Tissue Stiffness Simulation and Abnormality Localization using Pseudo-Haptic Feedback*

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Abstract—This paper introduces a new and low-cost tissue stiffness simulation technique for surgical training and robot-assisted minimally invasive surgery (RMIS) with pseudo-haptic feedback based on tissue stiffness maps provided by rolling mechanical imaging. Superficial palpation and deep palpation pseudo-haptic simulation methods are presented. Although without expensive haptic interfaces users receive only visual feedback (pseudo-haptics) when maneuvering a cursor over the surface of a virtual soft-tissue organ by means of an input device such as a mouse, a joystick, or a touch-sensitive tablet, the alterations to the cursor behavior induced by the method creates the experience of actual interaction with a tumor in the users’ minds. The proposed methods are experimentally evaluated for tissue abnormality identification. It is shown that users can recognize tumors with these two methods and the rate of correctly recognized tumors in deep palpation pseudo-haptic simulation is higher than superficial palpation simulation.

I. INTRODUCTION

Palpations are used to examine metastases [1], identify therapeutic margins for curative resection [2], [3], and detect arteries hidden in fatty mesentery [4]. Most of these medical tasks employ stiffness perception. Tissue that is stiffer than surrounding tissue could be recognized as a possible tumor [5]. During an open surgery, surgeons often manually palpate biological tissue to detect tissue abnormality such as tumors. But in robot-assisted minimally invasive surgery (RMIS) how to acquire tissue stiffness data and display it to the surgeon has been recognized as a problem by many researchers and clinicians [6]-[10].

Simulating the function of haptic sensations resulting from palpations is beneficial for tissue abnormality localization both in medical training and RMIS. To provide haptic feedback, haptic devices are required, but haptic interfaces are relatively costly. This paper presents a new tissue stiffness simulation technique for surgical training and RMIS using pseudo-haptic feedback (and thus do not require real haptic devices): the technique is based on tissue stiffness maps created from rolling mechanical imaging [11]-[13].

II. RESEARCH BACKGROUND

A. Soft Tissue Simulation

Extensive training is required for surgeons to learn most surgical procedures. To provide a Virtual-Reality (VR) environment, soft tissue modeling is significant [15]. The main models for soft tissue deformations include surface or volumetric tissue models, springs and particles models and finite element models [16]. Simplifications are commonly used to reduce computation times for tissue’s real-time deformation. Linear elastic models are an example of the trade-off between real-time computations and realism [17]-[20].

There have been a quite a number of surgical simulators with haptic feedback. For example, Nakao [14] proposed a haptic simulator for palpations in cardiovascular surgery based on the finite element method and two PHANToM devices. The cost of such simulators is still relatively high.

B. Intra-operative Soft Tissue Abnormality Localization in RMIS

There have been conducted a lot of research work on soft tissue abnormality localization in RMIS and related areas since last decade. Many researchers chose graphic display method to show tissue abnormalities to surgeons [6]-[19]. Some researchers tried to use haptic displays. Most methods are still at an experimental stage [6]-[10].

Trejos et al. [6], [7] proposed a tactile sensing instrument (TSI) and extended it to a tactile sensing system (TSS) by adding a visualization interface, which can present an live pressure map of the contact area to locate tumors during MIS. Miller et al. [8] presented a Tactile Imaging System (TIS). A capacitive array sensor attached to a MIS probe was used to scan the surface of the tissue. A vision-based algorithm was used for localization of the probe in the live video and overlaying the registered semi-transparent measured pressure distribution map on the video. Yamamoto et al. [9] presented an automated tissue property estimation method and a real-time continuous semi-transparent hue-saturation-luminance graphical overlay method. Based on ultrasound real time elastography and electrorheological fluids, Khaled et al. [10] developed a system which integrated haptic sensors and actuators. The results of elasticity images and reconstructed virtual objects on the actuator haptic interface were combined. The haptic display allows users to palpate the patient’s tissue, while imaging and carrying out a biopsy. The rolling indentation approach for the localization of tissue abnormalities during MIS is


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proposed in [11]-[13]. The stiffness distribution of a soft tissue surface can be visualized by using a force-sensitive wheeled probe to conduct a rolling indentation over it. Althoefer et al. [1] proposed an air-cushion force-sensitive indentation probe for rapid abnormalities localization within soft tissue organs.

C. Pseudo-Haptic Feedback

The concept of pseudo-haptic feedback relies on combining visual feedback with the resistance of an isometric device [22]. Pseudo force feedback is generated and controlled by the decrease or increase of the pressure on the isometric device [23]. For example, when the user is pressing a spring simulated by an isometric stick, the spring on the screen becomes shorter so that the user will have an illusion that the stick is compressed by the user’s hand. The stick itself is not compressed- hence the name “isometric”.

Some haptic properties have already been simulated by using pseudo-haptic feedback, including friction [24], stiffness of a spring [25], mass [26], and texture [27]-[29]. A pseudo-haptic texture simulating technique has been implemented in a medical simulator for loco-regional anesthesia [23]. Compared with using expensive and complex haptic devices, pseudo-haptic feedback is potentially much cheaper and more convenient to implement and use. Up to now, this cheap and simple technology has not been applied to the problem of soft tissue stiffness simulation.

III. PSEUDO-HAPTIC TISSUE STIFFNESS SIMULATION

A. Palpation

For superficial palpation, medical practitioners use their fingers or hands slide over the tissue surface to detect changes of tissue stiffness. Fig. 1 shows the reflected forces of superficial palpation. When doctors’ fingers are approaching a tumor, lateral force \( f_x \) will increase and the speed of fingers will decrease.

For deep palpation, medical practitioners use their fingers or hands press on tissue surface perpendicular to feel tissue stiffness. Reflected force will increase as indentation depth increase. When doctors press areas with tumors underneath, reflected forces will be bigger than pressing normal areas.

B. Pseudo-Haptic Tissue Stiffness Simulation

The concept of pseudo-haptic feedback for soft tissue simulation and abnormality localization has been proposed in this paper. Stiffness map of soft tissue should be acquired first. And then pseudo-haptic feedback technique will be applied to simulate tissue stiffness when palpations by changing the ratio of the speed of cursor movement to speed of finger movement. The user will then experience a corresponding resistance when the cursor speed is slower. Rather than applied to the user’s finger, virtual forces are directly exerted on the cursor. Fig. 2 illustrates lateral virtual force of superficial palpation pseudo-haptic simulation. Fig. 3 illustrates perpendicular virtual force of deep palpation.

IV. IMPLEMENTATION

A. Data Acquisition and Tissue Stiffness Identification

We used a rolling indentation probe to scan a silicone phantom organ with simulated tumors to create “ground truth” stiffness maps. Rolling mechanical imaging [11] [12] was proposed by Liu et al. aiming at providing force perception during RMIS. The rolling indentation probe can continually measure the tool-tissue interaction dynamics as it rolls over the surface of the tissue and generate stiffness maps rapidly. With the probe, we can obtain a force distribution matrix, which effectively is showing tissue’s elastic modulus at the given indentation depth [13].

The silicone phantom tissue sample was 150x150x17 mm³ with nine embedded simulated tumors, Fig. 4 and Table I. To obtain a rolling stiffness map, 36x150mm trajectories parallel to the x-axis with a shift of 4mm along the y-axis
between each two trajectories were defined. The start point of first trajectory is (0, 0) on the silicone phantom. A robot arm then was programmed to move the rolling indentation probe along the middle 34 trajectories at a speed of 45 mm/s with a constant rolling indentation depth. It took 2.5 minutes to cover the entire area. The sampling rate of reflection forces was 100 Hz. The rolling indentation depth was 3 mm. These procedures were repeated ten times. A force distribution matrix with 135×34 elements was generated.

![Image](image.png)

Figure 4. The silicone soft-tissue phantom with the locations of nine embedded simulated tumors

<table>
<thead>
<tr>
<th>Simulated tumors and coordinates</th>
<th>Cross sections of tumors</th>
<th>Thickness</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 (25,25)</td>
<td></td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>A2 (75,25)</td>
<td></td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>A3 (125,25)</td>
<td></td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>B1 (25,75)</td>
<td>10</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>B2 (75,75)</td>
<td>10</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>B3 (125,75)</td>
<td>10</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>C1 (25,125)</td>
<td>10</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>C2 (75,125)</td>
<td>10</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>C3 (125,125)</td>
<td>10</td>
<td>4</td>
<td>13</td>
</tr>
</tbody>
</table>

B. Superficial palpation pseudo-haptic tissue stiffness simulation protocol

1) Basic strategy:
   - Mouse cursor speed changing strategy

For simplification of program calculation, stiffness data was linearly mapped to integer numbers between 1 (stiffest) and 20 (softest) and was stored in a two-dimensional array. When the mouse moves, a mouse-movement event will be triggered; the current cursor position and last cursor position will be then obtained and corresponding stiffness level (Crt and Lst) will be read from the two-dimensional stiffness level array. The mouse movement speed was mapped to the difference value (Ds) between current stiffness level (Crt) and last stiffness level (Lst). Equation (1) was used to set the mouse speed according to the mapping relation between stiffness level difference (Ds) and mouse movement speed parameter (aMouseInfo).

\[
Ds = Crt - Lst
\]  

2) Auxiliary strategies:
   - Mouse cursor size changing strategy

   Auxiliary strategies were proposed to strengthen perception for superficial palpation simulation, which can be used as teacher signal during medical training. Employing the mouse cursor size changing strategy, the mouse cursor radius (r) changes from 1 to 20 pixels as a function of stiffness level difference (Ds):

\[
r = r_0 - k \cdot Ds
\]

(2) Flashing cursor strategy uses a flashing cursor, and when stiffness change exceeds a predetermined threshold of stiffness level difference (Dso), the cursor will start flashing. For shaking background strategy, the window will shake when the Dso becomes larger than the threshold. Shaking background can simulate vibration sensory stimuli without vibration actuators.

![Image](image.png)

Figure 5. Mapping relation between stiffness data difference (Ds) and mouse movement speed parameter (aMouseInfo)

3) Implementation:

Pseudo-haptic tissue stiffness simulation was evaluated for tissue abnormality localization using a three-button infrared mouse. The phantom tissue was represented using a white and rectangular 2D surface of 540×544 pixels, displayed on a monoscopic computer screen. One square millimeter of soft tissue is represented by 4×4 pixels. In order to evaluate the different strategies, six tests were conducted. Test 1 was only the basic strategy. From test 2 to test 6 were the combination of the auxiliary strategies and the basic strategy.

Test 1: Cursor speed changing strategy;
Test 2: Combination of cursor size changing and speed changing strategy;
Test 3: Combination of flashing cursor and speed changing strategies;
Test 4: Combination of flashing cursor strategy, speed and size changing strategies;
Test 5: Combination of shaking background and cursor speed changing strategy;
Test 6: Combination of shaking background, cursor speed, and cursor size changing strategy.
Participants were asked to conduct the tests of the study randomly. The test protocol of each test was explained to the participants and they were asked to scan the tissue surface with the mouse, and record coordinates of any located tumors. The parameters of equation (2) were as follow.

\[ r_0 = 10, \]
\[ k = 1. \]

In flashing cursor strategy and shaking background strategy, the threshold stiffness level stiffness \( D_0 \) was -3.

**E. Deep palpation pseudo-haptic tissue stiffness simulation protocol**

- Mouse cursor speed changing strategy

This method is based on a one-dimensional simulation, where the palpation follows a trajectory parallel to the \( x \)-axis. When tissue areas with a high stiffness are encountered, the cursor speed will decrease and the maximum-achievable indentation depth will become smaller. The phantom tissue cross section is a white rectangular 2D area of \( 540 \times 100 \) pixels. In this test, parameter \( k \) in equation (4) was 1. The mouse movement speed parameter (\( a_{MouseInfo} \)) and maximum indentation depth (\( Md \)) setting are according to current tissue stiffness level (\( Crt \)):

\[ a_{MouseInfo} = Crt. \]
\[ Md = Md_0 - k \cdot Crt. \]
V. EXPERIMENTAL EVALUATION FOR TISSUE ABNORMALITY LOCALIZATION

A. Superficial palpation pseudo-haptic tissue stiffness simulation

Fourteen participants, consisting of 11 men and 3 women, with normal or corrected vision participated in the evaluation study. All participants noticed tissue abnormalities in all tests. Table II shows the stiff points marked by participants and accuracy rate of each test. Test 3 got the highest accuracy rate. Fig. 6 shows the rolling indentation stiffness map and possible stiff points recorded by participants, in which correctly recognized stiff points were represented by “•” and wrongly recognized stiff points were represented by “ grind ”. Most wrong points were within the stiffer area around tumors B1, B2, C1, and C2. Fig. 7 presents the number of tumors found by participants in each test. In most tests, the recognized tumors number was around 3. The worst performance could be observed in test 5 (below 72%). The slightly poorer performance could be explained with the short time delay that occurs before the shaking background becomes active in response to a participant encountering a tumor. Fig. 8 shows how often individual tumors were recognized by users. C1 and B1 were most easily recognized, because stiffness gradients around tumor C1 and tumor B1 were the biggest. Since the stiffness gradient around tumor B2 was much lower, tumor B2 was recognized the fewest times. A2, A3, B3, and C3 were not recognized during the tests. The reason was the gradients around A2, A3, B3, and C3 were too low to detect.

B. Deep palpation pseudo-haptic tissue stiffness simulation

Participants were asked to scan the surface of tissue with superficial palpation method based on the cursor speed changing strategy. Once an area of potential abnormality was identified, they were asked to right-click the mouse, and then to use the deep palpation method to further explore the cross section in the vicinity of the identified abnormality (Parallel to the x-axis). They were asked to record identified tumor coordinates and tumor coordinates. Fig. 9 shows the marked points. As can be seen from the figure, all points found are on the tumors’ positions. With deep palpation simulation the participants showed to find the tumors’ coordinates much more accurately and easily.

<table>
<thead>
<tr>
<th>TABLE II.</th>
<th>RECORDED POINTS AND ACCURACY RATE FOR EACH TEST</th>
</tr>
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<tbody>
<tr>
<td>Test</td>
<td>Recorded points</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>67</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
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<tr>
<td>4</td>
<td>61</td>
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<td>5</td>
<td>57</td>
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<tr>
<td>6</td>
<td>56</td>
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<td>7</td>
<td>30</td>
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</tbody>
</table>

VI. CONCLUSIONS

This paper developed cheap, simple and effective superficial palpation and deep palpation pseudo-haptic tissue stiffness simulation methods for tissue abnormality localization using measured phantom tissue stiffness data without haptic interfaces. The evaluation results show that users can recognize tumors with these two methods. With deep palpation simulation the participants showed to find the tumors’ coordinates much more accurately and easily than superficial palpation. Performance comparison studies of the pseudo-haptic palpation simulation and manual palpation needs to be done in next step. Mapping stiffness data to mouse speed and size, and the threshold need more research in the future. Other input devices which can make palpation simulation more natural should be introduced. Improvement should be done to reduce the time delay of shaking background strategy. This two dimensional method should be extended to three dimensional palpation simulations.
REFERENCES


