International Journal of Natural and Engineering Sciences 4 (3): 19-25, 2010
ISSN: 1307-1149, E-ISSN: 2146-0086, www.nobel.gen.tr

Analysis of Tactile Detection and Examination of Simulated Arteries Using a Computational Approach

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Received : April 06, 2010
Accepted : June 25, 2010

Abstract

In this study, six basic models have been created in order to investigate stenosis in arteries using tactile sensing: tissue itself, tissue including a tumor, tissue including a healthy artery, tissue including a stenotic artery, healthy artery out of tissue, and stenotic artery out of tissue. After solving these models, the stress graphs for the nodes of the models which have key importance for transferring the tactile data were explored. It was observed that if the stress values of the nodes were constant and equal, the tissue is unlikely to have any tumor or artery embedded. Otherwise, if the stress graph included a peak, the tissue had a tumor or an artery. Additionally, it was observed that the stress graph of the tissue including an artery in comparison with the tissue including a tumor is time-dependent. Finally, the variation of the different parameters of this model such as artery diameter and artery depth on artery detection have been studied.

Keywords: Palpation, Stenosis, Modeling, Finite Element Method.

INTRODUCTION

Distinguishing between different tissues and organs during open surgery is mainly achieved by the surgeon's sense of touch; this sense helps to determine how much force to exert by the hands and how to avoid injuring nontarget tissues [1]. In some procedures tactile sensations are essential to quickly complete a task. For example, hard lumps in soft organs are detected by probing the tissue with fingers; arteries are localized during dissection by feeling for a time varying pressure; the structural integrity of a blood vessel wall is assessed by palpating or rolling it between the fingers [2,3]. However, in many surgical cases, surgeons may make mistakes during diagnosis of the physical properties of soft tissue, e.g., the arteries. The reasons of these errors are the limitations of human tactile sense and the surgeon's need for the high versatility in diagnosis of the vascular diseases.

Minimally invasive surgery (MIS) is a revolutionary surgical technique in which two or three incisions with nearly 1 cm diameter or so are being created on external surface of the body. Then, tiny long surgical tools are entered through these incisions into the body and the surgeon performs the operation by these tools. Some of these advantages are: reducing damage to healthy tissue, decreasing trauma, increasing healing process, reducing recovery times, etc [4-6]. Despite the advantages of MIS and its growing popularity [7,8] it suffers from one major drawback; it decreases the sensory perception of the surgeon who may accidentally cut or incur damage to some of the tissues.

Surgical simulation in medicine has been widely explored [9-16]. Surgical simulator whether for open surgery or MIS allows beginner surgeons to learn and correct their mistakes without negative consequences compared to working on real patients [17]. In other words, using virtual reality simulation, medical students, residents, and practicing physicians can learn treatment protocols and master basic and procedural skills before touching a real patient. They can review, repeat, and reassess their performance and find areas for improvement without compromising patient safety. The modeling of deformable soft tissue for surgical simulation has not been fully explored [9]. Some main problems and lacks of the surgical simulator are the inability of distinguishing between different simulated tissues, the simulating arteries in the tissues and detecting them, and determining the region of the stenosis of a simulated artery. It means that surgeons require more realistic simulation involving tactile sensation [10]. In addition, surgical simulators can be the future potential for simulated surgical instruments to operate on real patients, to achieve more accurate surgeries, and to release surgical doctors from possible human vision and physical limitation in performing operation procedures [17].

Unlike tumor detection [18-21], only a very few number of studies [22-24] could be found on detecting an artery in a tissue. It is important to note that these research activities are based on constructing a tactile device. This means that in them, numerical solutions were not performed for detecting of an artery in a simulated tissue and, also, the determining of location of the stenosis in a simulated artery was not employed. Many studies performed on simulation of soft tissue based on surgical simulation and graphical applications by different methods [10-17, 25-30]. But, we do not see any attempts on artery detection in these studies based on numerical methods.

In most surgeries, palpation is usually used and it plays a key role in estimating physical and mechanical properties of simulated soft tissues and embedded objects inside of them. For example, vascular surgeons generally employ palpation of arteries during surgery for diagnosis of its disease and the region of its extension [2]. In this regard, for the first time, we imitated palpation of a phantom of a simulated soft tissue including embedded objects and modeled it by finite element method. Then, we investigated the different changes appearing on the surface of the phantom as a result of the embedded objects. According to these results, we explored the presence of an artery in a simulated tissue and differentiated it from a tumor. Also, we distinguished a healthy artery from a stenotic artery. Furthermore, with modeling an artery without surrounding tissue, the existence of stenosis in the artery was assessed by palpating method. Additionally, the effect of physical and mechanical parameters of the model of the tissue including an artery on surgeon's ability in artery detection and its diagnosis were investigated.

MATERIALS AND METHODS

In every application of the tactile sensing method, physical contact between the hand (tactile sensor) and the tissue (object) has special importance. In the physical contact, a parameter of touch was used as a criterion for diagnosis. This criterion can be force, pressure (stress), displacement (strain), temperature, humidity, roughness, stiffness, and softness that appeared on the surface of the touched object. In this study, we selected the stress as the criterion of detection during palpation of the simulated soft tissue by finger model.

Modeling, Simplifications, and Assumptions

According to the physical standard for soft tissue simulation [31], a cubical phantom with the objects inside it was chosen as a simplified model of tissue and a tumor or artery. In the meantime, a circular tube with a stricture inside it was selected as a simplified model of a single artery. In order to simplify the modeling, the following parts, as illustrated in Fig. 1, were introduced:

1. Tissue itself (TI)
2. Tissue including a tumor (TIT)
3. Tissue including a healthy artery (TIHA)
4. Tissue including a stenotic artery (TISA)
5. Healthy artery out of tissue (HAOT)
6. Thirty percent stenotic artery out of tissue (SAOT).

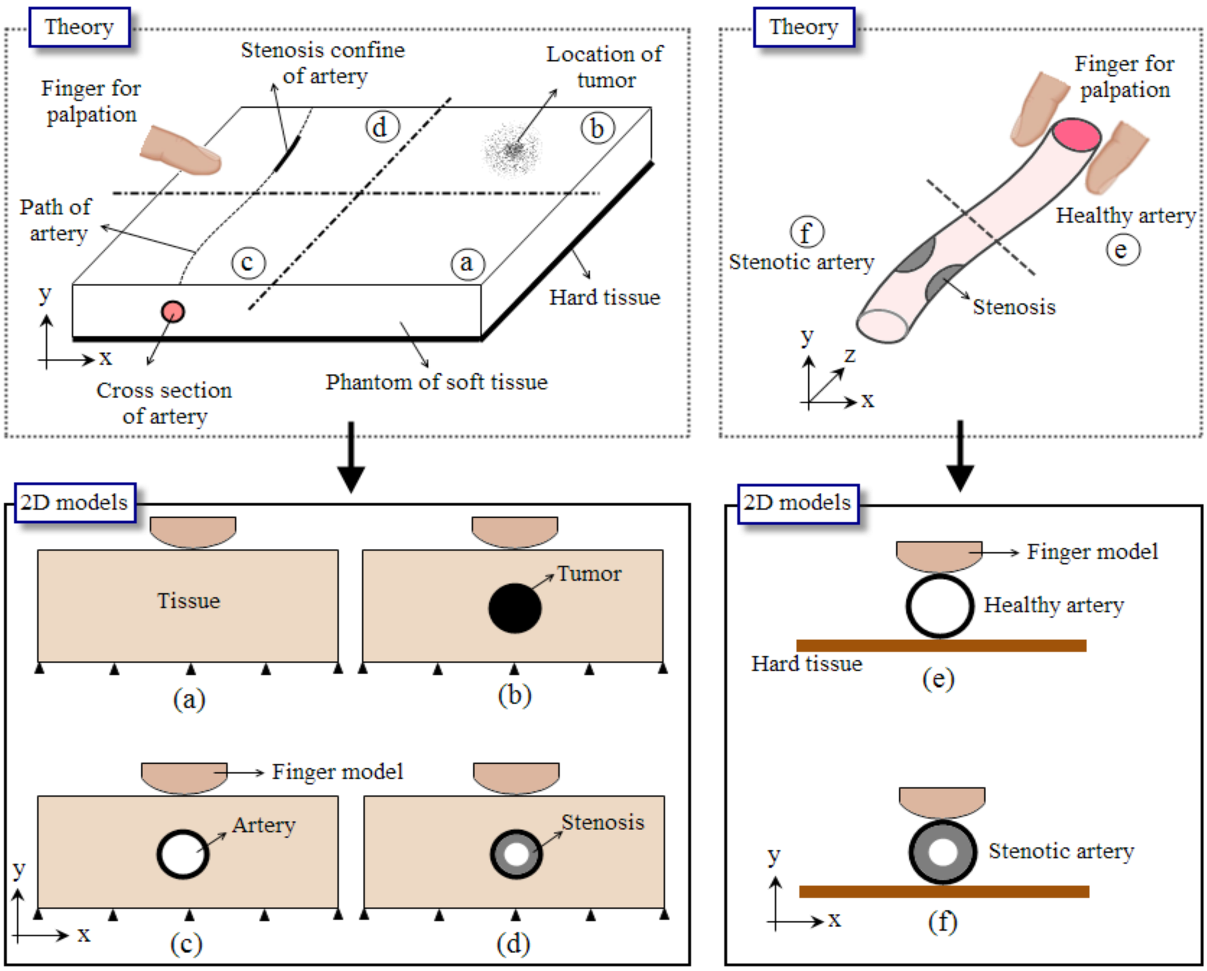

Figure 1. Schematic representation of four models of soft tissue: (a) TI, (b) TIT, (c) TIHA, and (d) TISA and two models of artery: (e) HAOT and (f) SAOT.

The cross section of each part, as shown in Fig. 1, has been selected as a two-dimensional rectangular model. The cross section of parts *b*, *d*, and *f* pass in *x-y* plane through the center of the tumor, healthy artery, and stenotic artery, respectively. Rectangular models *a* to *d* are 64×16.83 mm in size so that the left and right side of the tissues are far from the artery and the tumor and do not affect the stress distribution of the artery, the tumor, their environment, and the tissue-finger contact region.

In this modeling, arteries and tumor were assumed to be completely circular. The center of the tumor and the arteries were considered at a distance 12.66 mm from the top side and 32 mm from the left and right sides of the models. The inner diameter of brachial artery and the diameter of the tumor are 4.5 mm. The mean wall thickness of brachial artery was considered 0.63 mm. The simulated soft tissue and the artery were assumed elastic and isotropic with a modulus of elasticity of 50 [31] and 400 kPa [32,33], respectively. The modulus of elasticity of the tumor and the stenosis were assumed to be twenty times larger than the tissue and ten times larger than the artery, respectively. Poisson's ratio for all materials was considered 0.49.

The blood pressure waveforms of a healthy brachial artery and 30% stenotic brachial artery applied for modeling the artery inner pressure are shown in Fig. 2 [34].

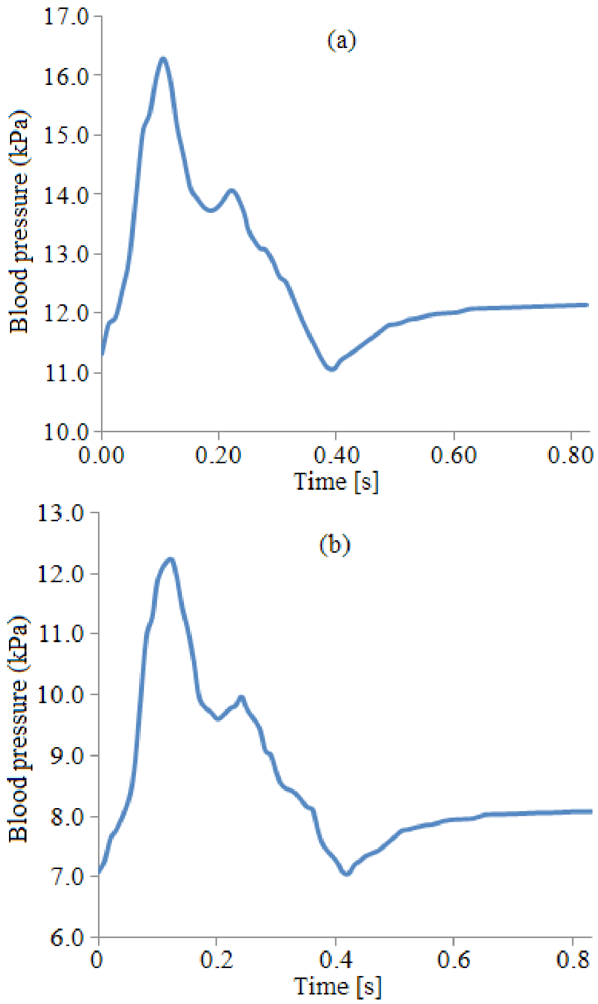

Figure 2. The variation of blood pressure versus time for (a) healthy brachial artery and (b) 30% stenotic brachial artery.

Finite element modeling and boundary conditions

This problem was modeled and solved by the numerical method of finite element analysis, using ABAQUS software (Release 7.6.1). For modeling of the palpation process using a finger, at first, we defined a contact between the finger and the top side of each model, then, we considered a constant displacement of 2.5 mm for the finger. For completing the simulation of palpation effect, the bottom line of each model was fixed in the direction of finger compression. At the same time, the side lines did not have any constraint. By doing this, it was possible to avoid rigid body motion and solve the problem statically for a duration of 1.825 second by finite element method. For keeping continuous strain as a consequence of the deformation in the touch site of different materials, we adhered the same nodes by gluing them together.

The models were meshed with CPS4R (a 4-node bilinear plane stress quadrilateral), which is well suited to modeling regular meshes. To obtain more accurate solution and reduce the duration of solving the problem, the region near the tumor, the arteries, the finger, and the contact area where the intense gradient of the stresses would occur, were meshed with finer elements than the other places.

Procedure

The aim of the present study is to investigate the effect of objects (artery or tumor) embedded in simulated tissue associated with the application of mechanical loading on the tissue and to compare them for finding a criterion for separating these issues. For palpating the models *a* to *d*, we solved the models by considering specified locations as {4n} mm, where n={1, 2, 3, …, 14, 15}, for the finger on their top line. For models TIHA and TISA, finger was put on the surface of tissue in each location, then, it was indented into tissue during 1 second. Afterwards, while holding the finger, the blood pressure was applied to the artery during 0.825 second. Finally, we extracted stress values of models in the mentioned locations and created stress graph versus defined path. We named these graphs as tactile map.

Also, we investigated two models HAOT and SAOT together for finding a criterion for arterial disease diagnosis. In addition, in order to analyze the artery detection and to diagnose its disease thoroughly, the variation of the model's parameters on surgeon's detection was studied.

RESULTS AND DISCUSSION

According to the procedure of this study, we extracted the results, i.e., the von Mises stress values of the top side of models, from each solution. The following outcomes can be elicited from stress graphs.

We observed that the values of stress graph taken from model TI by the defined procedure, are equal. This means that the stress graph of model TI is parallel to *x*-axis as shown in Fig. 3-(a). Because model TI consists of a homogenous and uniform material, the conditions related to each step of the palpating procedure are similar.

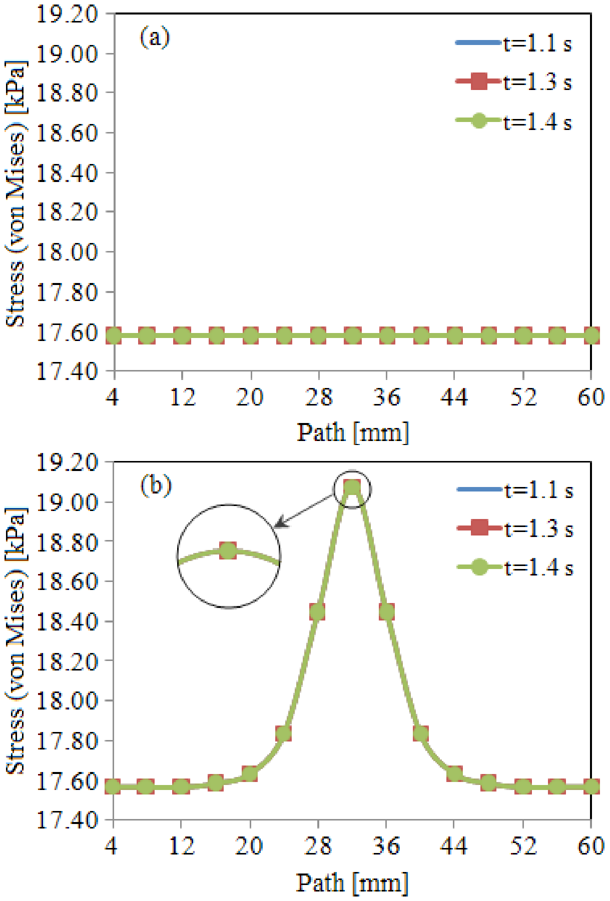

Figure 3. Tactile maps of models (a) TI and (b) TIT.

In stress graphs that are taken from models *b* to *d* by the defined procedure, there is an increase (overshoot) in the amount of stress. Figures 3-(b) and 4 show the stress graph of models TIT, TIHA, and TISA.

From the stress graphs extracted of models *b* to *d* at specific times 1.1 (systolic time, maximum blood pressure), 1.3 (arbitrary time), and 1.4 (diastolic time, minimum blood pressure) seconds, it is observed that the amounts of the stress peaks in model *b* are equal at these times. In other words, the stress graph of model TIT is not time-dependent. Also, the amounts of the stress peaks in models *c* and *d* at specific times 1.1, 1.3, and 1.4 seconds are different as shown in Fig. 4. This means that the stress graph of models TIHA and TISA are time-dependent. This is because the pulsatile effect of blood on arteries' wall.

From appearance aspect, Figs. 3-(b) and 4-(b) are similar. If we zoom in a part of graphs, e.g., location 32 mm it is seen that in graph TIT the stresses at three times 1.1, 1.3, and 1.4 seconds are equal, but, in graph TISA they are not the same. The difference between its maximum and minimum stress at this location is 22.6 Pa.

In the stress graphs taken from bottom side of the finger in models *e* and *f*, we observed a peak in each stress graph and its dependence on time. Also, in stress graphs of Fig. 5, it can be found that the stress peak for a stenotic artery is larger than a healthy artery. This is because the stiffness of the stenotic artery is larger than healthy artery. Meanwhile, it can be observed from Fig. 5 that the amplitude of the stress variation versus time in model HAOT is larger than model SAOT. This is due to the fact that the stenotic artery has a thicker wall than healthy artery. This reduces the transmitting of the effect of blood pressure from inner surface of artery wall to outer surface of it.

As shown in Figs. 6 to 9, we investigated the effect of the parameters of model TIHA including the artery diameter, the elastic modulus of the artery, the artery depth, and the tissue indentation caused by the finger displacement on artery detection in location 32 mm.

Figure 6 shows the tactile map of the difference of the maximum and minimum stresses, which has been considered as the intensity of the arterial pulse, for different values of the artery depth. It can be seen from this graph that by increasing the artery depth in the tissue, the pulse intensity becomes smaller and finally we predicted it will disappear.

Figure 7 indicates a tactile map in which the pulse intensity is plotted against the tissue indentation. Increasing indentation causes the difference of the maximum and minimum stresses to be enhanced. It should be considered that the finger displacement in modeling is less than the amount which causes the complete collapse of the artery. Figure 8 depicts the effect of the artery diameter in the detection of the pulse intensity as a tactile map. The results obtained in this research demonstrate the enhancement of the artery detection due to an increase in the artery diameter. Figure 9 points out a tactile map in which the pulse intensity is plotted against the elastic modulus of the artery and indicates that increasing the elastic modulus of the artery causes the pulse intensity to be reduced.

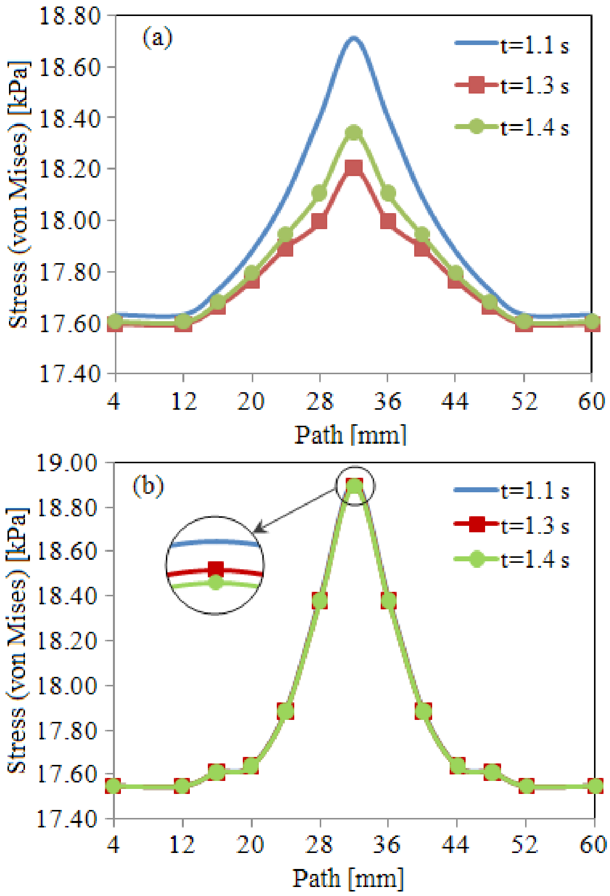

Figure 4. Tactile maps of models (a) TIHA and (b) TISA.

In order to compare and investigate the accuracy and quality of the results, the tactile maps of models TIT and TIHA were compared with the results of other research groups. Although the method of researches are different, it is possible to compare the results with each other from a qualitative rather than a quantitative point of view. Dario's [23] and Beasley's [24] research works are based on the experimental activities and Hosseini's [35] research is based on a numerical method. It can be observed that in the model tissue which included a tumor we saw that in all three research activities, as in our results, there exists a time-independent peak in the stress graph. Also, the stress graph of the model tissue included an artery has a time-dependent peak similar to the other mentioned research works.

CONCLUSION

According to extracted results of Figs. 3 and 4, surgeon can detect the existence of an artery in a tissue by feeling the pulsatile effect on the tissue surface during palpating it. From the results presented in Fig. 5, it can be deduced that the separation of a healthy artery from a stenotic one is possible for surgeon by comparing their stiffness and pulse intensity. The artery which has stiffer and lower pulse intensity is the diseased artery.

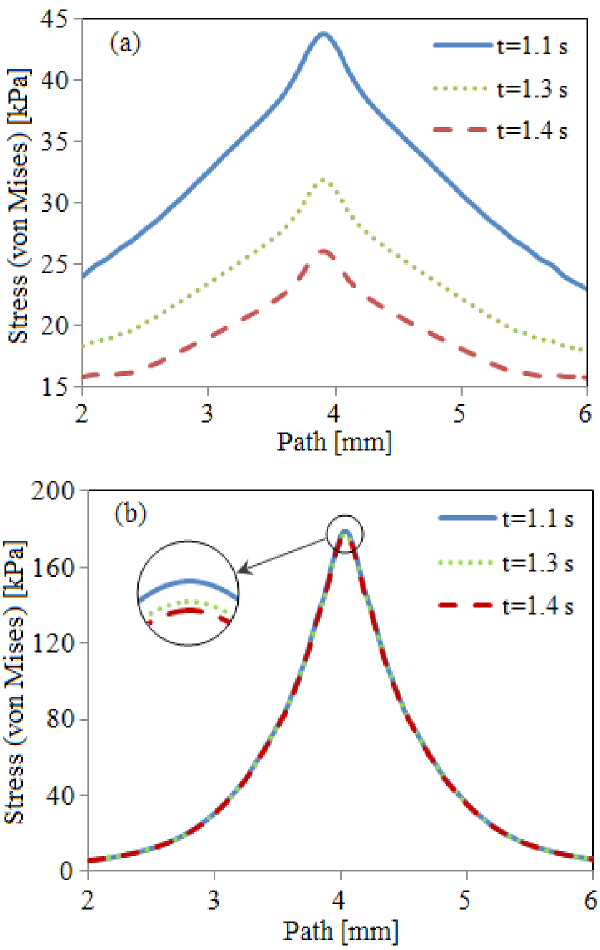

Figure 5. Stress graph of bottom side of finger in models (a) HAOT and (b) SAOT at three different times.

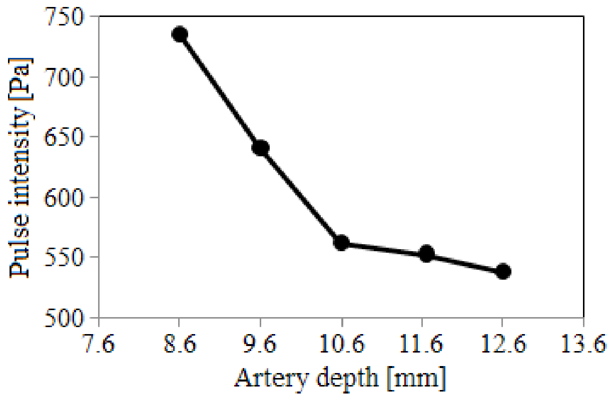

Figure 6. Tactile map of pulse intensity in model TIHA for different depths of artery.

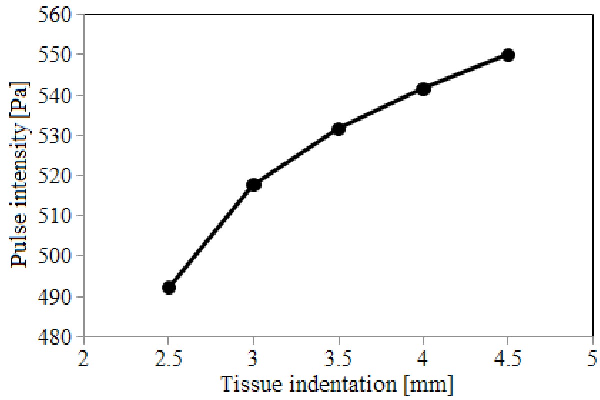

Figure 7. Tactile map of pulse intensity in model TIHA for different tissue indentations.

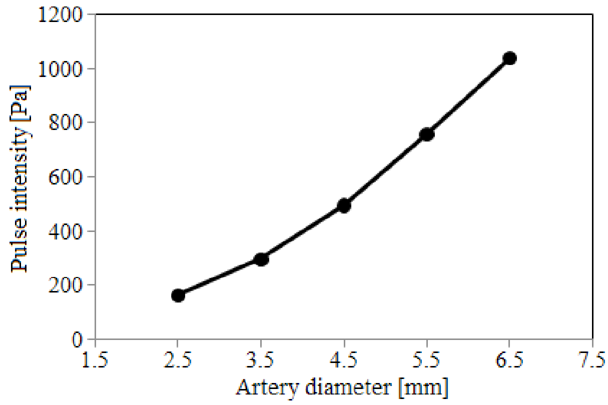

Figure 8. Tactile map of pulse intensity in model TIHA for different artery diameters.

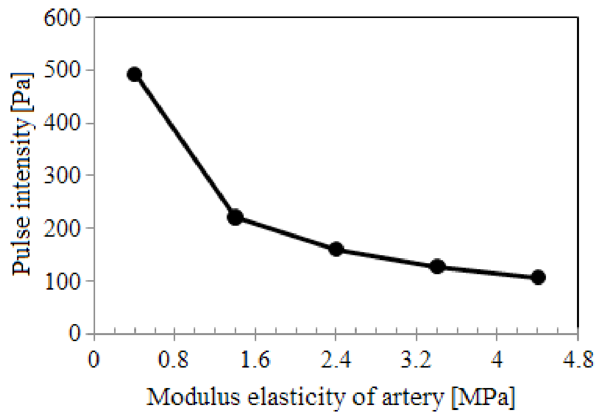

Figure 9. Tactile map of pulse intensity in model TIHA for different elastic modulus of artery.

A significant and discriminating aspect of this study is the assessment of the different parameters of model TIHA on artery detection. It can be concluded: 1) if the artery was placed far from the tissue surface, the surgeon can feel the arterial pulse with difficultly, 2) increasing tissue indentation by finger displacement causes the surgeon to feel the arterial pulse more conveniently and with more accuracy, 3) finding an artery with large diameter in a tissue can be performed by a surgeon quickly and conveniently in comparison with an artery with small diameter, and 4) increasing the elastic modulus of the artery causes the surgeon to feel the lower arterial pulse.

One of the most important features of this research is the benefit of the concept of our results in constructing the surgical simulators for trainee surgeons. Here, they can palpate the different tissues in surgical simulator and distinguish between them based on tactile feedbacks and, also, can easily obtain adequate information about embedded objects during palpating the simulated soft tissue. If the concept of our result about the existence of the stenosis in an artery was used in graphical display of surgical simulators, it can help trainee vascular surgeons to practice more for distinguishing between healthy artery and stenotic artery without any kind of penetration into the artery wall. For example, we can refer to what happens in current procedures of real vascular surgery. Therefore, surgeons can review, repeat, and reassess their performance and find areas for improvement without compromising patient safety. The other use of these results is its capability of being extended to the field of robotic surgery simulators, where the sense of touch is absolutely necessary for the trainee surgeons to compensate for their inability to palpate the operation sites by long rigid tools. In this regard, tactile maps can add more information to the unfavorable visualization provided for surgeons in MIS and robotic surgery simulators.

Acknowledgements

The authors gratefully acknowledge Sina Trauma and Surgery Research Center of Sina Hospital for providing the financial support for this project.

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