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A Stiffness Probe Based on Force and Vision Sensing for Soft Tissue Diagnosis

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***Abstract*— this paper introduces a novel approach of stiffness measurement based on force and vision sensing for tissue diagnosis. The developed probe is mainly composed of a force sensor and an image acquisition unit capable of obtaining contact area of probe-soft tissue interaction. By measuring the change of diameter of contact area during indentation test, the indentation depth can be determined. The stiffness of target soft tissue then can be evaluated by measuring indentation force and depth simultaneously. The probe can generalize a mechanical image to visualize the stiffness distribution for localization of abnormalities when sliding over soft tissue.**

The performance of the developed probe was validated by experiments on multiple materials including silicone phantoms and pork organs. The results show that the probe can perform stiffness measurement effectively when the probe indents or slides on the tissue surface.

I. Introduction

Tissue stiffness is an important parameter in finding tumors within organs since diseased tissue is typically stiffer than the surrounding tissue [1], allowing it to be easily identified when palpated in open surgery. Furthermore, it can provide useful information for various biomedical applications such as health monitoring and tissue cutting.

To understand the stiffness distribution of soft tissue, several techniques have been proposed. The most generally utilized method is based on the force-displacement response of the target soft tissue. An instrument indents the tissue and the applied force is measured after a constant deformation or angular displacement is applied [2-3]. P. Peng et al. [4] proposed a novel type of stiffness sensor based on Micro-electro-mechanical systems (MEMS).

Liu et al. have proposed a new rolling indentation approach for identification and localization of tissue abnormalities during minimally invasive surgery (MIS) [5]. This approach employs a force-sensitive wheel to roll over a soft tissue organ, allowing rapid measurement of the tissue stiffness. Based on this approach, a fiber-optic probe has been developed for conducting rolling indentation. The probe is composed of one force sensor and four indentation depth sensors. It can measure the indentation depth and the indentation force at the same time. However, the main limitation of this instrument is that the moving parts could reduce the reliability and it could be difficult to fabricate in mass production.

No-contact probes have been proposed as well in recent years. Kaneko et al. have proposed one endoscope camera that can acquire stiffness and vision data within human stomach [6]. The stomach is deformed by an air puff and a camera is used to measure the relative displacement of deformation. Based on this idea, a non-contact stiffness imager was proposed to detect the stiffness distribution using a visual pattern. However, only visual pattern doesn't provide surgeons with accurate stiffness value of target tissue.

The probe proposed in this paper is based on several of the aforementioned technologies and techniques for stiffness measurement. The probe uses force and vision sensing in order to determine the stiffness of soft tissue organs, integrating a force sensor with a clear sphere mounted at one end of a shaft which is connected to a miniature microscope mounted at the other end of the shaft, Fig.1 (a). The digital microscope displays and records the contact area between the sphere and tissue, information which can be used to calculate the indentation depth. The force sensor is used to measure the indentation force during test. By combining the depth and force measurements, the tissue stiffness can be mapped. Moreover, since the sphere is clear, it can also be used by surgeons to observe the tissue visually, doubling the probe's purpose as an endoscope.

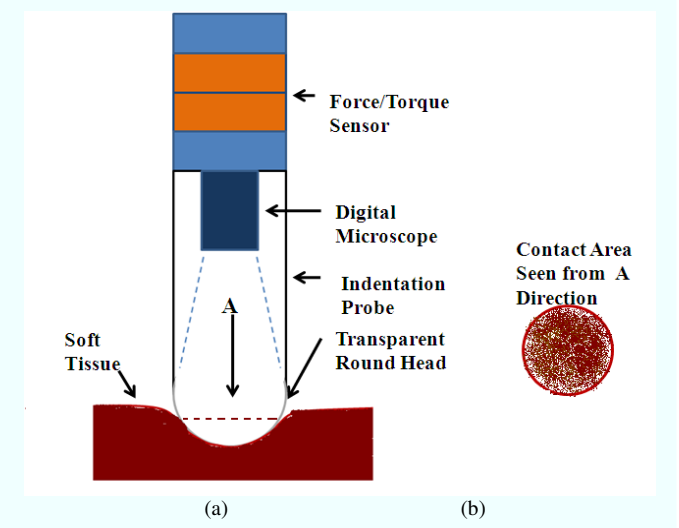

Fig. 1 (a) the stiffness probe integrates a force/ torque sensor with a clear sphere mounted at one end of a shaft which is connected to a miniature microscope mounted at the other end of the shaft. (b) Contact area acquired from the digital microscope.

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This paper is organized as follows. In section II, we describe the prototype and the working principle of the stiffness probe. In section III, we discuss experiments of indentation depth measurement. In section IV, experiments of tissue abnormality identification from sliding indentation is investigated. Finally, discussions and conclusions are drawn in section Ⅴ.

Ⅱ. The Development of Probe and Working Principle

A. *System of Stiffness Probe*

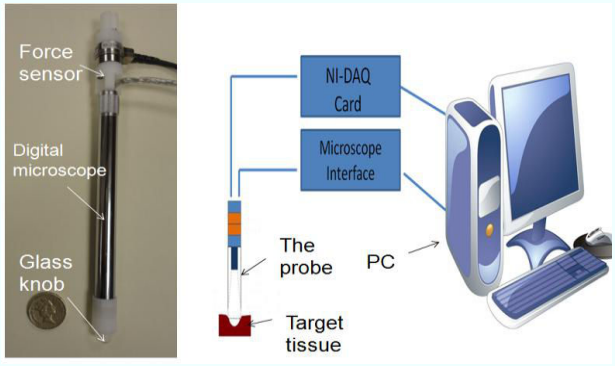
Fig. 2(a) shows the overview of the prototype of the proposed stiffness probe. The probe mainly consists of a 6-axis force/torque sensor (Mini17, ATI Industrial Automation) for measuring of the indentation force, a digital microscope with 400× magnification for capturing contact area of probe-tissue interaction, a transparent round head made from borosilicate glass. The diameter of the glass knob is 10 mm. The image sensor of the digital microscope is 1.3 Megapixel Complementary metal-oxide-semiconductor (CMOS)sensor with a maximum capture resolution of 1600×1200 pixels. These parts are all integrated with acrylonitrile butadiene styrene (ABS) plastic connectors made by a rapid prototyping process with a maximum diameter of 17 mm.

Fig. 2(b) shows the overview of the complete experimental system, comprising the proposed probe, a NI DAQ system, an image processing system and a PC.

B. *Sensing Principle of Indentation Depth &Contact Area*

Generally, when the soft tissue deforms due to given force of the proposed probe, a contour map pattern using the brightness distribution of the light source of digital microscope can be observed. Due to the round-shape head of the probe, circular area will appear around the point where the indentation depth happens. With increasing of indentation depth, the diameter of circular marks obviously increases.

However, it is hard to see the indentation depth directly from the vision data captured by the digital microscope. In order to analyze the effect of the indentation, the edge of the contact area is detected by image processing. Under general circumstances, the contact area is approximately a circle.



(a) (b)

Fig. 2 (a) overviews of the proposed stiffness probe. (b) Overview of experimental system.

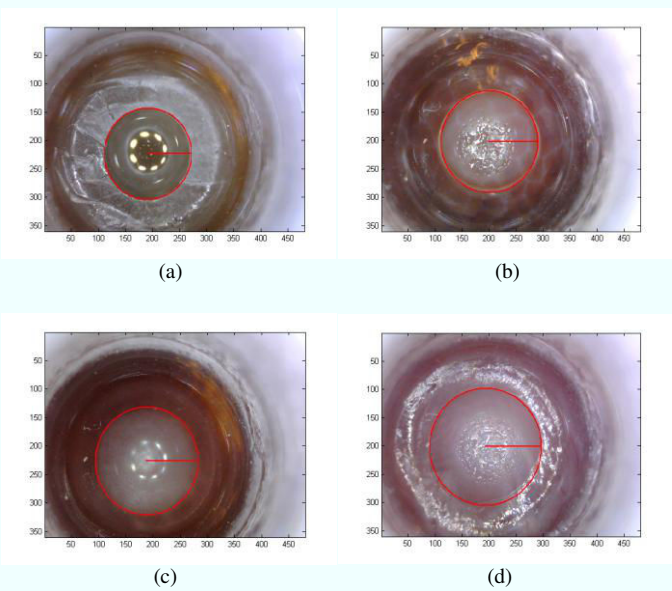
Hence, a circle which has the most approximately area is used to describe the contact area. By measuring the diameter of the contact area (image processing software,HIG, from Holdtecs, Shuyou Ltd, is used for measurement), the indentation depth can be estimated. Knowing the indentation force and depth, we can obtain the stiffness of the target tissue.

Experiments to capture the contact areas were conducted on silicone phantoms, porcine liver, porcine kidney and porcine heart. The ex-vivo samples used in these experiments were fresh porcine organs obtained from a local store. These samples were obtained on the day of the experiments and transported to the lab within approximately 20 minutes after purchasing them. The lab conditions were as follows: lab temperature = 18.1°C, lab humidity = 30%. The protocol utilized for these experiments is listed below:

1. One point of the sample was selected randomly and the probe was hold by hand to carry out a single indention manually.
2. The digital microscope was activated to capture the image of interaction of probe-soft tissue using the HIG software.
3. The captured image was analyzed using the HIG software and the contact area is drawn automatically by using the "Extract Circle" menu. Three points of the edge of the contact circle need to be input manually. It's noted that the focal length of camera is assumed to be a constant value.

Results showed that the approach of measuring the contact area is applicative on simulated soft tissue and real organs of pork, Fig. 3. It is noted that the accuracy for measurement of diameters of the contact area is 0.01mm by using commercial image processing software, which is applicative for measuring deformation of the soft tissue.

To obtain the indentation depth, the relation between



(a) (b) (c) (d)

Fig. 3 the red circles show the captured contact area during indentation experiments using the developed probe. (a) contact area on silicone phantom, (b) contact area on pork liver,(c) contact area on pork kidney, and (d) contact area on pork heart. All units are in "pixel".

the indentation depth and the diameter of the contact area need to be calibrated using mathematic model. Then the indentation depth on samples with different stiffness can be estimated using the model. The calibration is described in detail in Section III.

C. Identify Stiffness using Indentation Force and Depth

The investigated tissue organ is assumed to have the following properties: 1) the tissue is linear elastic since biological tissues exhibit linear elasticity with small deformation (a relative strain under 10 to 15%) [7]; 2) the curvature of tissue surface is much larger than the diameter of the roller; 3) the normal tissue of the organ is isotropic, homogenous and incompressible. While this assumption may cause the difficulties of indentifying deep embedded tumors in the tissues, the probe is design to non-invasively identify the tumors from large solid organs such as liver and kidney with small indentation depths. According to the above assumption, Tissue stiffness can be represented using the tissue's elastic modulus through the measurements of indentation force and indentation depth [7].

The elastic modulus of tissue can be estimated as:

$$E = \frac{3f(1+\nu)}{8h_i\sqrt{rh_i}}, \quad (1)$$

Where E is the elastic modulus, f is the tissue reaction force normal to tissue surface, ν is the Poisson ratio (For incompressible material, ν =0.5), h_i is the indentation depth and r is the radius of the sphere head of indenter.

To validate the linear elastic assumption, indentation tests were conducted on silicone phantom and pork organs. During experiments, the probe indented into samples by 5 mm at a speed of 5mm/second, driven by a robotic manipulator Mitsubishi RV-6SL, Fig. 4.The image acquisition speed is 20 frame/second.

Fig. 5 shows the results of the experiments. It was found that Eq. 1 fit the measurements well when the indentation depth is small (R^2 >0.96, h_i< 3.2 mm). The estimated results show good agreement with existing literatures [6, 8, 9].

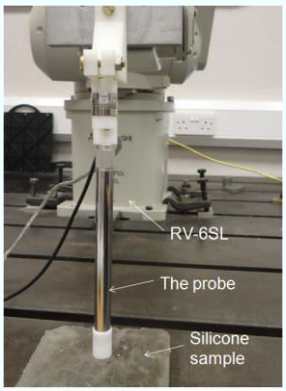


Fig. 4. The experimental setup for calibrating the relation of indentation depth and diameter of contact area using the proposed stiffness probe.

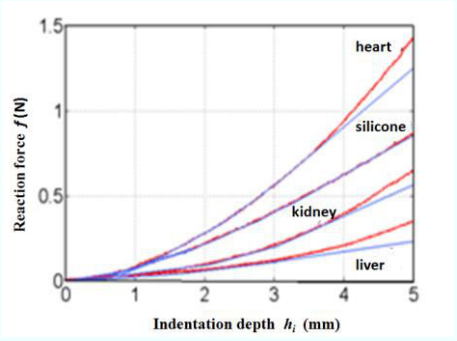


Fig.5. The relation of tissue reaction force with the indentation depth of the stiffness probe; the blue solid lines are the estimations using eq.1, the red solid lines are the experimental measurements.

III. Experiments of Indentation Depth Measurement

A. Calibration of Relation of Indentation depth and Diameter of Contact Area

The calibration is necessary because the relation of the indentation depth (h_i) and the diameter of contact area (d_c) can be varied for different materials. To calibrate the relation of h_i and d_c. Experiments were conducted on four silicone phantoms (SP1, SP2, SP3 and SP4) made from the RTV6166 gels with different stiffness. The dimension of these silicone samples is with the dimension of 100 mm ×100 mm × 30 mm. The elastic moduli of SP1, SP2, SP3 and SP4 were measured as 8.4 KPa, 18.2 KPa, 30.6 KPa and 51.2 KPa respectively.

The relation of h_i and d_c was modelled using an exponential function described in [8]:

$$h_i = A(e^{Bd_c} - 1), \quad (2)$$

Where A and B are the coefficients need to be calibrated since they are related to the tissue mechanical properties, size of indenter and the displacement of contactors.

Fig. 6 shows the results for calibrating the relation of h_i and d_c using the stiffness probe. Coefficient B was fixed to 0.46 for all the samples and coefficient A was estimated as was 0.32 for SP1, 0.21 for SP2, 0.18 for SP3 and 0.14 for SP4.It was found that Eq.2 provides well approximation for all the samples (R^2 >0.95).

Fig. 6 also shows that the measured d_c increases as the increase of tissue stiffness at same indentation depth h_i. This implies that the indentation depth will be over-estimated for high stiffness if the probe is calibrated based on low stiffness.

To investigate the error of the measurement of h_i, the calibration result of SP1 is used for measurement of other three samples. It was found that the over-estimation of h_i increases with the increase of tissue stiffness (16%, 26% and 39%). According to Eq. 1, the over-estimation of h_i will lead to the under-estimation of the elastic modulus for area with higher stiffness. However, the estimated elastic modulus has an incremental relationship with the ground truth of stiffness (14.4KPa, 21.4KPa and 30.7Kpa). This indicates that the probe is capable of differentiating soft tissue stiffness.

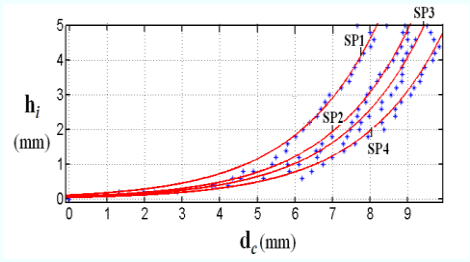
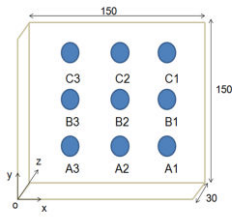


Fig. 6 The relation of h_i and d_c for four silicone phantoms with different stiffness; the blue pentagrams are the averaged measurements and the solid red lines are the fitted curves.

Ⅳ.Tissue Abnormality Identification Using S liding Indentation

To analyse the capability for tissue abnormality identification and localization using the proposed probe, Sliding indentation tests were carried out on a silicone phantom embedded with nine spherical simulated tumors made from rubbers. Fig. 7 shows the dimensions of the simulated soft tissue and the localization of the simulated tumors. The elastic modulus of the tumor was 219 KPa and that of the silicone phantom was measured as 14.7± 2.4 KPa .

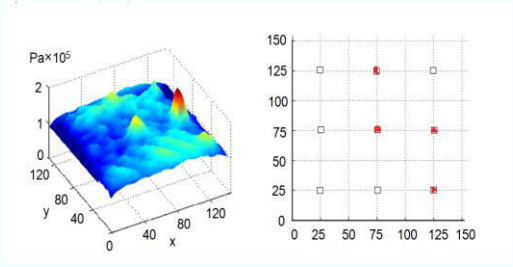


Nodules	Depth	Location (x, y)
A1	5	125, 25
A2	10	75, 25
A3	15	25, 25
B1	5	125, 75
B2	10	75, 75
B3	15	25, 75
C1	5	125, 125
C2	10	75, 125
C3	15	25,125

Fig. 7 Schematics of the silicone phantom buried with nine simulated tumors and their locations and buried depths.all units are in "mm".

The silicone phantom has an uneven surface and the average surface height is 30 ± 1.16 mm. In order to follow the linear elastic assumption of tissue, the maximum indentation depth was selected as 4 mm. The probe was driven by robotic manipulator at a speed of 5 mm/second and the image acquisition speed is 20 frame/second.

Prior to tests, the probe was programmed to follow multiple paths defined within a plane parallel to the *x*-*y* plane defined in Fig. 7. The height of the plane was defined as 27mm causing an average indentation depth of 3 mm. To evaluate the robustness and repeatability of the probe, sliding indentation experiments were repeated five times.



(a) (b)

Fig. 8 (a) the stiffness map produced by sliding over the tissue using the proposed probe with an average indentation depth of 3 mm; (b) the identified locations of tumors for each experiment

After each test, the estimated tissue elastic moduli along the rolling path were fused together to generate a stiffness map [5]. Fig. 8(a) shows the generated stiffness map and Fig. 8(b) indicates the location of the detected tumors.

Compared with the ground truth, the errors of the identified tumor locations are ranged from 0.28 mm to 1.54 mm in *x* axis and from 0.32 mm to 1.98 mm in *y* axis. The standard deviations are ranged from 1.24 mm to 1.50 mm along the *x* axis and from 1.22 mm to 1.96 mm along the *y* axis. This indicates that the accuracy and reputability of the localization of the identifiable tumors by using the proposed probe are very well.

Ⅳ.Conclusions and Discussions

This paper introduces a stiffness probe which can measure both the tissue reaction force and the indentation depth during sliding indentation. Tests indicate that using the probe for identification of tissue abnormality is applicative.

In biomedical field, the probe has the potential to aid clinicians to localize the position of tumor. Furthermore, it can also acts as an endoscope, helping the surgeons to observe certain area of organ directly without any redundant tools. Due to its simple sensing structure without any moving parts, it is easy to manufacture and the probe can be miniaturized for many biomedical applications.

However, there are several limitations of the probe. First, it is time consuming to processing a mass of images. Secondly, this probe has difficulties to identify the deep embedded tumors inside the soft tissue. This suggests that more study for bench mark of the probe need to be investigated in the future.

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