT AND APPROACH

Our system has a palpation phase and a needle insertion phase to locate and pierce breast cancer lesions (Fig.1):

1) Detection of the lesion: High-resolution imaging technology of diagnostic systems distinguishes cancerous tissue from normal tissue. Nevertheless, manual palpation is also important for locating a lesion before treatment. Tactile information and visual information provided by other methods such as ultrasound confirms the location of the lesion. We used both palpation and ultrasound imaging to detect target areas (Fig. 1a).

2) Needle insertion: Earlier, we designed a model for simulating deformation and displacement [15-21]. The model determines the optimal path for placing the needle tip into a displaced cancer lesion. Unlike the liver, the breast is located outside the abdominal cavity and, therefore, is exposed. Therefore, other medical equipment such as a palpation probe can easily approach the breast. It has the potential to provide a solution to the problems of cancer displacement that is different from that provided for the abdominal organs.

Then, we research a palpation-based needle insertion method for diagnostic biopsy and treatment of breast cancer. Palpation-based needle insertion into breast tissue as described here minimizes cancer displacement by the probe. After locating the target, the probe presses on it to provide stability (Fig. 1a). Then, the needle for biopsy and treatment follows the same path as the probe (Fig. 1b).

This robotic system for needle insertion has the following potential advantages: 1) The success rate is high, because displacement is small; 2) Tissue damage is minimal; and 3) The procedure is fast. The same device palpates and inserts the needle sequentially.

We also reported on some aspects of the palpation method [22] as well as the concept of palpation-based needle insertion [23]. The current work evaluates the accuracy of needle insertion for treating breast cancer. Numerical simulations and experiments *in vitro* of both "palpation based needle insertion" and "normal needle insertion" were carried out for this evaluation.

III. VALIDATION by SIMULATION

This section shows evaluation of palpation based needle insertion by numerical simulations. Both "palpation based needle insertion" and "normal needle insertion" were simulated out for this evaluation to compare the results.

A. Numerical simulation

1) Breast model: We have already reported the validation of our breast model by comparing physical properties of the hog's breast [22]. Therefore, this paper gives specific descriptions of the development of the breast model.

Figure 2 depicts the mesh and shape of the model. The model breast was a flattened hemisphere, 100 mm in diameter. To develop the mesh, we used the Delaunay method to divide the object into triangular elements, based on the outline of the target. The mesh formed two circles. One had a diameter of 5.0 mm that circumscribed the triangular elements of the mesh. The other had a diameter of 1.0 mm that circumscribed elements within a radius of 20 mm from the point of needle contact. The breast model had a cancerous area thirty times firmer than normal tissue. As a boundary condition, we set the dorsal side of the model as the fixed end considering the effect of the sternum.

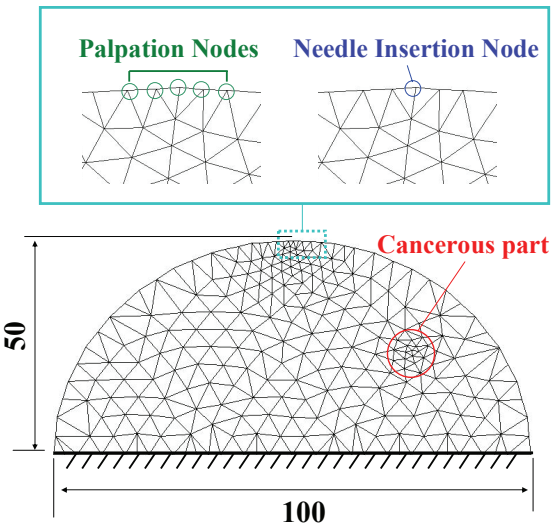


Fig. 2 Boundary condition of the breast model with cancer and produced mesh. A 2D slice of the breast model is defined using mesh triangular elements. This model shape is the same as the shape of cross section of the breast used in the experiment. The rear side of model is set to be fixed end. The total node number is 256.The total element number is 435, while the model thickness is 20 mm.

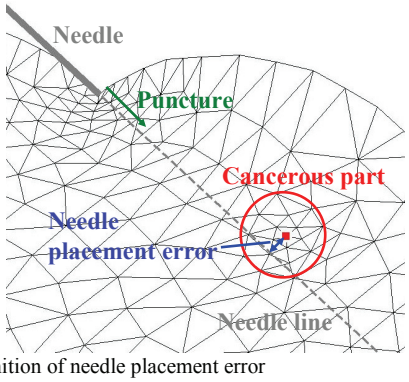


Fig. 3 Definition of needle placement error

2) Definition of insertion error: Piercing tissue with a needle involves pressing before puncturing. Accurate needle insertion requires alignment of the needle axis with the target lesion at the time of puncture. Insertion error is evaluated by L, which represents the distance between the center of the target lesion and the line of insertion at the time of puncture:

$$L=\frac{|aX_c+bY_c+c|}{\sqrt{a^2+b^2}} \quad (1)$$

where (X_c, Y_c) are coordinates of the center of the target lesion. The axis direction of the insertion is as follows:

$$ax+by+c=0 \quad (2)$$

The distance between the insertion line and target position should be as close to 0 as possible at the time of puncture.

3) Condition of normal insertion: The superior edge of the areola is a preferred location for insertion, so needle direction was downward from the upper half of the breast. We set the needle line to the center of the initial position of the target lesion. Displacement of a node at needle contact was a constant velocity of 4 mm/sec. Simulation concluded when stress on the element at needle contact equaled that at the point of puncture, 100KPa [23]. We measured time series data for model deformation, needle insertion error (1), and stress near the needle.

4) Condition of palpation-based insertion: We assumed that a palpation probe 5 mm in diameter entered the superior edge of the areola. Probe orientation was in the direction of the center of the lesion at each step of the simulation. Five nodes near the contact point underwent a 20 mm displacement at 4 mm/sec during palpation phase. Then, a central node of the palpated nodes underwent displacement at a constant velocity of 4 mm/sec (needle insertion phase). Simulation ended when the stress on the element at needle contact equaled that at the point of puncture, 100 KPa. Again, we measured time series data of model deformation, needle insertion error (1), and the stress near the needle.

B. Results and Discussion

1) Normal insertion: Figure 4 plots a time-series of stress for a simulation of normal needle insertion as well as the insertion error, L. Stress increased at a higher rate when needle displacement was large (t > 2 sec). At the time of puncture, stress near the needle was 100 KPa, and L was 2.8 mm. A model of deformation confirmed the center of the target lesion receded from the needle line during insertion, and a large insertion error occurred at the time of puncture (Fig. 5).

2) Palpation-based insertion: Figure 6 plots a time-series of stress near the needle during simulation of palpation-based insertion as well as the insertion error, L. The stress rate increased slowly during palpation phase (t < 5 sec) but was higher during insertion phase (t > 5 sec). L increased in proportion to displacement and was 0.7 mm at the time of puncture, only 25% of the error for normal needle insertion. Deformation results confirmed the center of the target lesion moved away from the needle line during insertion (Fig. 7).

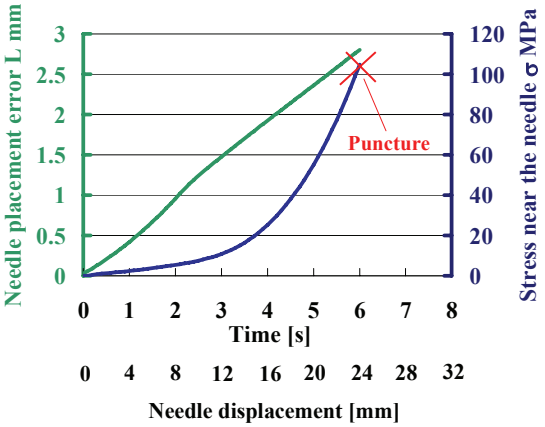
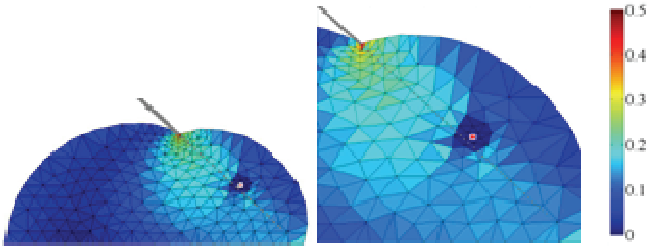
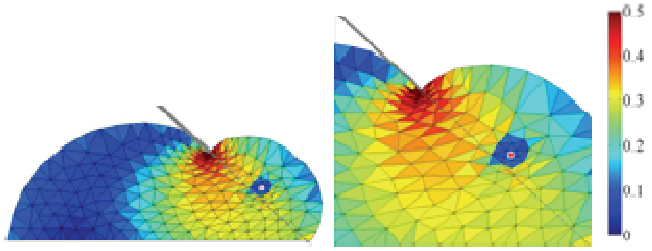


Fig. 4 Simulation of "Normal needle insertion".



(a-1) over view (a-2) enlarged view

(a) time:3 [s], needle displacement: 12[mm]



(b-1) over view (b-2) enlarged view

(b) time:6 [s], needle displacement: 24[mm]

Fig.5 Model deformation of " Normal needle insertion". The color of each element represents the strain of the element.

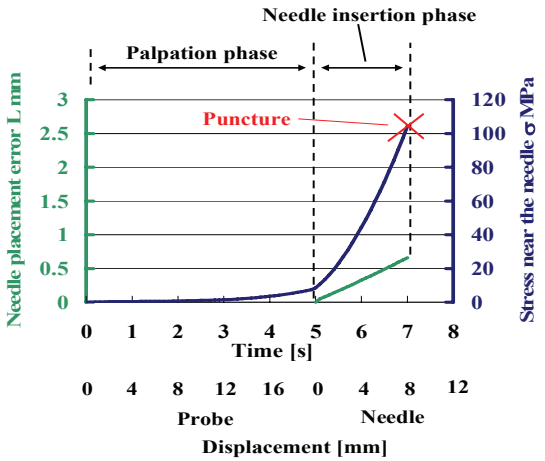
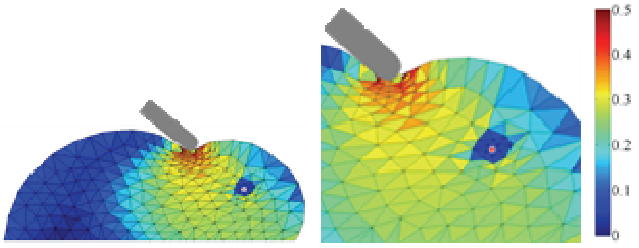
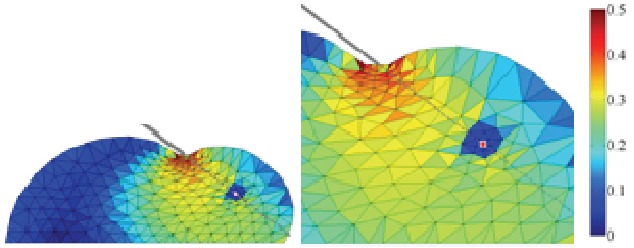


Fig. 6 Simulation result of "Palpation based needle insertion".



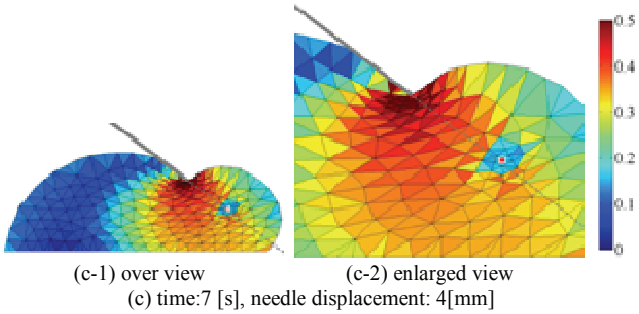
(a-1) over view (a-2) enlarged view

(a) time:5 [s], probe displacement: 20[mm]



(b-1) over view (b-2) enlarged view

(b) time:5 [s], needle displacement: 0[mm]



(c-1) over view (c-2) enlarged view

(c) time:7 [s], needle displacement: 4[mm]

Fig.7 Model deforamtaion of "Palpation based needle insertion". . The color of each element displays the strain of the element.

3) Discussion: During palpation-based insertion, stress near the needle was relatively small in early palpation phase but increased rapidly. Puncture occurred when there was little displacement of the target lesion. The results appear to explain the smaller L for palpation-based insertion. Accurate placement was possible, because pressure applied by the probe increased stress near the needle.

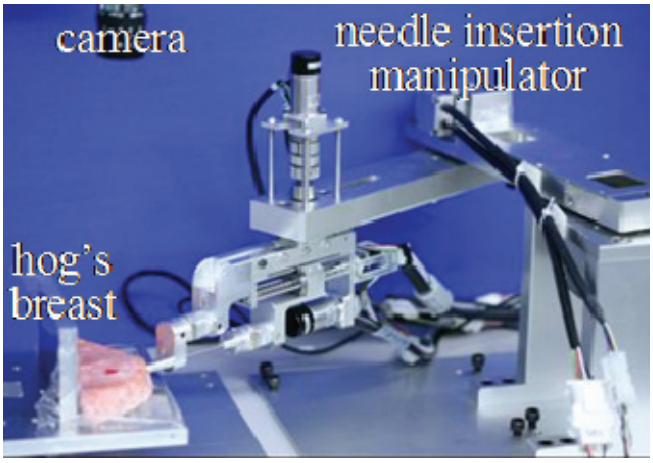
IV. VALIDATION by EXPERIMENTS *In Vitro*

This section shows evaluation of palpation based needle insertion by experiments *in vitro* using hog's breast. For this evaluation, both palpation based insertion and normal insertion were conducted for this evaluation to compare the results..

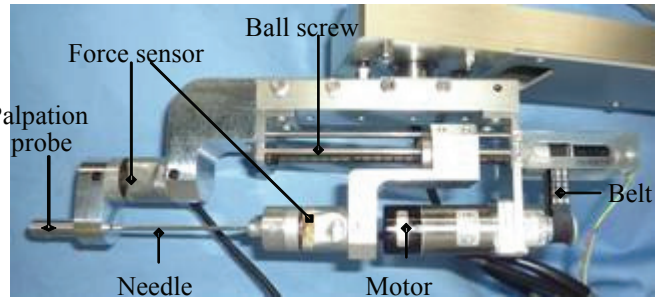
A. Experimental Setup

Figure 8 depicts the needle insertion manipulator and CCD camera used for *in vitro* experiments.

1) Hog breast with mock cancer: We used flattened hemispherical hog breast tissue, 100 mm in diameter and 20 mm thick. A silicone cylinder, 10 mm in diameter and 20 mm long, served as a mock cancer lesion embedded in the tissue (Fig. 9).



(a) Over view of *in vitro* experiment



(b) Enlarged view of the tip part of the needle insertion manipulator

Fig. 8 Experimental setup of *in vitro* experiment (the needle insertion manipulator, CCD camera and the hog breast)

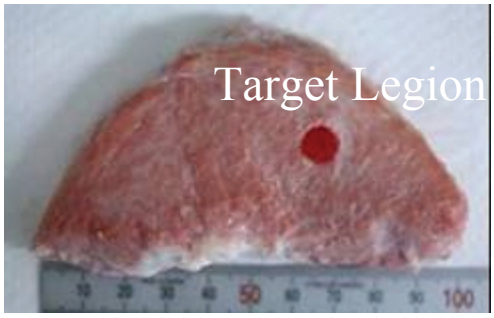


Fig. 9 Hog breast with a mock breast cancer of a cylindrical hard silicone

2) Needle insertion manipulator: The manipulator had four degrees of freedom for planar movements and components for positioning and integrating the apparatus. The positioning component had three serial joints with rotation degrees of freedom. The integrating component had two parts with separate drives, one for the palpation probe and another for needle insertion. The 5 mm diameter palpation probe had a center hole for inserting a 1.5 mm diameter needle. Six-axis force/torque sensors (NANO 1.2/1, BL AUTOTEC) attached to the root of the probe and needle.

3) Target position: To determine needle placement accuracy, we measured target location using a CCD camera and an image processing computer. This camera was set instead of US equipment. In clinical application, the medical US equipment is used for diagnostic imaging systems.

4) Needle and palpation probe position: We calculated needle tip and palpation probe tip positions from the angle of each joint of the manipulator, measured by encoders attached to the motors.

B. *Experimental Condition*

1) Needle placement error: We stopped needle movement when target position and needle tip were closest. Figure 10 shows the placement error, L, defined by the distance between the needle axis and the center of the mock cancer. It is important that the placement error L calculated using (1) be as close to 0 as possible when the needle movement was stopped.

2) Condition of normal insertion: Needle direction was downward from the upper half of the breast at a constant velocity of 4 mm/sec toward the center of the initial position of target lesion. Insertion was complete when target position and needle tip were closest. We measured force loaded on the needle, target position, and needle tip position to determine the placement error.

3) Condition of palpation-based insertion: The 5 mm diameter palpation probe pressed on the superior portion of hog breast. The probe moved 15 mm at 4 mm/sec during palpation phase with a position directed at the center of the lesion on the probe axis. Then, we inserted a needle at a constant velocity of 4 mm/sec. Insertion stopped when target position and needle tip were closest. Again, we measured the force loaded on the needle, target position, and needle tip position to determine the placement error.

C. *Result and Discussion*

1) Result of normal needle insertion: Figure 11shows the initial condition of the hog breast tissue and deformation of after needle insertion. We recorded a time-series of the force loaded on the needle and needle placement error (Fig. 12). Force increased nonlinearly at a higher rate when the time was longer than 6 sec. Needle puncture occurred at 8.5 sec, and L was 1.8 mm when displacement increased.

2) Palpation-based insertion: The two panels of Fig. 13a depict the initial condition of the hog breast in palpation phase and an image at the end of the phase. Likewise, those of Fig. 13b depict the initial condition of the needle insertion phase and the deformation at the end of the phase. Figure 14 plots the time-series of force loaded on the needle and needle placement error, L.

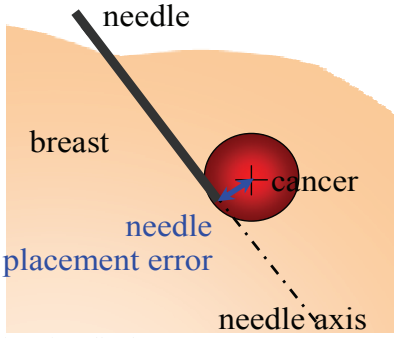
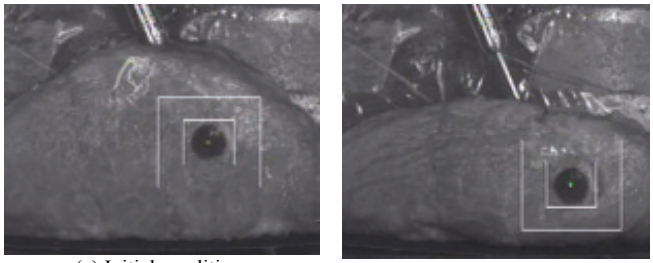


Fig. 10 Definition of needle placement error



(a) Initial condition (b) Final condition

Fig. 11 Camera image of " Normal needle insertion"

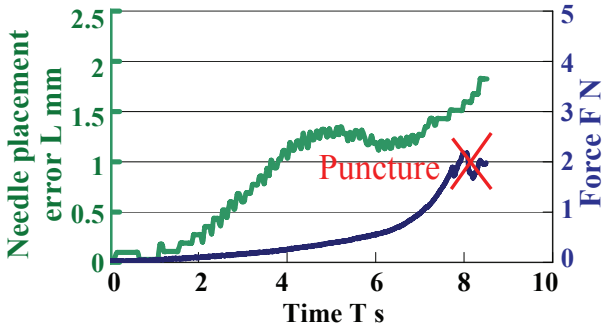
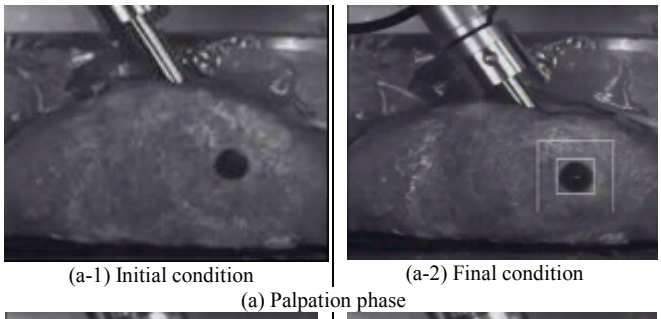
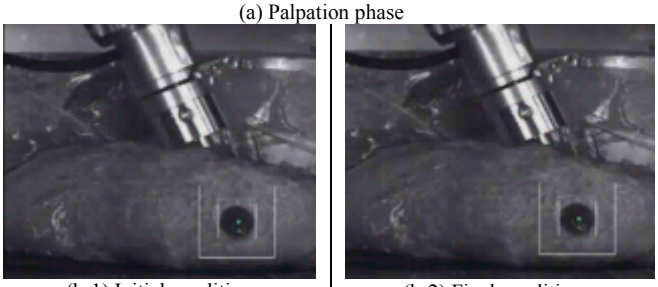


Fig. 12 Experimental result of "normal needle insertion"; time change of needle placement error and force value



(a-1) Initial condition (a-2) Final condition

(a) Palpation phase



(b-1) Initial condition (b-2) Final condition

(b) Needle insertion phase

Fig. 13 Camera image of " Palpation based needle insertion"

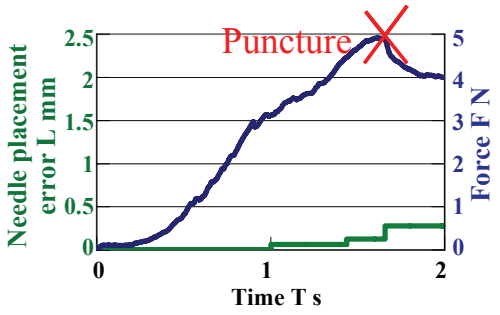


Fig. 14 Experimental result of "palpation based needle insertion"; time change of needle placement error and force value

Force increased nonlinearly at a higher rate than that of normal needle insertion when time exceeded 0.5 sec. Needle puncture occurred at 1.5 sec, and L for palpation-based insertion was 0.3 mm, only 15% of the error for normal insertion. During palpation-based insertion, puncture occurred when there was little displacement of the target lesion by the probe pressure.

3) Discussion: The findings suggest the error in needle displacement for palpation-based insertion is significantly less than that of normal insertion. Accordingly, this robot-assisted approach offers a promising alternative to traditional methods of needle biopsy and treatment of breast cancer.

V. SUMMARY AND FUTURE WORK

We describe here a palpation-based needle insertion method for diagnostic biopsy and treatment of breast cancer. The mechanical palpation probe locates cancerous tissue from force information and reduces tissue displacement during needle insertion. We compared palpation-based needle insertion to normal needle insertion by numerical simulation of a breast tissue model and by experiments *in vitro*. The data showed palpation-based needle insertion had a smaller error in both tests. During palpation-based insertion, accurate placement was possible, because the probe presses on the breast to increase stress near the needle before insertion and provide little displacement of the target legion during insertion phase. Our findings suggest the procedure is a safe, effective alternative to traditional methods of breast tissue biopsy.

Future research will focus on improving the reliability and accuracy of needle insertion for biopsy and treatment of breast cancer. We will also look for new ways to optimize the force of pressing the probe during palpation phase and construct a 3D model of human breast tissue. Our goal is to construct a surgical robot that incorporates both the needle insertion and palpation systems for clinical applications.

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