Finite Element Modelling of Soft Tissue Rolling Indentation

Kiattisak Sangpradit, Hongbin Liu, Prokar Dasgupta, Kaspar Althoefer and Lakmal D. Seneviratne

Abstract—We describe a finite element (FE) model for simulating wheel-rolling tissue deformations using a rolling finite element model (RFEM). A wheeled probe performing rolling tissue indentation has proven to be a promising approach for compensating for the loss of haptic and tactile feedback experienced during robotic-assisted minimally invasive surgery (MIS) [1-6]. A sound understanding of wheel-tissue rolling interaction dynamics will facilitate the evaluation of signals from rolling indentation. In this paper, we model the dynamic interactions between a wheeled probe and a soft tissue sample using the ABAQUS finite element analysis software package. The aim of this work is to more precisely locate abnormalities within soft tissue organs using RFEM and hence aid surgeons improving diagnostic ability. The soft tissue is modeled as a nonlinear hyperelastic material with geometrical nonlinearity. The proposed RFEM was validated on a silicone phantom and a porcine kidney sample. The results show that the proposed method can predict the wheel-tissue interaction forces of rolling indentation with good accuracy and can also identify the location and depth of simulated tumors accurately.

Index Terms—Soft tissue abnormality localization, Minimally Invasive Surgery, Haptic Feedback, Finite Element Modelling, Rolling Indentation, Tumour detection, Soft tissue organ diagnosis

I. INTRODUCTION

MINIMALLY Invasive Surgery (MIS) is performed through small incisions, resulting in reduced trauma, recovery times and hospitalization costs [14]. However, the loss of tactile feedback is a significant drawback with MIS, preventing the surgeon from directly palpating specific tissue regions [10-13]. This sensory reduction is only partially compensated for by employing highly magnified stereo vision during MIS. A wheeled probe for the rapid identification of mechanical properties of soft tissue during MIS was proposed in [1-6]. A sound understanding of wheel-tissue rolling interaction dynamics will facilitate the evaluation of signals from rolling indentation. This paper presents a Rolling Finite Element Model (RFEM) to simulate soft tissue rolling indentation, in order to predict soft tissue behavior and identify abnormal tissue regions, such as tumors buried within a soft tissue organ.

II. BACKGROUND

Biological soft tissue is highly nonlinear, viscoelastic, anisotropic, heterogeneous, and nearly incompressible with a porous internal structure. Their mechanical properties also depend on environmental factors such as pH value, temperature and tissue health [7]. The stress-strain relationship of soft tissue is time and strain rate dependent [8, 9, 15, 17, 19] and there is a significant variation in mechanical characteristics of tissues of different pathological states [14, 17, 18, 19]. Hence, employing a mechanical probe to estimate tissue properties provides a potentially useful means of identifying malignant tissue. Many researchers have used FE techniques to simulate soft tissue behavior and for soft tissue parameter identification [20-23]. Tillier et al. applied hyper-elastic constitutive equations, using ANSYS FE software, to identify tissue properties from experimental measurements [20]. The method was applied to lamb kidney and the human uterus, showing good agreement with experimental data. Liu et al. [21] applied a nonlinear hyper-elastic, 8-chain network (Arruda-Boyce model) constitutive equation to model soft tissue undergoing large indentations by using ABAQUS software, and identified two material parameters, the initial modulus and locking stretch. Kerdok et al. used the Arruda-Boyce model with ABAQUS to identify the properties of breast tissue [22]. Zhang et al [23] used FE analysis to simulate indentation behaviour of residual limb tissue. Pinchon et al [25] proposed a FE model for soft tissue deformation based on nonlinear elasticity and anisotropic behavior. Zhong et al [26] presented a methodology for predicting the deformations of soft objects, based on the analogy between heat conduction and elastic deformations. Szekely et al [27] developed a full-scale FE simulation of elastic tissue deformation in complex systems such as the human abdomen. Schwartz et al [28] extended the linear elastic tensor-mass method to simulate biological soft tissue, for planning surgical treatment of liver cancer. Duyssak et al [29] used a spring-mass system to simulate facial soft tissue deformation during lower jaw bone realignment.
Rolling indentation gives continuous measurements of the tissue mechanical response, while covering a large tissue area in a relatively short time [1, 3, 5]. However, a systematic methodology is required to accurately interpret signals from rolling indentation. This paper presents a rolling finite element model (RFEM) for soft tissue, to predict tool-tissue interaction forces during rolling indentation, and hence identify and locate tissue abnormalities.

III. EXPERIMENTAL ESTIMATIONS OF TISSUE PARAMETERS

In this paper the hyperelastic, Arruda-Boyce equations are used to model tissue behavior and the material properties are assumed to be non-linear, incompressible and isotropic. Hyperelastic materials can be described using a strain energy function, $U$, which is defined as the strain energy density at a given location in the material. Equation (1) gives the Arruda-Boyce strain energy function [30]:

$$U = \mu \sum_{i=1}^{3} \frac{C_{ij}}{\lambda_{ij}^2} (I_{ij} - 3^+) + \frac{1}{D} \left[ \frac{j_{ij}^d - 1}{2} - \ln (J_{ij}) \right]$$

(1)

With

$$C_1 = \frac{1}{2}, \quad C_2 = \frac{1}{20}, \quad C_3 = \frac{11}{1050},$$

$$C_4 = \frac{19}{7000}, \quad C_5 = \frac{519}{673750}$$

(2)

where:

- $U$ = The strain energy density
- $\mu$ = The initial shear modulus
- $\lambda_{\text{m}}$ = The locking stretch
- $J_{ij}$ = The elastic volume ratio
- $C_i$ = Material constants defined in equation (2)
- $D$ = Is a measure of compressibility and is zero for fully incompressible materials
- $I_1$ = The first invariant of the deviatoric strain, given in terms of the principal stretches $\lambda_1, \lambda_2$ and $\lambda_3$:

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$

(3)

The true stress is given by:

$$\sigma_{\text{true}} = \sigma_n \cdot \lambda_n$$

(5)

Differentiating equation (1) gives:

$$\sigma_n = \mu \left[ \left( \lambda_n^{-1} - \lambda_n^{-1} \right) + \frac{1}{5 \lambda_n^2} \left( \lambda_n^{-1} - \lambda_n^{-1} \right) + \frac{11}{175 \lambda_n^4} \left( \lambda_n^{-1} - \lambda_n^{-1} \right) + \frac{19}{875 \lambda_n^6} \left( \lambda_n^{-1} - \lambda_n^{-1} \right) + \frac{519}{67375 \lambda_n^8} \left( \lambda_n^{-1} - \lambda_n^{-1} \right) \right]$$

(6)

The locking stretch, $\lambda_{\text{m}}$, can be obtained from the limiting chain stretch, $\lambda_{\text{m,lim}}$, which is the stretch at which the stress starts to increase without limit, the value of, $\lambda_{\text{m}}$, can be obtained from [31]:

$$\lambda_{\text{m}} = \left[ \frac{1}{3} \left( \frac{\lambda_{\text{m,lim}}^2 + 2}{\lambda_{\text{m,lim}}} \right) \right]$$

(7)

A uniaxial compression test is conducted on rubber and silicone material and porcine kidney, using an INSTRON 5543 machine, Fig.1, to experimentally estimate the material properties. A silicone cube of 15x15x15 mm$^3$, a rubber cylinder (hard nodule) of 10 mm diameter and 10 mm length and a kidney cube of 15x15x15 mm$^3$, was compressed by 6 mm at a speed of 1 mm/sec.

Fig.1 Uniaxial compression tests using the INSTRON 5543 machine, (a) Silicone tissue phantom (b) Rubber used to simulate tumours (c) Porcine kidney.
The Arruda-Boyce model requires two parameters, $\mu$ and $\lambda_m$, to describe nonlinear, hyperelastic material behavior. These parameters for rubber, silicone and porcine kidney are estimated by comparing the uniaxial compression test results, Fig 1(a), 1(b), and 1(c), with the Arruda-Boyce strain energy function, using Matlab, and the results are lists in Table I.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>PROPERTIES OF THE TEST MATERIALS</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$\mu$, shear Modulus (kPa)</td>
</tr>
<tr>
<td>Rubber</td>
<td>73.40</td>
</tr>
<tr>
<td>Silicone (RTV6166 gel)</td>
<td>4.98</td>
</tr>
<tr>
<td>Porcine kidney</td>
<td>1.58</td>
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</tbody>
</table>

IV. ROLLING INDENTATION EXPERIMENTS

A. Silicone Phantom Tests

The rolling indentation tests are performed using a wheeled probe attached to the distal tip of a Mitsubishi RV-6SL 6-DOF robot manipulator. An ATI NANO17 Force/Torque sensor was mounted between the wheeled probe and the manipulator distal tip to measure the three force components ($F_x$, $F_y$, $F_z$) imparted by the tissue onto the wheel, Fig 3.

Rolling indentation, experiments are performed on a silicone phantom and a porcine kidney sample. The silicone phantom is made from RTV6166 gel [16], and embedded with rubber nodules to simulate tumors. The tissue phantom is a 30 (height) $\times$ 150 (length) $\times$ 50 (width) mm$^3$ block, containing three embedded nodules (cylinders of diameter 10mm x length 10 mm) located in the tissue phantom as indicated in Fig 2.

During the experiments, a wheeled indenter (8mm diameter and 8mm length) is used to perform rolling indentation on the tissue phantom, at a constant indentation depth and a constant speed of 45mm/s, covering the top surface from left to right, Fig 3. During the tests, the force exerted by the phantom onto the wheel is recorded. Four tests, with indentation depths of 3mm, 4mm, 5mm and 6mm, were performed, with each test repeated 3 times. The averaged test results are shown in Fig 11.

B. Porcine Kidney Tests

Experiments are conducted on an Ex-vivo porcine kidney sample (weight= 0.2 kg, lab temperature =15.1C, lab humidity =30%) with a rubber cylinder embedded within the kidney sample, at a depth of 10 mm from the top surface, Fig 4.

Fig. 2 The silicone phantom with three rubber nodules.

Fig. 3 The experiments on the silicone phantom.

Fig. 4 A rubber cylinder embedded within the porcine sample

Fig. 5 The probe path during rolling indentation.
The wheeled probe was then rolled over the kidney top surface at a speed of 45 mm/s, Fig.5, while keeping the indentation depth approximately constant at 4 mm; the tests were repeated three times. During the tests, a plastic cling film of negligible thickness was used to cover the kidney sample to prevent tissue damage and loss of water from the sample.

V. ROLLING INDENTATION FINITE ELEMENT SIMULATION

A. FE Modelling of the Silicone Phantom

The silicone phantom is modeled using ABAQUS, as a planar rectangle (dimensions of 30 mm by 150 mm), with three holes corresponding to the nodule locations, Fig. 6. The FE mesh consists of 4884 four-node bilinear plane stress quadrilateral elements (ABAQUS element CPS4R).

![Fig. 6 2D FE model for silicone.](image1)

![Fig.7 2D FE model for rubber nodules](image2)

![Fig.8 Assembled 2D finite element model for silicone phantom.](image3)

The three rubber nodules are modeled as 10 diameter 2D-circles, Fig. 7, using 114 four-node bilinear plane stress quadrilateral elements (ABAQUS element CPS4R). The three nodules are then assembled into the holes in the silicone model, Fig. 8, positioned at depths of 10 mm, 15 mm and 20 mm from the top surface. The indenter was modeled as a 8mm diameter 2D-circle with 25 elements of the two-node 2D linear rigid link (ABAQUS element R2D2). Both the ABAQUS elements used in this paper (CPS4R and R2D2) use reduced integration and hourglass control, assuming non-linear, isotropic, incompressible, and hyperelastic material behavior.

![Fig. 9 ABAQUS simulation of rolling indentation on the silicone phantom.](image4)

In the FE model, the contact between the rubber and silicone is defined as “rough” and that between the indenter and silicone phantom as “frictionless” (ABAQUS contact). The lower surface of the silicone phantom is grounded and the experimental tests were repeated using FE simulations. Each rolling indentation FE simulation test requires approximately 10 minutes of computational time, on a 2.8 GHz Pentium (R)D machine with 3.5GB of RAM.

B. FE modelling of the porcine kidney sample

The porcine kidney is modeled as a two-dimensional planar entity using the ABAQUS finite element software, with all dimensions obtained from measurements on the test sample. The kidney FE mesh consists of 2021 ABAQUS CPS4R elements, Fig.10. The rubber cylinders were modeled as described in the previous section, using 32 ABAQUS CPS4R elements. The simulated tumor is positioned at a depth of 10 mm from the surface, inside the kidney model, Fig. 10. The indenter is modeled as described in the previous section.

The porcine kidney experimental tests are repeated using FE simulations. Each FE simulation test requires approximately 8 minutes of computational time on a 2.8 GHz Pentium(R) D machine with 3.5GB of RAM.

VI. EXPERIMENT RESULTS AND ANALYSIS

A. Silicone phantom

The experimental and FE model simulation results for the silicone phantom are shown in Fig.11. As seen in Fig.11 and Table II, the RFEM results are in good agreement with the corresponding experimental data; the RMS errors range from 0.0289 to 0.1449, with the errors increasing with tumor depth.
TABLE II
THE RMS ERRORS BETWEEN FINITE ELEMENT AND ROLLING INDENTATION TESTS

<table>
<thead>
<tr>
<th>Rolling Indentation depth, Rd</th>
<th>3mm</th>
<th>4mm</th>
<th>5mm</th>
<th>6mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS Error</td>
<td>0.0289</td>
<td>0.0613</td>
<td>0.1050</td>
<td>0.1449</td>
</tr>
</tbody>
</table>

B. Porcine kidney

Fig. 12 shows the rolling-tissue interaction forces from porcine kidney experiments and RFEM simulations. The FE model predictions are in good agreement with the experimental results, with an RMS error of 0.05. Both results show an increased stiffness (force peak) at the vicinity of the embedded tumor. These results show the ability of RFEM to simulate a complex material like biological soft tissue.

Fig. 13. Silicone phantom FE simulations with varying tumour locations: (a) The hard nodule is placed at eight locations and (b) The RFEM of the silicone phantom.

VII. LOCALIZING ABNORMALITIES WITHIN SOFT TISSUE

It has been shown that the wheel-tissue rolling interaction signals can be used to rapidly detect the presence of abnormalities within soft tissue during MIS [1-6]. However, localizing the abnormalities requires a detailed understanding of the underlying physics. Hence it is informative to study the relationship between the locations of abnormalities and the tissue force-displacement characteristics, during rolling interactions. This section investigates the variation in reaction forces with respect to the tumor depth using FE simulations.

The tumor was placed at eight different locations, along the mid-plane of the block, at depths of 8, 10, 12, 15, 18, 20, 22 and 24 mm, Fig. 13(a). The rolling indentation was performed at four different depths; 3, 4, 5 and 6 mm. The rolling length is 60mm; a tumor is embedded at the mid-plane of the phantom block.
Fig. 14. (a) RFEM results for 4 different rolling indentation depths, with 8mm tumor depth. (b) Peak forces for eight different tumor depths with 6mm rolling indentation depth.

It is noted that the horizontal location of the tumor can be determined by using the peak of the rolling force profile. The peak force increases with increased rolling indentation depth, Fig. 14 (a), and the peak force decreases with increased tumor depth, Fig 14 (b). In this section we investigate whether the magnitude of the indentation force can be correlated to the tumor depth for localization.

Fig. 15 shows RFEM results at an indentation depth of 3 mm, for various tumor depths. The results indicate that there is a measurable increase in stiffness for tumor depths of 8 mm, 10 mm and 12 mm, Fig. 15 (b). However, deeper tumors (depths of 15-24 mm), with a 3mm indentation depth, does not appear to give a distinguishable variation in stiffness, Fig. 15 (c).

For a given rolling indentation depth, the peak force values appear to approach a constant asymptote, with increasing tumor depth, Fig. 16. Hence the rolling indentation method has the potential to locate the depth of tumors, with the maximum identifiable tumor depth depending on the indentation depth. Only three tumor depths are identifiable with an indentation depth of 3 mm (8, 10 and 12mm), seven tumor depths (15mm, 18mm, 20mm and 22mm) are identifiable with an indentation depth of 6mm.

From the RFEM curves in Figure 16, an empirical equation can be generated by curve fitting, to relate peak force to tumor depth, for this particular set of experimental data, Table III.
TABLE III
EMPirical Equations For Tumour Depth: \( N_d = \text{Simulation Tumor Depth}, F = \text{Peak Force} \)

<table>
<thead>
<tr>
<th>Rolling indentation depth</th>
<th>Empirical equation</th>
</tr>
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<tbody>
<tr>
<td>3mm (10mm)</td>
<td>( N_d = 246.38F^2 - 502.75F + 262.91 )</td>
</tr>
<tr>
<td>4mm (10mm)</td>
<td>( N_d = 36.057F^2 - 119.44F + 106.71 )</td>
</tr>
<tr>
<td>5mm (10mm)</td>
<td>( N_d = 36.206F^2 - 159.17F + 182.57 )</td>
</tr>
<tr>
<td>6mm (10mm)</td>
<td>( N_d = 12.983F^2 - 78.552F + 126.92 )</td>
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</table>

To investigate the ability of the empirical equations in Table III to identify tumor depths, the experiments with the silicone phantom (section IV-A) were carried out. The predicted depths and the prediction errors are shown in Table IV. It is noted that the predicted tumor depths are accurate, with errors ranging from 0.19 mm to 0.75 mm.

TABLE IV USE OF EMPIRICAL EQUATIONS TO IDENTIFY TUMOUR DEPTH (NI-NOT IDENTIFIABLE).

<table>
<thead>
<tr>
<th>True simulated tumour depth</th>
<th>Predicted depth (mm)</th>
<th>Error (mm)</th>
<th>Predicted depth (mm)</th>
<th>Error (mm)</th>
<th>Predicted depth (mm)</th>
<th>Error (mm)</th>
<th>Predicted depth (mm)</th>
<th>Error (mm)</th>
<th>Predicted depth (mm)</th>
<th>Error (mm)</th>
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<tbody>
<tr>
<td>Rd=3mm</td>
<td>A1(15mm)</td>
<td>10.19</td>
<td>0.19</td>
<td>10.75</td>
<td>0.75</td>
<td>9.69</td>
<td>0.31</td>
<td>9.68</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>Rd=4mm</td>
<td>A2(15mm)</td>
<td>NI</td>
<td>NI</td>
<td>15.43</td>
<td>0.43</td>
<td>15.56</td>
<td>0.56</td>
<td>14.46</td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td>Rd=5mm</td>
<td>A3(20mm)</td>
<td>NI</td>
<td>NI</td>
<td>NI</td>
<td>NI</td>
<td>19.70</td>
<td>0.30</td>
<td></td>
<td></td>
<td></td>
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</table>

VIII. CONCLUSIONS

This paper presents a rolling finite element model (RFEM) to simulate the rolling tissue indentation technique, which can cover a large tissue surface in a relatively short time. It is concluded that a rolling finite element model shows good correlation with experimental data. Following the abnormality localization, it shows good understanding on the relationship between the locations of abnormalities and tissue reaction forces during rolling interaction. Hence, it has a potential to predict tumour location. Future work will be carried out to develop generalised algorithms to identify the mechanical properties of tumours as well as tumour depths, using real-time RFEM.

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REFERENCES


