Localization of Abnormality using Finite Element Modeling of Prostate Glands with Robotic System: A Preliminary Study

Hyosang Lee, Yeongjin Kim, Yong Kyun Shin, Bummo Ahn, Koonho Rha, and Jung Kim

Abstract—Combined with medical robotic system, mechanical property characterization of the prostate could enhance the diagnosis and localization of prostate cancer. However, despite the importance of localization, complex geometry and boundary conditions of the prostate make localization difficult. This paper proposes a method for localizing abnormality using finite element modeling of the prostate glands. Ex-vivo experiment was performed to resected human prostate tissue for six regions of the prostate using robotic system which was previously designed to induce sweeping palpation. For each region, three dimensional prostate computational models from the CT image segmentation were developed for mechanical property characterization and local property criteria construction. The measured force responses were applied to the prostate model fittings and mechanical property of ex-vivo experiments were estimated. By using comparative study with local property criteria from the prior indentation study, suspicious regions were localized. The results showed that the suspicious regions were discriminated and the sensitivity was 66.7%.

I. INTRODUCTION

MECHANICAL property characterization with medical robotic system could provide precise and quantitative information for prostate cancer diagnosis because the robotic system could be quantitatively controlled to induce mechanical loadings to target organs. It could also be used to localize the abnormality in prostate diagnosis. Mechanical properties of cancerous tissues vary with respect to progression of diseases and prostate cancer has higher elastic modulus than normal tissues [1]. Surgeons could diagnose prostate cancer in early stage by inducing mechanical loading to the prostate using their fingers. However it has limitation in terms of objectivity [2]. Medical robotic systems have been emerged for diagnosing prostate cancer noninvasively by inducing mechanical loadings to tissues.

Several researches have been done to enhance the accuracy of the prostate cancer diagnosis. Fearing et al. used a robotic palpation for inclusion probing on silicone phantoms [3]. Tanaka et al. developed an active palpation system to detect tumors. It was used to perform in vivo clinical tests with human prostates [4]-[6]. They were able to discriminate the tumor from normal tissue. Medical images such as magnetic resonance imaging or ultrasound have been used to diagnose prostate cancer, however it is difficult to identify a tumor accurately due to its low image resolution. Recently elastography has been emerged to obtain elasticity images by using mechanical waves [7]-[9]. Liu et al. proposed an approach for identification of the inner structure and the mechanical properties of soft tissues with rolling mechanical imaging that was applied to the system to identify the location, shape, and size of nodules [10]-[13]. A mechanical system which could perform palpation and obtain mechanical images was developed [14][15].

In our research group, Ahn et al. obtained the elastic modulus of the human prostate tissues from the ex vivo experiments and characterization. They showed that the cancerous prostate tissue is stiffer than the normal tissue [16][17]. We also developed a robotic palpation system which induces sweeping palpation to the prostate and performs needle biopsy [18]. Although several medical robotic systems which could precisely induce mechanical loadings to the prostate and measure the mechanical behavior has been developed, less study has been focused on integrated systems that could quantitatively and objectively localize the abnormality.

In spite of the importance of tumor localization, inaccurate mechanical characterization methods limit the clinical validity. Due to the complex boundary condition and geometry of human prostate tissue, simple geometric models could not provide accurate mechanical properties. In order to obtain the elastic modulus of the prostate accurately, it is necessary to apply a finite element analysis which models the prostate glands. Figure 1 shows the diagnostic scheme. A robotic system could induce mechanical loadings to prostate and measure force response using attached force sensor. Using the CT image of the patient, prostate model is constructed. Finite element analysis is performed to calculate elastic modulus of the prostate using the measured force response. Finally diagnosis is made using elastic modulus of the normal prostate criteria.

In this paper, a method to localize the abnormality using the robotic system which could induce mechanical loadings to the prostate and finite element analysis which models the prostate glands is introduced.

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In section II, the developed robotic system is presented. *Ex vivo* experiments using the developed system is presented in section III. The localization of abnormality using finite element analysis from the experiments is presented in section IV. Six finite element prostate models for six regions to estimate the mechanical properties of the prostate are also presented. In section V, local normal property criteria which is constructed from the prior indentation experiment results for six regions of the prostate is presented. The results are compared with the local normal property criteria and the suspicious regions are subsequently determined. Finally, the determined regions are compared with the pathological results.

II. ROBOTIC SYSTEM

The robotic system was used to induce mechanical loadings to the prostate and measure its responses. The details of the developed robotic system are described in [18]. The system consists of a manipulation part and a wire-driven palpation part. The manipulation part locates the palpation part to the target position including the orientation of the system. In order to remove any pain and risk of patients, this part has a remote center, which is the incision point. Motion range of the manipulation part could insert the palpation probe to 100 mm from the incision point and cover 40 mm (width) · 40 mm (height) in place to reach the target (prostate). A position control was performed using simple PID control law. Using the forward kinematics of the manipulation part, position and orientation of the palpation probe was calculated.

The wire-driven palpation part was designed to induce mechanical loading to the target tissue and to measure the biological tissue behavior against the loading as shown in Fig. 2. A force sensor was attached to the palpation part. It had a hole at the center and had three strain gauges (KFRS, Kyowa, Japan). Its diameter was chosen as 8 mm for safety. The strain gauges were calibrated using a commercially available force transducer (Senstech Co. Ltd., Korea) that is pre-calibrated using 5g, 10g, 20g, 50g, 100g weights. The manufactured sensor showed linearity between the sensor signals and the loads (Fig. 3). Moore-Penrose least-squares method was used to calibrate the developed sensor and the result showed 7.5 % RMSE. This means that the developed sensor could measure the mechanical response against mechanical loading. The mechanical loading was induced from palpation probe which was driven from wires. Two wires which has 0.36 mm diameter were connected to the palpation probe. These wires were pulled by DC motor attached at palpation part. A rotation of the DC motor determined the rotation angle of the palpation probe. This rotation induced mechanical loadings to the prostate surface and force sensor measured reaction force.

III. EX VIVO EXPERIMENTS

The developed robotic system was used to perform *ex vivo*
experiments to the resected human prostate which was obtained from the patients of Severance Hospital, Yonsei University in Seoul, Korea. The experimental setup of the ex vivo experiments is shown in Fig. 5. A specimen was laid and fixed. Manipulation part located the palpation probe to the prostate and aligned normal to surface. Because the prostate has complex and irregular surface, the alignment was done manually. After the alignment, the palpation probe was contacted onto the surface. This contact point was set to be an initial point of mechanical loadings. The probe was induced a 5 mm depth palpation along the normal direction respect to the surface of the prostate. Then the probe was rotated to left and right repeatedly according to the induced palpation. Force responses were measured according to the rotation of the probe. These procedures were applied to the 6 regions of the prostate as shown in Fig. 6. From previous research which was done by our group, elastic modulus among the region was different for normal prostate [17]. For this reason, mechanical loadings were induced to six regions for five times of the rotation.

IV. FinitE Element Localization

Finite element models, which consist of the prostate and the palpation probe, were developed and further optimized with the experimental data because the prostate has complex geometries and boundary conditions. It also underwent large deformation for 5 mm palpation.

CT image of the prostate was used for reconstruction of three dimensional structures of the prostate. We used AMIRA software (Template Graphics Software, Inc., USA) to model the prostate as tetrahedral mesh for three-dimensional volume. Six prostate models were developed for each region as seen in Fig 7. ABAQUS software (SIMULIA, USA) was used for finite analysis. Palpation probe was modeled as rigid surface. The displacement boundary conditions were applied to the palpation probe and to the anterior side of prostate. The anterior side of the prostate was constrained to the substrate. The contact conditions between the probe and the models were assumed to be hard contacts and frictionless. We use the Young’s modulus and Poisson’s ratio to represent the mechanical properties of the prostate. The reaction force values of simulation were fitted to the experimental results.

Fig. 5. Experimental setup for Ex vivo human prostate experiments. The prostate is laid at the support and fixed. Palpation probe is located to the prostate and is aligned normal to the surface.

Fig. 6. Picture of the resected prostate (a) and schematic of six regions of the prostate (b).

Fig. 7. Three dimensional prostate mesh models for region 1 with tetrahedral mesh.

Fig. 8. Steps to localize the cancer by using local normal criteria.
These FE property characterizations are used to estimate the mechanical properties of the prostate and construct the normal property criteria. Then, the estimation results from the experiments were compared with the local normal criteria in order to diagnose and localize prostate cancer. Figure 8 shows the steps for cancer localization using the optimized elastic modulus criteria. First, local reaction forces of experiments are obtained and then local elastic moduli are estimated by FE prostate model. Second, local normal criteria which represents range between the upper bound and the lower bound was constructed from the database. Finally, localization was performed from comparison of the estimated local elastic modulus and the local normal tissue criteria.

V. RESULTS

The force responses of the 6 regions are shown in Fig. 8. Because the palpation depth depended on the rotation angle of the palpation probe, measured force showed a bell shape. Although only six regions were selected for entire regions, perceptible differences were observed among the experiments. Although amplitude of the force responses could be varied from the differences of elasticity of each region, geometrical differences and boundary conditions also affected the amplitude of the force responses. In order to consider these differences, finite element analysis was applied to calculate elastic modulus of the prostate. The stress distributions of the developed models are shown in Fig. 9. From the 5 mm depth indentation, the stresses are distributed around the palpation probe. A proposed method for localization of abnormality was compared with pathological results for validation. The pathological information such as tumor location and volume information was documented by the pathologist. The overall mechanical properties were estimated from the prior indentation study and were used for the normal criteria [17]. The normal criteria of each the regions was calculated from average elastic modulus value and standard deviation of the region (Table 1). The optimized elastic modulus according to the regions is presented in Fig. 10. The region 1 demonstrated the highest elastic modulus of 17.2 kPa, followed by the region 2 (16.2 kPa), the region 3 (15.6 kPa), the region 5 (12.0 kPa), the region 4 (10.5 kPa) and the region 6 (8.9 kPa). Using the normal criteria, suspicious regions were determined. Then we compared them to the pathological result as shown in Table 2. Region 3, 5 are selected to suspicious region using proposed procedure. Pathological results showed that region 3, 4, 5 has tumor under 2 mm depth from the surface. Its size was 6.7 g.

![Fig. 8. Force responses of the 5 times sweeping palpation for 6 regions of the prostate.](image)

![Fig. 9. Stress distributions of three dimensional prostate model.](image)

### TABLE 1. NORMAL PROPERTY CRITERIA RANGE DETERMINED FROM THE PRIOR INDENTATION EXPERIMENT RESULTS [20].

<table>
<thead>
<tr>
<th>Regions</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper bound (kPa)</td>
<td>19.2</td>
<td>19.2</td>
<td>13.3</td>
<td>13.3</td>
<td>8.98</td>
<td>8.98</td>
</tr>
<tr>
<td>Lower bound (kPa)</td>
<td>8.59</td>
<td>8.59</td>
<td>4.67</td>
<td>4.67</td>
<td>3.22</td>
<td>3.22</td>
</tr>
</tbody>
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VI. DISCUSSIONS

Providing mechanical properties of the prostate to physicians is critical for early diagnosis of the prostate cancer since mechanical properties of the prostate indicate the pathological state. Human prostate has highly complex
geometries and boundaries. It also undergoes large deformation. All these conditions make robotic system difficult to obtain accurate mechanical properties of the prostate. A robotic system with finite element characterization could play an important role in localizing the abnormality and it could be used to diagnose the prostate cancer. In this paper, localization of abnormality using the developed robotic system and finite element characterization is presented. Using the system, ex-vivo experiments were performed for 1 resected human prostate. Finite element analysis based on the prostate gland model was carried out. From the analysis, two regions were localized using the local normal criteria. Of the six regions of prostate specimens, region 3, 4 and 5 were reported to contain cancerous tissue on pathologic examination. The concordance rate between the palpation experiment and pathologic results (sensitivity) was 66.7% (2/3). Although the experiments were performed to only 1 resected prostate, the proposed procedure showed a possibility to diagnose the prostate cancer.

In the future, more ex vivo experiments will be performed to validate the usefulness of the system. The in vivo experiments on animal will also be carried out using the developed system for the purpose of verifying its safety and its potential as a clinically practical tool for prostate cancer detection. Once the safety of the system is validated, human experiments will be operated by the urologists in the operating room of a hospital.

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Fig. 10. Localization results by comparing local normal property criteria. Upper bound and lower bound for each region are shown. The region 3 and 5 shows abnormally high elastic modulus compared to the normal criteria.