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Quantitative Palpation to Identify the Material Parameters of Tissues Using Reactive Force Measurement and Finite Element Simulation

Takeharu Hoshi, Yo Kobayashi, Tomoyuki Miyashita, and Masakatsu G. Fujie

Abstract—**In this paper we present a new robotic palpation method to perform quantitative measurement of the material parameters of human tissues, for use in medical applications. The proposed method is achieved by the use of a system that integrates a robotic component and a numerical simulation component. The robotic component is used to measure the contact force and displacement at each point on the human body contacted by a robotic probe. The numerical simulation component identifies the material parameters using the proposed method, where two data sources are used, namely, (1) the measured data from the robotic part, and (2) simulated deformation data obtained by the finite element method. In order to validate the proposed system, we report initial results from several phantom tissue experiments, which demonstrate the ability of the system to quantitatively determine the elastic moduli of tissues. We also discuss several potential challenges in the future of the proposed system.**

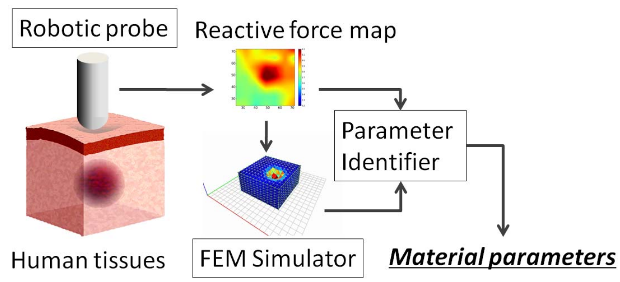

Fig. 1. Concept of the proposed method for providing the material parameters of the human tissues

I. Introduction

TECHNOLOGIES for minimally invasive surgery using robotic and computational engineering are increasingly gaining attention in today's medicine [1], [2]. Since these new technologies enable less invasive surgery than conventional technologies while providing patients with better medical results, future applications in the field are most likely to be widespread. In particular, computer assisted dynamic simulation of the human body based on numerical human tissue models may have important applications in various medical situations. Examples of such applications include diagnosis systems, surgical planning systems, surgical training systems, and surgical robot control systems. Consequently, medical researchers have recently expressed great interest in technologies for dynamic simulation of the human body.

Although computer assisted dynamic simulations have been expected to become widespread, practical methods to obtain appropriate and realistic simulation results have not yet been reported. This is primarily because determining the material parameters of human tissues, which in turn determine the accuracy of the dynamic simulation by the human tissue model, is generally difficult. This difficulty arises from two sources. First, there is no method by which to accurately, directly and non-invasively measure the distribution of tissues over the entire human body. Second, individual differences in the properties of human tissues, which are related to factors such as age, sex, clinical history and lifestyle, make it increasingly difficult to determine the values of the material parameters. Thus, if no method to quantify material parameters of human tissues is developed, the use of computer assisted dynamic simulation may lead to a reliability problem from a medical point of view. In our work, we have focused on this problem of uncertainty of the material parameters of human tissues, and propose a new method that allows the material parameters of the human tissues to be identified.

A. Previous Work

Here we briefly review research related to computer assisted dynamic simulation using human tissue models, and to material parameter identification problems.

1) Modeling and simulation of the human body: Various projects have investigated computer assisted dynamic simulation. Conventional studies on computer assisted dynamic simulation have focused on simulation for preoperative planning or for teaching purposes [3], [4]. Recently, however, there has been a great deal of interest in simulation for intra-operative surgical robot control based on tissue models. For example, DiMaio et al. [5] proposed a

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T. Hoshi is with the Graduate School of Science and Engineering, Waseda University, Shinjuku Ward, Okubo, 3-4-1, Tokyo, Japan (corresponding author: phone +81-3-5286-3412; fax +81-3-5291-8269; e-mail: hoshi@aoni.waseda.jp). Y. Kobayashi, T. Miyashita, and M. G. Fujie are with the Faculty of Science and Engineering, Waseda University, Tokyo, Japan.

system to measure the extent of planar tissue phantom deformation during needle insertion. Alterovitz et al. [6] investigated the simulation of needle insertion for prostate brachytherapy. Kobayashi et al. [7], [8] reported the material properties of the liver in order to realize physically accurate models, and investigated physical organ modeling for use in a surgical robot control method.

2) Parameter identification problems: The uncertainty in the material properties of human tissue has been researched extensively. One solution to the problem of identifying the values of human material parameters is to use direct measurement devices that sample data directly from living human tissues. Ottensmeyer et al. [9] proposed a data acquisition tool for directly measuring the mechanical properties of tissues during surgery. Although this type of solution is helpful for confirming diagnoses, it is inherently invasive. An alternative, non-invasive approach is a measurement technique known as elastography, which involves the use of static or oscillatory deformations [10]. Although it is certain that this technique will become a useful tool for diagnosis, it is likely that the primary concern of research in the field of elastography will be to allow medical staff to visualize materials rather than to quantify the material parameters.

Studies dealing with the identification of material parameters of general objects have conventionally been reported in the areas of civil engineering or structural engineering research [11], [12]. In contrast to objects in these research areas, however, human tissues differ in various ways from earth ground or structural objects. As for research dealing with objects that are similar to the human body in their material properties, several research projects have investigated soft materials in recent years. Wang et al. [13] researched an identification method for rheological objects based on 2D finite element formulation. Although this method has the potential to accurately model the behaviors of rheological objects in certain circumstances, its applicability would be limited because it would depend on proper modeling and measurement procedures. Sangpradit et al. [14] reported a concept of a robotic indentation tool using 2D finite element analysis, and showed its preliminary experiments. The present authors addressed the problem of determining the values of human material parameters for surgical use [15], [16]. The previously proposed algorithm [15], [16] was intended to modify and correct the values of the material parameters intra-operatively, where we assumed that the spatial distribution and approximate properties of the tissues would be detected before the start of the surgical procedures.

B. Objectives

The primary objective of this paper is to present a new robotic palpation method to perform quantitative measurement of the material parameters of human tissues (Fig. 1). More specifically, the present paper shows the formulations and a system design for the method. The secondary objective is to demonstrate the efficacy as well as the limitations of the proposed method based on experiments with the test system we developed, where spatial force sensing data and 3D deformation simulation using finite element analysis were used. These efforts contribute to building guidelines by which to develop similar robotic medical systems to identify the material parameters of tissues.

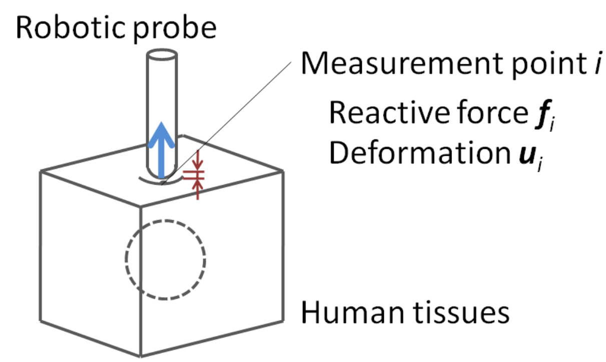

Fig. 2. Concept of the proposed robotic system for measuring contact force and deformation

C. Contents

The background, the previous work, and the objectives of the paper are presented in this chapter. The rest of the present paper is organized as follows. Section II introduces the proposed method and system design. Experimental conditions to verify the proposed method are described in Section III. Section IV discussed the experimental results. Finally, Section V presents the conclusion and describes areas for future research.

II. Method

In this section, we present a method to determine the material properties of the human tissues. The problem is defined, and a solution for this is proposed. In addition, a deformation model is obtained by the finite element method (FEM), and a formulation to optimize the parameter of the material parameters is proposed.

A. Problem Definition and Solution

The basic concept of the proposed method for providing the material parameters of human tissues is to compare the behavior of the simulation results obtained using tissue models with actual deformations of tissues as obtained by a robotic sensing system. We take this strategy of the proposed method as a kind of problem of inverse analysis. The reason for this is that the distribution of the material parameters, which determines the behavior of human-body deformation, must be estimated from the available measurements related to tissue deformation.

Here we present a system to provide appropriate material parameters of human tissues by using both robotic and numerical simulation components. The robotic component incorporates sensors for measuring the contact force and displacement at each point on the human body contacted by a robotic probe (Fig. 2). The advantage of using a robotic sensing tool is the ability to quantify measurement data with a high degree of accuracy. The dynamic simulation component identifies the most appropriate material parameters based on the contact force, and displacement data measured by the robotic component. Under the assumption of the existence of such a system, we must next formulate a method by which to provide the most appropriate material properties of the human body for the observed data obtained by the robotic component.

One solution to this problem is to use optimization techniques. Here, we assume that the values of the material parameters (e.g., Young's Modulus) are described as a parameter vector $\boldsymbol{\theta}$. Under this assumption, the optimal parameter vector $\boldsymbol{\theta}^*$ is described as follows:

$$\theta^* = \underset{\theta}{\operatorname{argmin}}(J(\theta)) \qquad (1)$$

where $\boldsymbol{\theta}^*$ is obtained by minimizing the loss function $J(\boldsymbol{\theta})$, which is an indication of the degree of adaptation between the real deformation and the simulated deformation. An appropriate function by which to formulate the loss function is given by the sum of squares of errors as follows:

$$J(\theta) = \frac{1}{2}\sum_i (f_i^{observation} - f_i^{model}(\theta))^2 \qquad (2)$$

where $f_i^{observation}$ and f_i^{model} are the values of the real and simulated deformation at the i-th point of measurement. Under these assumptions, the problem is how to formulate the simulated deformation f_i^{model} as a function of the parameter vector of the material properties. This problem is described in the following subsections.

B. Deformation Model

Since the finite element method (FEM) is one of the most common methods by which to model dynamic behaviors, in the present study we use the FEM to model the deformation of human tissues. In the FEM theory, the element stiffness matrix $\boldsymbol{K}^e$, which expresses the local stiffness, is given as

$$K^e = \int_V B^{eT} C^e B^e dV \qquad (3)$$

where $\boldsymbol{B}^e$ is the matrix that relates the strain and displacement, V is the volume of the element, and $\boldsymbol{C}^e$, which is referred to as the material matrix, is the matrix defined by the material parameters. In particular, if the element of the FEM is a four-node tetrahedral, elastic, and isotropic element, the material matrix $\boldsymbol{C}^e$ is written as:

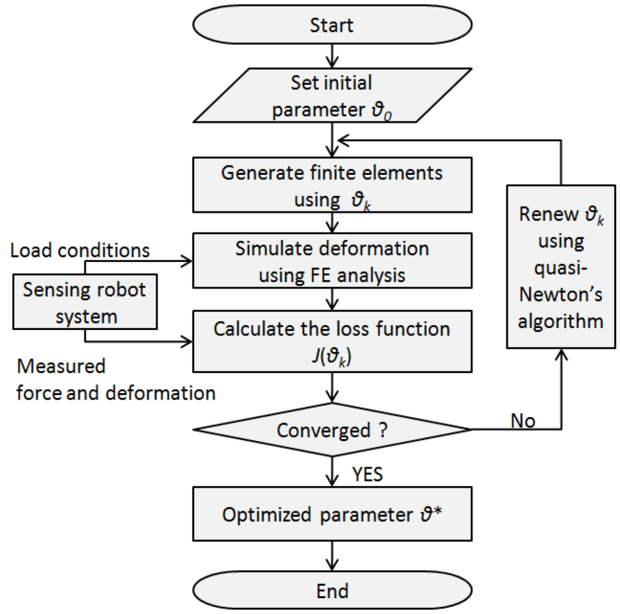

Fig. 3. Algorithm for optimizing the parameters of the human tissues using reactive force measurement and FEM simulation

$$C^e = \begin{bmatrix} \lambda^e + 2\mu^e & \lambda^e & \lambda^e & 0 & 0 & 0 \\ \lambda^e & \lambda^e + 2\mu^e & \lambda^e & 0 & 0 & 0 \\ \lambda^e & \lambda^e & \lambda^e + 2\mu^e & 0 & 0 & 0 \\ 0 & 0 & 0 & \mu^e & 0 & 0 \\ 0 & 0 & 0 & 0 & \mu^e & 0 \\ 0 & 0 & 0 & 0 & 0 & \mu^e \end{bmatrix} \qquad (4)$$

where λ^e and μ^e are the Lame material constants at each local finite element, given by the Young's modulus E^e and the Poisson's ratio ν^e as follows:

$$\lambda^e = \frac{\nu^e E^e}{(1+\nu^e)(1-2\nu^e)}, \quad \mu^e = \frac{E^e}{2(1+\nu^e)}. \qquad (5)$$

In this case, the deformation is solved using the following equation:

$$\underline{\boldsymbol{u}} = \boldsymbol{K}^{-1}\underline{\boldsymbol{f}} \qquad (6)$$

where $\boldsymbol{K}$, which is referred to as the global stiffness matrix, is calculated as the total of the element stiffness matrix $\boldsymbol{K}^e$. Thus, $\boldsymbol{K}$ is associated with the material parameters E^e and ν^e at each nodal point. In (6), $\underline{\boldsymbol{u}}$ and $\underline{\boldsymbol{f}}$ are the discretized displacement vector and the force vector, respectively, at each nodal point in the FEM model.

Next, based on the fact that $\boldsymbol{K}$ is associated with the material parameters, the displacement vector $\underline{\boldsymbol{u}}$ can be related to the parameters of the distribution model:

$$\underline{\boldsymbol{u}} = \underline{\boldsymbol{u}}(\boldsymbol{K}(\boldsymbol{\theta}), \underline{\boldsymbol{f}}) \qquad (7)$$

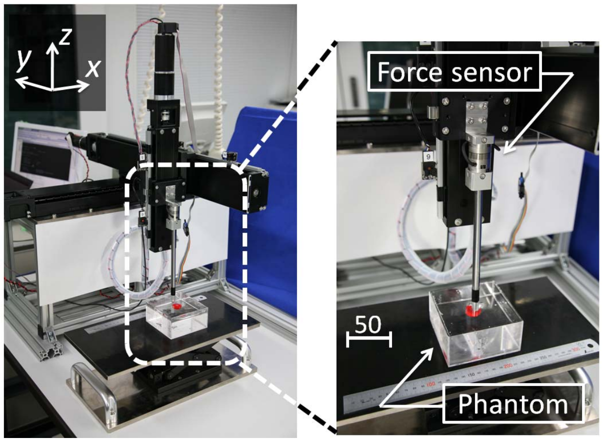

Fig. 4. Our experimental setup

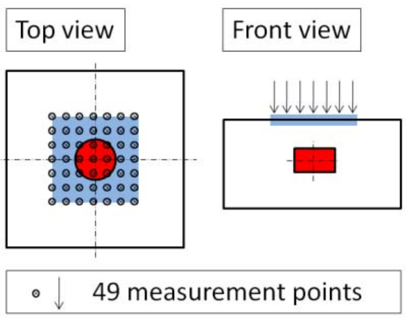

Fig. 5. (a) Measurement points for the contact force and displacement

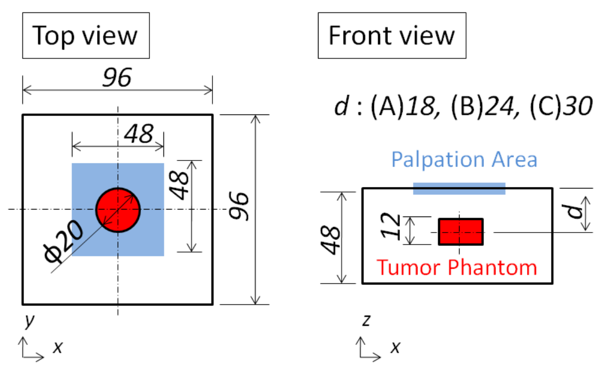

Fig. 5. (b) Specifications of the tissue phantom

Here, since $\underline{\boldsymbol{u}}$ is a function of $\boldsymbol{\theta}$, it can be used for the calculated information $f_i^{model}(\boldsymbol{\theta})$ in (2).

C. Optimization of the Material Parameters

Here, we consider the method by which to optimize the parameter in (1). In the present paper, we use the Broyden Fletcher Goldfarb Shanno (BFGS) quasi-Newton method to minimize the loss function and concurrently optimize the parameters of the human tissues. Typically, this quasi-Newton method is a fast and multi dimensional optimization approach for solving nonlinear problems. It seeks a point at which the gradient of an evaluation function is the zero vector. The framework to optimize the parameters of material parameters, where the robotic sensing system and the FEM simulator are integrated, is shown in Fig. 3.

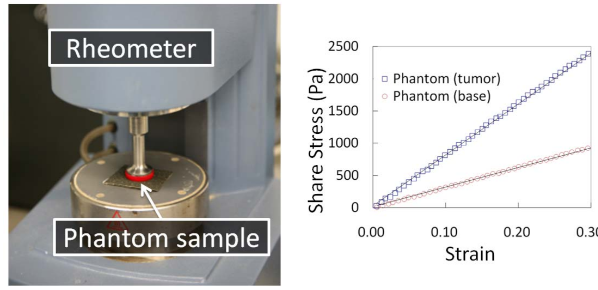

Fig. 6. Tissue phantom properties

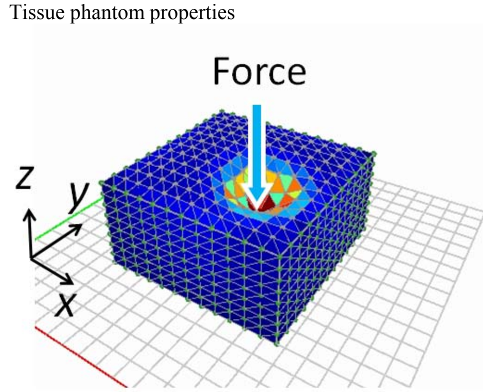

Fig. 7. Our FEM software

III. Experimental Conditions

In this section, we describe the conditions under which the experiments were conducted, (1) in order to assess the feasibility of the proposed system, and (2) in order to comparatively assess the effect of the position of a tumor. We implemented a test system that incorporates a sensing robot and an FEM simulator. The sensing robot provides measurement data of reactive force on the surface contacted by a robotic probe (Fig. 4). In this experiment, we used silicone phantoms instead of a real human body. Following are details of our experimental setup.

A. Experimental Manipulator

The experimental manipulator has 3 degrees of freedom of orthogonal linear movements. A force sensor (MICRO 5/50-SA, BL AUTOTEC Ltd.) and a probe were attached to the manipulator. In the experiment, the manipulator was programmed to indent the phantom by 20 mm at 49 points on the top surface of the phantom as shown in Fig. 5, in order to generate the reactive force map. The reactive forces exerted on the probe were sampled by the force sensor and a digital

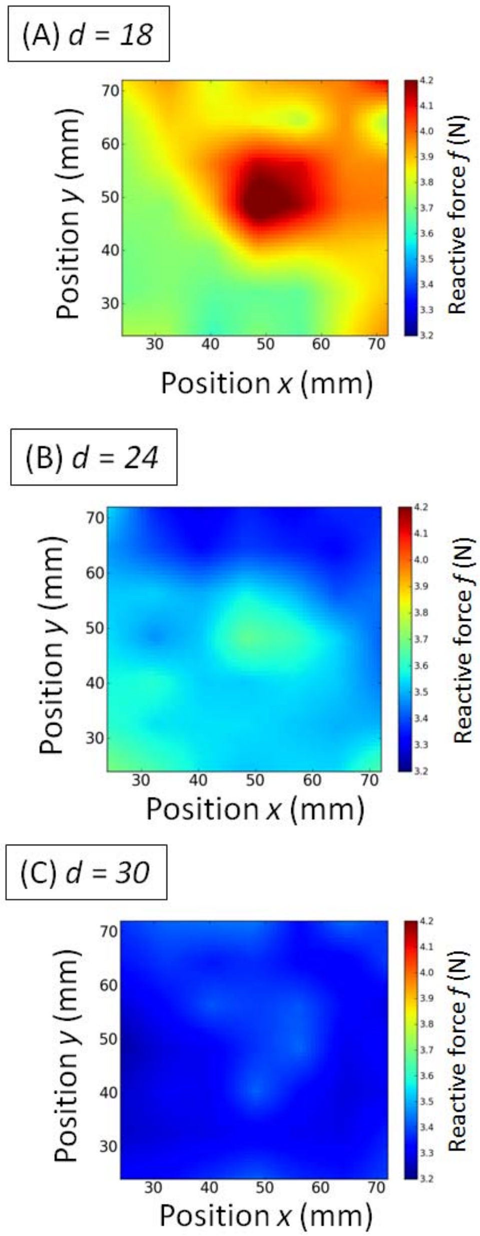

Fig. 8. Reactive force maps measured by the test system

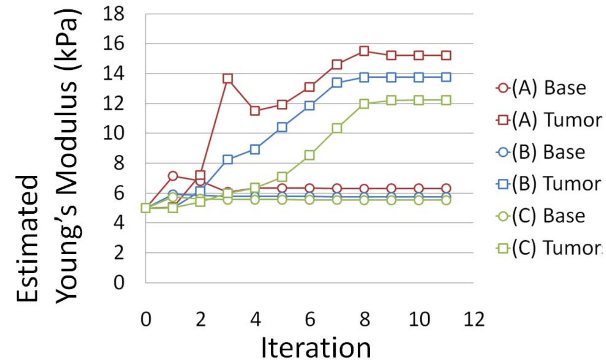

Fig. 9. Estimation process of Young's modulus

TABLE I
INITIAL AND IDENTIFIED YOUNG'S MODULI

Case	Initial Estimation kPa	Identified kPa
(A) E_{base}	5.00	6.31
E_{tumor}	5.00	1.52×10^{1}
(B) E_{base}	5.00	5.75
E_{tumor}	5.00	1.38×10^{1}
(C) E_{base}	5.00	5.53
E_{tumor}	5.00	1.22×10^{1}

low-pass filter.

B. Tissue Phantoms

We made silicone phantoms that simulated tumors and normal human tissues (Fig. 5). In general, tumors have stiffer characteristics than normal tissues; for example, Krouskop et al. reported in [17] that the fibrous adenoma tissue samples from the breast are approximately 3 times stiffer than normal mammary gland tissue. Hence, we made up the phantoms from two kinds of silicone materials (KE-1603A/B and KF-96-50CS, Shinetsu Silicone Co.) in order to prepare them to be of comparable level in stiffness ratio with real human tissues. The Young's moduli of the prepared phantoms of tumors and base bodies were 2.41×10^{1} kPa and 8.89 kPa respectively, where these values were calculated by the relation between the share stress and strain as measured by a rheometer (AR550, TA-Instrument). In the cases of the silicone rubber that we used, the phantom samples showed elastic behaviors as seen in Fig. 6. Thus, we determined the shear modulus of each phantom by using linear regression analysis, and calculated the Young's modulus using the Poisson's ratio ν as in the following relation:

$$E = 2(1+\nu)G. \qquad (8)$$

where it appears that the Poisson's ratio of silicone rubber generally has a value from 0.48 to 0.49. Therefore, we assume the Poisson's ratio of each phantom to be 0.49 in this experiment.

The phantoms were made into a hexahedron of 96 mm in width, 96 mm in depth, and 48 mm in height. Their bottom and side surfaces were constrained by acrylic walls. We made 3 sets of phantoms, where the depth d of the center of the tumor is positioned at 18 mm, 24 mm, and 30 mm, respectively, as illustrated in Fig. 5. In the experiment, we defined these cases as (A), (B), and (C), respectively.

C. Deformation Model using FEM

The FEM simulator for calculating the deformation was implemented in C++ and, in part, Python (Fig. 7). The

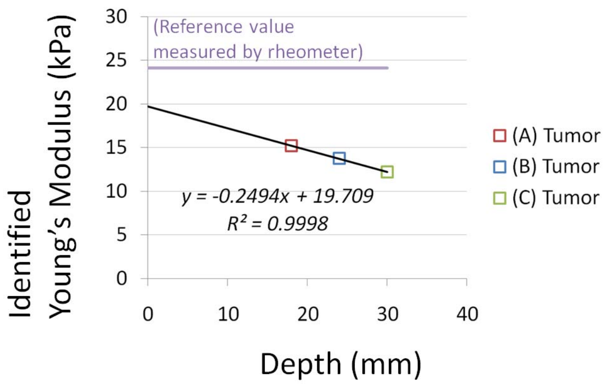

Fig. 10. Relation between the identified Young's Moduli and the values of depth of tumor phantoms

simulator is used to examine three-dimensional solids constructed of four-node linear tetrahedron elements. The FEM model in the present experiment includes 2,601 nodes and 12,288 elements. In the experiment, the FEM model is of the same size as each phantom described above. A total of 49 points on the top surface were designated as contact points to simulate the forces in the same condition of the manipulation for the phantoms. In this experiment, we assume the Poisson's ratio to maintain the constant value of 0.49 due to the silicone rubber properties of the phantoms.

D. Material Parameters to Identify

In these experiments, we choose the Young's modulus as the material property to be identified because the Young's modulus is one of the most fundamental material parameters of the human tissues in the deformation problem. Based on Eq. (1), the parameter vector $\boldsymbol{\theta}$ is described as $\boldsymbol{\theta} = \{E_{\mathrm{base}}, E_{\mathrm{tumor}}\}$, where E_{base} and E_{tumor} were defined as the Young's Moduli of the base body and the tumor area in a phantom, respectively. These two parameters were estimated concurrently, based on the proposed algorithm in Fig. 3.

IV. Results and Discussion

In this section, we demonstrate the experimental results by the proposed system, and discuss the efficacy and the limitations of the proposed method based on the results.

Figure 8 shows the reactive force maps on each of the tests using phantoms (A), (B), and (C). These maps in Fig. 8 visually demonstrate that the reactive force was locally increased by the effect of the existence of the tumor phantoms.

Figure 9 and Table 1 show the parameter-estimating process for each of the conditions of the three experiments. In this experiment, all the estimated parameters converged after eleven iterations of our proposed algorithm to identify the material parameters of tissues. Here, the running time of each estimation step was approximately 1.0×10^2 seconds, where the parameter-estimation algorithms were executed with a multi-thread program on an 8-core 3.00-GHz Intel Xeon PC. While we found that the parameters converged to the same order as values measured by the rheometer, the parameters of tumor phantoms showed different identified values. Figure 10 illustrates the relation between the identified Young's Moduli and the values of depth of tumor phantoms to check the effect of the depth of tumor phantoms. This result of the relation analysis revealed strong correlations between the identified values and the depth of the specific tissues. While the relation in the result of the experiment could be modeled as a linear dependence, we suggest that much more investigation is needed to find out all the factors that influence the estimation accuracy. We have also suggested other possible factors, including size, shape, etc..

The discussion in this section can be summarized as follows:

1) This study contributes to finding that the robotic palpation system based on the proposed method has a certain potential ability for identifying the parameters of human tissues.
2) However, in the present investigation, additional studies on the relation between the estimation accuracy and possible factors have been suggested before arriving at any generalization.

V. Conclusion

The present study proposes new concepts for providing the material parameters of the human tissues. The proposed system incorporates a robotic sensing system and a numerical dynamic simulation system. The method and formulation of the proposed system are also described herein. Experiments using a test system and phantoms have been carried out in order to demonstrate the feasibility of the proposed method. The experimental results reveal that the proposed method shows the ability to quantitatively determine the elastic moduli of tissues. Several potential challenges regarding the future of this system are also discussed.

We plan to perform further analysis based on the findings obtained in this study. In addition, we will research studies about complexities of properties of the human tissues because they have been conducted by regarding the tissues as having inhomogeneous, anisotropic elastic and viscous, and non-linear behaviors. We also intend to develop a more practical system that integrates a robotic system and a dynamic simulation system for clinical use in the future.

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