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Inclusion Detection with Haptic-Palpation System for Medical Telediagnosis

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***Abstract*—Detection of abnormalities in subcutaneous tissue is an important issue in medical diagnosis. Surgeons palpate this type of tissue to perceive pathologies through haptic sensation. This paper presents the framework of a real-time haptic-palpation system with inclusion detection to manipulate biological soft tissues and perceive their structures and material properties non-invasively. A user with a haptic device guides a robotic manipulator to perform palpation tasks and can detect the location of inclusions inside a soft medium (silicone-molded tissue phantom). For the objective measurement of the depth of the inclusion, a finite element (FE) model was developed to predict the reaction forces for various inclusion depths. The methods presented in this paper can be applied to the early detection of prostate cancer or breast cancer in telediagnosis.**

I. Introduction

PALPATION has been used for the detection of diseased tissues as a diagnosis procedure as well as for the positioning of anatomical landmarks. When surgeons attempt to detect tumors in some specific human organ tissues, they discriminate between tumors and normal tissues through stiffness differences. As the stiffness of a tumor is different from that of surrounding intact tissue [1], surgeons can distinguish tumors from healthy tissue by palpation using their sense of touch. For example, to obtain prognostic information for the early detection of prostate cancer, a digital rectal examination (DRE) is widely used to detect malignant or benign prostate tumors. Urologists insert a gloved and lubricated finger into the rectum of the patients in an effort to detect by palpation tumors that can develop in the posterior region of the prostate. Due to early detection and improvements in the treatment of prostate cancer, the 5-year relative survival rate for all patients has increased from 69 % to nearly 99 % in the last 25 years [2].

There is increasing demand for medical diagnoses of patients in remote areas. Hence, teleoperation for diagnoses and medical examinations has been widely studied. A system enabling a surgeon to palpate remote patients can improve clinical management by enabling the early detection of tumors. In telediagnosis, most communication channels for diagnostic information are audio and visual channels [3]; however, the stiffness characteristics of objects can be discriminated equally well through a haptic channel [4]. Recently, haptic feedback has been applied in medical interventions with robotic manipulators to sense a physical environment at a remote site in such procedures as robotic surgeries. The feedback of haptic information can provide surgeons with precise collision information between objects, enabling the surgeon to control the manipulating force during surgical tasks with safety and dexterity. In addition, it can offer valuable information (e.g., tissue elasticity) pertaining to diagnostic examinations. Several studies related to medical diagnoses through stiffness sensations have been conducted for virtual reality-based training systems [5], [6], stiffness discrimination using haptic sensors [7], and haptic feedback through robotic devices [8]–[10]. Nonetheless, there are few studies on the subject of telepalpation systems with haptic feedback [11].

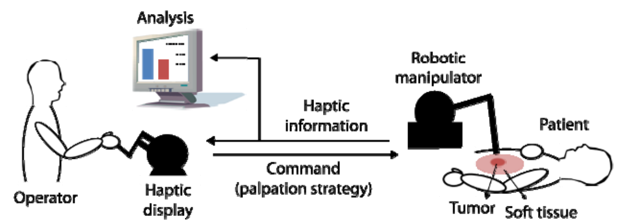

Fig. 1. Conceptual diagram of a haptic-palpation system for medical telediagnosis.

In this paper, an inclusion detection method with a real-time haptic-palpation system for medical telediagnosis is presented. A user with a haptic device guides a robotic manipulator equipped with a force sensor to perform manipulation tasks, and the measured haptic information is then transferred to the user through a haptic device. Using this procedure, the user can feel the material properties of a soft medium and detect the location of inclusions inside of it (Fig. 1). In addition, the objective measurement of the depth of the inclusion is achieved using force-displacement data based on the finite element (FE) model of a soft medium and the developed matching algorithm.

II. Methods and Materials

A. System Setup

The experimental haptic-palpation system consists of a haptic interface and a robotic manipulator (Fig. 2). The PHANToM Premium 1.0 model from SensAble

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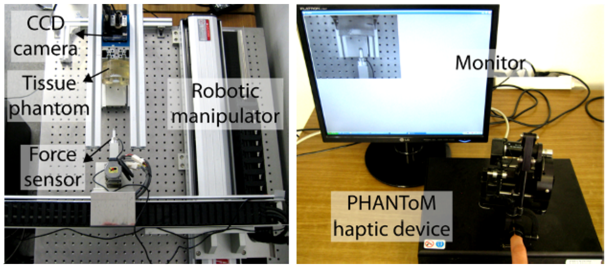


(a) (b)

Fig. 2. Experimental haptic-palpation system: (a) a linear planar manipulator with a force sensor at the end-effector, a tissue phantom, and a CCD camera, (b) a master haptic device and a monitor.

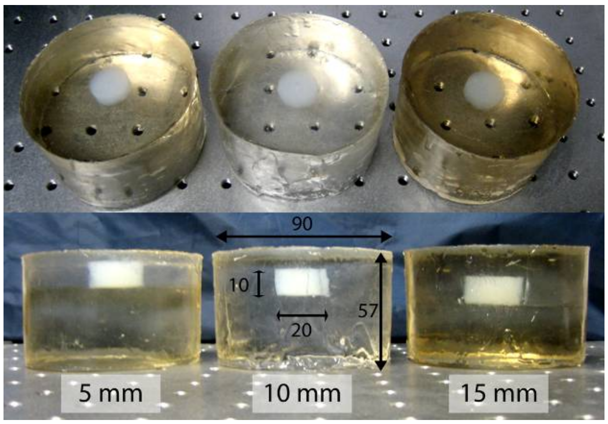


Fig. 3. Soft tissue phantoms with different depth inclusions.

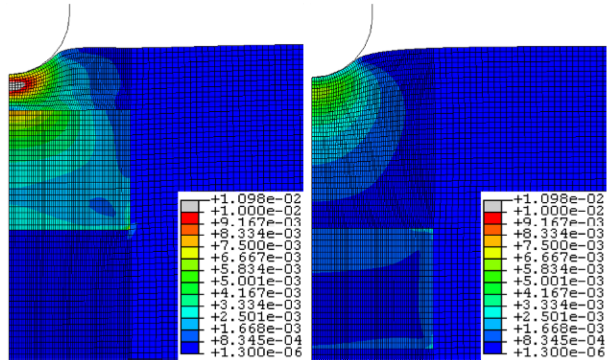
Technologies Inc. is used as a master interface. A linear planar manipulator (500 mm × 500 mm) with an indenter (10 mm diameter round tip) at the end-effector performs the palpation tasks guided by the haptic interface. The contact force is measured using a one-axis force transducer (Senstech Co. Ltd., SUMMA-5K, Korea) with a resolution of 50 mN and is transmitted to a computer (Pentium-IV 2.40 GHz) through a data acquisition system (National Instrument, USB-6211, USA). The deformation of the tissue phantom and the motion of the robotic manipulator were captured by a CCD camera (SVS340MUCP, SVS-Vistek, Seefeld, Germany with a 640 × 480 pixel resolution and maximum of 250 fps) for visual feedback for the user.

The tissue phantoms used in this study were molded from silicone (DongYang Silicone Co. Ltd., DSE 7310, DLE 40, Korea). Three phantom models were created for inclusion detections with 5 mm, 10 mm, and 15 mm depth inclusions from the surface (Fig. 3).

In the telemanipulation control structure, the position of the PHANToM is applied to the robotic manipulator for the position command, and the displayed force F_h for force feedback is computed by

$$F_h = \alpha_s F_s + k_p (p_s - \beta_s p_m), \qquad (1)$$

where the second term on the right side indicates the virtual force that is created by a virtual spring for position coupling between the PHANToM and the manipulator [12]. k_p is the virtual spring constant, and p_s and $\beta_s p_m$ are the manipulator tip and the scaled PHANToM positions, respectively. F_s and α_s are the measured force from the transducer and a force scaling factor, respectively ($\alpha_s = \beta_s = 1$ for a non-scaled master-slave). When the PHANToM and the manipulator tip position are different due to delayed reaction, the virtual force, proportional to the position difference, is computed to make the position error zero. Although force feedback in a telemanipulation system induces the problem of system stability and performance [13], this paper focuses on the sensation of stiffness differences to detect inclusions rather than the development of a stable or a perfectly transparent system.



(a) (b)

Fig. 4. Resulting force distribution by FE analysis; (a) 5 mm and (b) 15 mm depth inclusion.

B. FE Modeling for Tissue Phantom

In order to provide the quantitative information of inclusions in a telepalpation, an inclusion depth detection algorithm is developed based on the database of the tissue phantom. A FE model of the tissue phantom was constructed to predict the reaction forces of various inclusion depths, including the geometries of the tissue phantom and the indenter. An axisymmetric half tissue phantom model was developed with a half width of 45 mm and a height of 57 mm. The elasticity of a tissue phantom was measured in an off-line indentation experiment using a Hertz-Sneddon model [14]. The estimated Young's modulus (E) of the tissue phantom and the inclusion are 15.3 kPa and 13.1 MPa, respectively. The estimated elasticity and a Poisson's ratio of 0.49 were applied to the model. Displacement boundary conditions are applied to the indenter and to the tissue phantom, while symmetric boundary conditions are used along the axis of symmetry. The tissue phantom is constrained to assume perfect contact with the base and frictionless surface. The FE analysis was performed using ABAQUS/Standard 6.5.1. (Simulia, USA) and the force response for the given input displacement was recorded (Fig. 4).

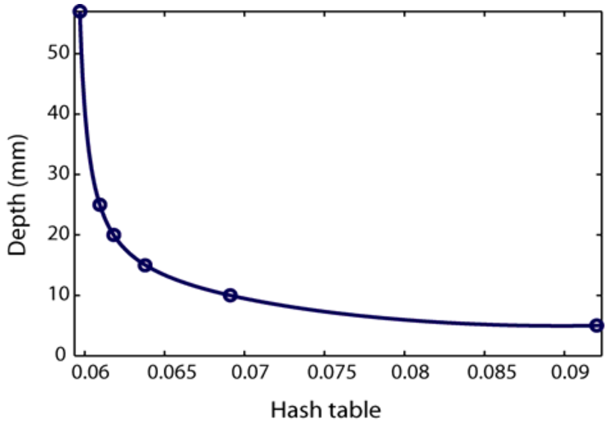


Fig. 5. Depth estimation curve for the hash function.

C. Inclusion Depth Estimation

Based on the force-displacement data from the FE model, the inclusion depth from the surface was estimated. The force-displacement data from the FE model is fitted by a cubic polynomial for various inclusion depths.

$$f_d = c_1 d^3 + c_2 d^2 + c_3 d + c_4 \quad (2)$$

where f_d and d are a reaction force and an input displacement, respectively. During the haptic palpation tasks, the measured force-displacement data was also fitted by (2) and matched to the preprocessed data from the FE analysis. For fast matching for a real-time haptic palpation application, a hash function was used as a mapping function between the inclusion depth and parameters in (2). The input key for the hash function is c_1, c_2, c_3, and c_4, and the hash function h is defined as the coefficient folding $\sum c_i$. Inclusion depths of 5 mm to 25 mm with increments of 5 mm were analyzed for the FE model, and the function of the depth and the hash table was fitted (Fig. 5) and obtained as

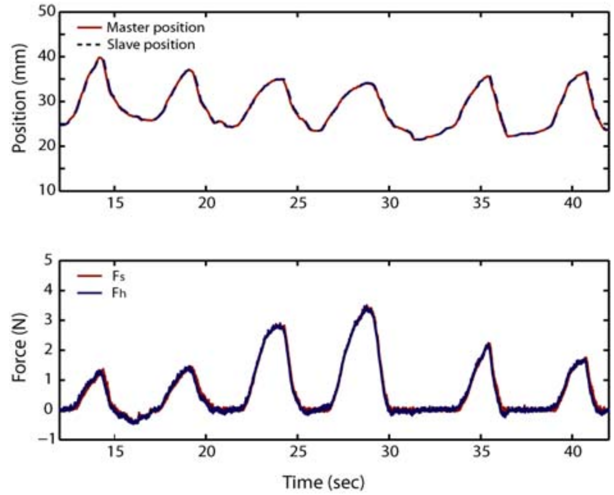
$$depth = \frac{9008h^3 - 2124h^2 + 168.5h - 4.372}{h - 0.05914}, h = \sum c_i . \quad (3)$$

Finally, the estimated depth information is displayed to the user through a monitor.

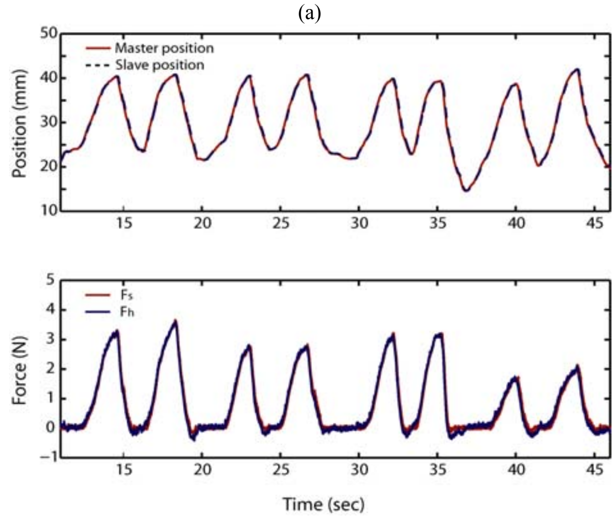
III. Experimental Results

In the experiment, the user can feel the force along with the vertical direction (indentation) of the surface during the interactions, and Chlorhexidine cream (Arlico Pharm. Co. Ltd., Korea) was used to make the frictionless surface. To perceive the flat surface stiffness differences due to inclusion, the user can palpate the soft tissue phantom with various interaction strategies. The tapping (indentation direction) strategy is required to assess surface stiffness compared to lateral direction stroking [15].

Fig. 6 shows the results of indentation (tapping) experiments with inclusion depths of 5 mm and 15 mm. In both results, when the user exerts the same amount of deformation, larger amounts of force are induced on the surface position with the inclusion (third and fourth peaks in Fig. 6(a) and the first, second, fifth, and sixth peaks in Fig. 6(b)). The user perceives the stiffness difference and the



(a)



(b)

Fig. 6. Indentation (tapping) experiment for (a) 5 mm and (b) 15 mm depth inclusion.

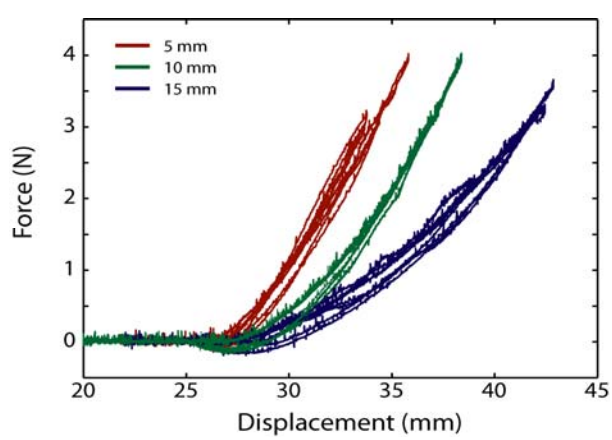


Fig. 7. Force-displacement curve from the experiment.

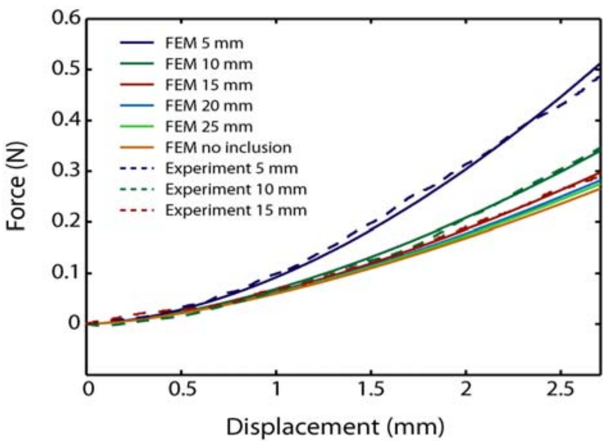


Fig. 8. Force-displacement curve from the FE analysis and the filtered experiment data.

TABLE I
INCLUSION DEPTH ESTIMATION

Exact value		Estimated value	
Depth	$h(\sum c_i)$	Depth	$h(\sum c_i)$
5.0	0.0920196	5.1039	0.0925485
10.0	0.0691126	9.8251	0.0697493
15.0	0.0637914	13.2451	0.0654103

position of the inclusion through kinesthetic perception via the position and force of PHANToM.

The inclusion depth detection algorithm is performed in real time during the interaction with the inclusion. Fig. 7 presents the raw force-displacement data. The data is recorded during movements in the indentation direction (that is, before a reversal), and different force responses can be observed. The data is low-pass filtered and the filtered data is curve-fitted to (2). The filter frequency was determined empirically as 20 Hz. In Fig. 8, force-displacement data is presented from the FE analysis and the experiments. The results show a reasonable match between the experiment and the FE model. The result for the estimated depth information is shown in Table I.

IV. CONCLUSION

In this paper, inclusion detection with a real-time haptic-palpation system is presented. When a user with a haptic device guides a robotic manipulator equipped with a force transducer and performs the palpation operation, the user can feel stiffness differences and detect the location of internal inclusions. In addition, the objective measurement of the depth of an inclusion is achieved using force-displacement data based on the FE model with the proposed estimation algorithm. Experimental results demonstrate the feedback of the stiffness sensation to a user as well as the detection of the inclusion. The methods presented in this paper are expected to have various applications for medical telediagnosis, such as tumor detections in prostate cancer or breast cancer cases and hidden artery detection during minimal invasive surgical procedures.

In a future work, an FE model for human intra organs will be created in conjunction with our previous work [16] for a clinical experiment using a developed minimally invasive motorized indenter. In addition, the system will be updated for inclusions of various sizes and stiffness values and for soft tissue phantoms with non-flat surface (random surface topography). Psychophysics experiments for human subjects will also be conducted to validate the benefits of force feedback and for the determination of detection thresholds with various inclusion conditions. In addition, network latency will be considered as a transparency issue.

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