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Evaluation of a New Method for Detection of Kidney Stone during Laparoscopy Using 3D Conceptual Modeling

Elnaz Afshari, Siamak Najarian, Naser Simforoosh, and Siamak Hajizadeh Farkoush

Abstract**—**Minimally invasive surgery (MIS) is now being widely used as a preferred choice for various types of operations. The need to detect various tactile properties, justifies the key role of tactile sensing that is currently missing in MIS. In this regard, Laparoscopy is one of the methods of minimally invasive surgery that can be used in kidney stone removal surgeries. At this moment, determination of the exact location of stone during laparoscopy is one of the limitations of this method that no scientific solution has been found for so far.

Artificial tactile sensing is a new method for obtaining the characteristics of a hard object embedded in a soft tissue. Artificial palpation is an important application of artificial tactile sensing that can be used in different types of surgeries. In this study, a new method for determining the exact location of stone during laparoscopy is presented.

In the present study, the effects of stone existence on the surface of kidney were investigated using conceptual 3D model of kidney containing a simulated stone. Having imitated palpation and modeled it conceptually, indications of stone existence that appear on the surface of kidney were determined. A number of different cases were created and solved by the software and using stress distribution contours and stress graphs, it is illustrated that the created stress patterns on the surface of kidney show not only the existence of stone inside, but also its exact location. So three-dimensional analysis leads to a novel method of predicting the exact location of stone and can be directly applied to the incorporation of tactile sensing in artificial palpation, helping surgeons in non-invasive procedures.

Keywords**—**Kidney Stone, Laparoscopic Surgery, Artificial Tactile Sensing, Finite Element Method.

I. INTRODUCTION

KIDNEY STONE is one of the most painful and prevalent diseases of urinary system that mankind has confronted since ancient times. In this regard, surgery is one of the common methods used to remove the stone.

Laparoscopy is one of the methods of minimally invasive surgery (MIS) that can be useful in different surgery operations [1], [2]. This method of surgery has a lot of advantages in comparison with the traditional open surgery method such as less pain, less infection, less time of recovery, etc [3]. In contrast with these valuable advantages, a significant disadvantage of this method is missing a considerable amount of surgeon's tactile sensing that is exploited to recognize different organs and tissues and also different characteristics such as stiffness, viscoelasticity, tissue's external surface, etc in open surgery [4], [5]. At this moment, determination of the exact location of stone during laparoscopy is one of the limitations of this method that no scientific solution has been found for so far [6].

Artificial tactile sensing is a new method for obtaining the characteristics of a hard object embedded in a soft tissue [7], [8]; this includes detecting the presence or absence of the object or even mapping a complete tactile image [9]-[11]. Artificial palpation is an important application of artificial tactile sensing that can provide a great deal of information about different characteristics of soft tissues or state of manipulation of them [12], [13]. However, the previous studies in this field have usually been limited to investigation of cancerous tumors in the breast tissue and obtaining tumor's different characteristics [14]-[16]. A two-dimensional model is usually used to simulate the tumor and breast tissue, and the characteristics of the tumor are obtained from diagrams of stress distribution on the surface of the tissue [17]-[19].

In this study, by conceptual 3D model of kidney containing a simulated stone and investigating all effective parameters involved in this problem, indications of stone existence that appear on the surface of kidney is determined.

The results of this study can be directly applied to the incorporation of tactile sensing which leads to detect the stone's exact location during laparoscopy.

II. MATERIALS AND METHODS

In each application of tactile sensing, physical contact between a tactile sensor and object is very important [20]. In this physical contact, one of the parameters of contact is used as a factor for sensor stimulation. The factor can be load, pressure, heat, moisture, roughness, stiffness or softness. The

Elnaz Afshari is M.Sc. Student with the Department of Biomedical Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran. (Phone: 0098 9122471431; e-mail: elnaz.afshari@yahoo.com).

Siamak Najarian is with the Department of Biomedical Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran. (Phone: 0098 021 6454 2378; email: najarian@aut.ac.ir).

Naser Simforoosh is with the Urology and Nephrology Research Center, Shahid Labbafi Nejad Hospital, Shahid Beheshti University of Medical Sciences, Tehran, Iran. (Phone: 0098 021 22588016; e-mail: simforoosh@iurtc.org.ir)

Siamak Hajizadeh Farkoush is M.Sc. Student with the Department of Biomedical Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran. (Phone: 0098 9329238753; e-mail: farkoush@aut.ac.ir).

important point is that this factor must appear on the surface of the object where the sensor and object's contact is occurred; otherwise it would not be a suitable factor in tactile sensing approach [21], [22].

In this study, having imitated surgeon's palpation during open surgery and modeled it conceptually, changes appearing on the surface of kidney as a result of stone existence inside were studied.

III. PROBLEM DEFINITION

In open kidney-stone-removal surgeries, surgeons use their tactile sense to determine the exact location of the stone. By palpating the different areas of kidney surface, they find the exact location of stone and proceed to expel it. However, it is not possible for surgeon to do so during laparoscopy. This matter causes a lot of problems.

IV. MODELING AND SIMPLIFICATIONS

According to the physical standard for soft tissue simulation [23], a cube with a stiffer object inside it, was chosen as a simplified model of kidney and stone respectively. According to the anatomy of kidney, dimensions of the cube are selected to be 7 cm × 7 cm × 5 cm.

V. ASSUMPTIONS

The kidney tissue and kidney stone were assumed to be elastic and isotropic material in this work. The elastic modulus of kidney tissue was assumed to be 2500 Pa [24]. Kidney and stone's Poisson ratio were assumed to be 0.4 and 0.3 respectively. Mechanical properties of the stone were extracted using the research done by Cohen and Whitfield in 1993 [25]. Fig. 1 shows the elastic modulus of different kinds of prevalent stones that are formed in kidney.

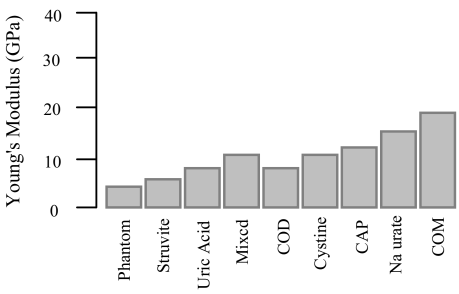

Fig. 1 Elastic modulus of different kinds of stones

To analyze the problem thoroughly, the following 'input parameters' were defined as the parameters that affect the stress distribution on the surface of kidney and their effects were investigated:

1. Kidney surface loading (compression), *c*.
2. Stone diameter, *d*.
3. Stone embedment depth, *t*.
4. Stiffness of stone, *E*.

Fig. 2 shows a schematic view of the kidney (cube), the stone (sphere) and the input parameters.

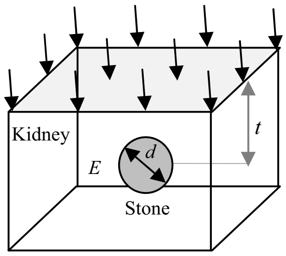

Fig. 2 Schematic view of the kidney (cube) and stone (sphere), showing input parameters

Input parameter ranges shown in Table I.

TABLE I
RANGES OF INPUT PARAMETERS

c (mm)	*d* (cm)	*t* (cm)	*E* (GPa)
2	1	2	3
3	1.5	2.5	6
4	2	3	9
5	2.5	3.5	12
6	3	4	15

VI. FINITE ELEMENT MODEL AND BOUNDARY CONDITIONS

This problem was modeled and solved by the numerical finite element method, using ABAQUS software (Release 7-1, Version 6). The common surface between kidney and stone was glued together in order to keep continuity of strain as a result of deformation. The side surfaces of the model did not have any constraints but the lower surface was fixed in the direction of upper surface compression. By doing this, it was possible to avoid rigid body motion and to solve the problem statically.

The model was meshed with tetrahedral elements which show quadratic displacement behavior and is well suited to modeling irregular meshes. In order to obtain a more accurate solution, the regions near the stone, where it was estimated that an intense gradient of stress would occur, were meshed with finer elements than those of other places.

VII. PROCEDURE

A code with the general form of "m: *c, d, t, E*" was defined to show the value of each input parameter and the code "m: *c=5* mm*, d=1.5* cm*, t=2.5* cm*, E=5* GPa" was dedicated as the main model. Any new model was constructed by changing only one input parameter of the main model so that it was possible to analyze the variation of kidney surface response vs. changes of any of the input parameters.

VIII. RESULTS

According to the different values of input parameters, 17 different cases were modeled and solved by the software. The two following specific results were extracted from each solution:

1. *The stress distribution contour on the surface of kidney*: in a stress analysis problem, the stress distribution contour is one of the important results. In this research we analyze this one.

2. *Stress graphs*: in addition to analyzing the stress distribution contour, using software's abilities we will extract graphs which can be useful in analyzing the surface effects of stone existence inside the kidney. This graph is taken on a path defined by a straight line in the middle of the upper surface of the cube from the left to the right side.

According to stress distribution contours and stress graphs, two main results were elicited:

- *The appearance of the signs of stone existence on the surface of kidney:* based on stress contours, by embedding a stone in kidney stress distribution on the surface of kidney changes and it increases near the location of stone. This is the basic conclusion we obtain from our analysis and it confirms the accuracy and reliability of the artificial tactile sensing method for detection of the stone during laparoscopy. Fig. 3 shows the stress distribution contour for main model and demonstrates that exerting compression to kidney tissue which contains a stone causes a non-uniform stress distribution at the contact surface.

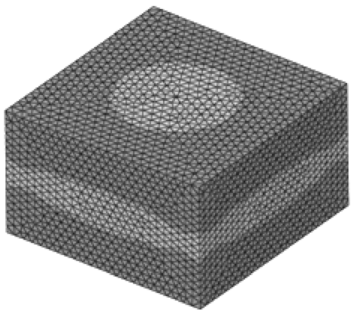

Fig. 3 Stress distribution contour for main model

- *Maximum value of stress graph*: In stress graphs that are taken along the defined path, there is an increase (maximum) in the amount of stress that not only demonstrates stone existence, but also shows its exact location. Fig. 4 shows the stress graph on the surface of kidney for the main model.

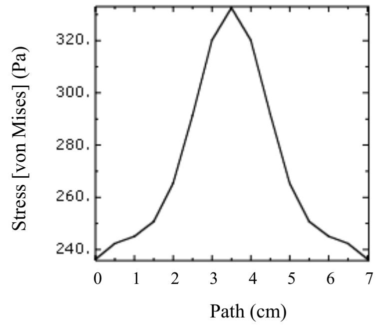

Fig. 4 Stress graph on the surface of kidney for the main model

IX. DISCUSSION AND COMPARISSION OF RESULTS

In order to analyze the problem thoroughly, we varied the input parameters at each step and then we investigated the effects of the parameter in tactile sensing approach. Fig. 5 shows stress graphs for different values of parameter *c* from Table I, displayed together.

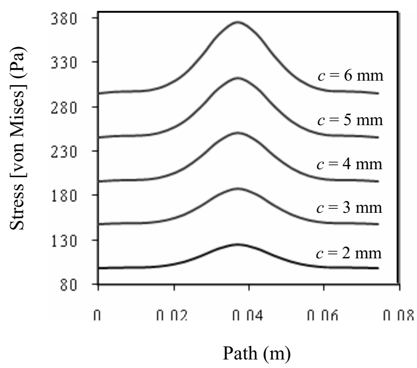

Fig. 5 Stress graphs for different values of parameter *c*

It is clear in Fig. 5 that by exerting more compression on the surface of kidney, the stress has increased. The interesting fact is that the maximum value point still corresponds with the exact location of stone embedment point.

By mapping the maximum stress values on another graph, variations of tissue response according to the changes of input parameters were obtained. Fig. 6 shows variations of maximum stress value due to variation of loading on the surface of kidney (compression). Increasing tissue compression causes the maximum stress to be enhanced.

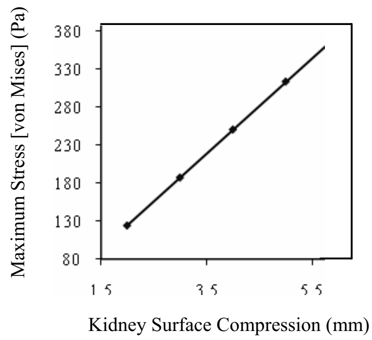

Fig. 6 Variations of maximum stress value due to variation of compression (*c*)

Fig. 7 shows variations of maximum stress value against variation of stone diameter. It is expected that the bigger the stone is, the more the stress will be. This trend is inversed in Fig. 8, in which the maximum stress value is mapped against stone embedding depth.

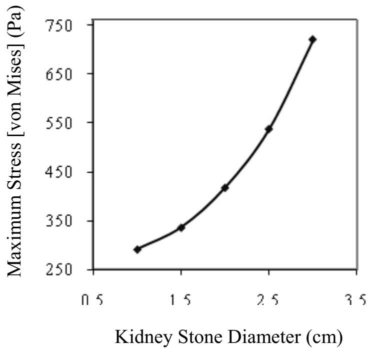

Fig. 7 Variations of maximum stress value due to variation of stone diameter

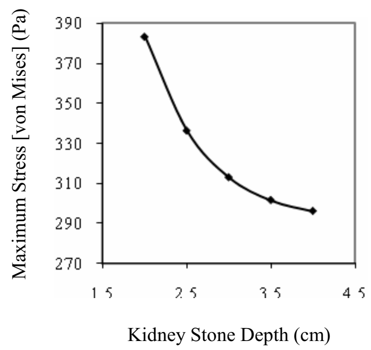

Fig. 8 Variations of maximum stress value due to variation of stone embedding depth

In spite of our expectation about stone's stiffness parameter, no change was observed in the maximum stress on the surface of kidney with varying the stiffness (The maximum stress on the surface of kidney is always 313.18 Pa). It seems that the high stiffness of kidney stones has leads to the fact that its alteration has no effect in change of the maximum stress on the surface of kidney.

As we mentioned, most of the researches accomplished in this field are limited to analysis embedment of cancerous tumours in the biological tissue of breast. Unfortunately in spite of our endeavors, no similar research about embedment of stone in the kidney was found to compare and investigate the accuracy and quality of our results. So we had to compare the graphs with the research results of a group of researchers working on the modeling of tumour in breast tissue [26]. So we compare diagrams of tissue response to variation of common input parameters.

Figures 9-11 show the results of the two research activities together; the continuous lines refer to the present study, and the dashed lines refer to the other research.

Fig. 9 shows similar increasing rate resulting from both researches with increasing the loading on the surface of kidney and breast tissue. In addition, according to linear elastic assumption for kidney and stone it is expected that the linear rate of increase is maintained outside the experiment range.

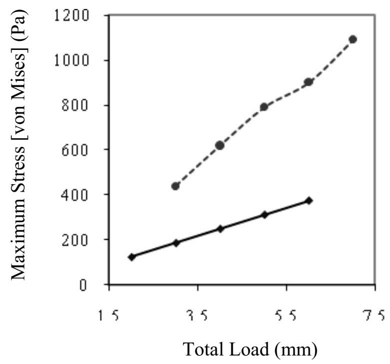

Fig. 9 Comparison of maximum value of stress vs. loading

According to Figures 10 and 11, comparison between the relationship of the maximum value of stress with diameter and embedment depth of stone and tumour in two researches show the same variation.

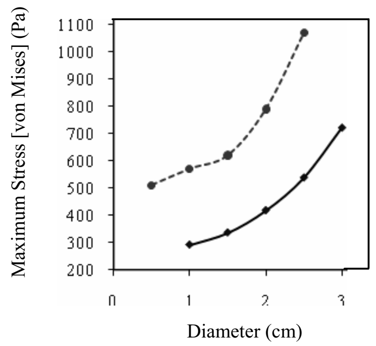

Fig. 10 Comparison of maximum value of stress vs. diameter

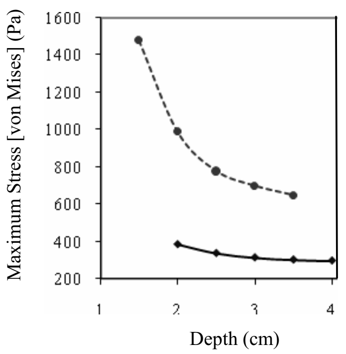

Fig. 11 Comparison of maximum value of stress vs. depth

Finally we drew interesting conclusions according to the analysis of kidney tissue response to the parameter variations such as:

1. The most important factor in determination of the exact location of stone is the stone's stiffness (for stones formed in the body). However, stone's stiffness variation does not change the stress emerged on the surface of kidney which is due to the large value of stone's elasticity modulus.
2. Stone embedment depth has little influence on the stress seen on the surface of kidney, thus in tactile sensing approach it is not important how deep the stone is embedded.
3. According to the analysis, it seems that kidney stone diameter and the amount of kidney surface compression has the most surface effects in artificial tactile sensing approach.

X. CONCLUSION

According to the fact that kidney stone is one of the most painful and prevalent diseases of urinary system and one common method to remove the stone is surgery, it is valuable to improve minimally invasive surgery approaches and use them in kidney stone removal. A significant aspect of this study is the introduction of a new application for artificial tactile sensing approach in laparoscopy and making it suitable to be used in kidney stone removal surgeries.

The present paper proposes a novel method based on artificial tactile sensing to determine the exact location of stone during kidney-stone-removal laparoscopy. We intend to demonstrate the reliability and accuracy of this method by means of 3D conceptually modeling the problem and using finite element analysis.

Another important feature of this research is the use of its results during open kidney-stone-removal surgeries. During these surgeries, sometimes the surgeon misses the stone and confronts with difficulties to find and expel it in which case our method can be helpful.

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