Article
Development of a finite element based haptic interactive surgery simulation from Computer Tomography data

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Abstract: Virtual models are important for training and teaching tools used in medical imaging research. We introduce a workflow that can be used to convert volumetric medical imaging data (as generated by Computer Tomography (CT)) to computer-based models where we can perform interaction of tool with the tissue. This process is broken up into two steps: image segmentation and tool-tissue interaction. We demonstrate the utility of this streamlined workflow by creating models of a liver. A FE model for probe insertion has been developed using cohesive elements to simulate the tissue rupture phenomena. FE based simulations are performed and the results are compared with that of various published papers. An analytical model that governs the reaction forces on the needle tip has also been developed. Expressions for reaction forces acting in both axial and transverse directions on a symmetric tip needle and a bevel tip needle are developed. These models consider local tissue deformation by the needle and the frictional forces generated due to the inclusion of the needle in the tissue, but do not consider the role of tissue rupture toughness parameter $G_C$ due to which some differences are visible in FE based simulations and these analytical results.

Keywords: Computer Tomography; insertion modelling; finite element model; tissue rupture; image segmentation.

1. Introduction

Majority of surgical procedures involve tissue rupture and damage by a needle, scissors or blade. Hence accurate modelling of these invasive needle-tissue interactions is very important for development of a surgical simulator. Modelling and simulation of invasive surgical procedures are complex due to tissue rupture/damage, presence of friction, and varying boundary conditions. Linear elasticity-based FE models are the most predominate technique to model these invasive surgical procedures as well.

DiMaio et al. [15] developed a linear elastic FE based 2D needle insertion model, where phantom tissue was used to acquire tissue properties. They used condensed FE technique during pre-processing to achieve real-time haptic feedback. Alterovitz et al. [32] used this model to simulate needle steering and Goksel et al. [33] extended this model for 3D simulations.

Due to high computation cost associated with FE based models for invasive surgical procedures, and also, the difficulties associated with the characterization of non-linear behavior tissue during rupture, only a few studies have used non-linear model for simulating soft-tissue. Nienhuys and van der Stappen [34] used the Neo-Hookean model for simulating needle insertion in a three-dimensional model, but they have not provided any comparison of the simulation results with any experimental data. Picinbono et al. [35] have used a nonlinear isotropic model to simulate cutting of liver, but no validation or comparison for the simulation results was provided.
1.1 Analytical Modelling of Needle-Tissue Interactions:

An ideal mechanics-based model of the forces acting on needle tip would require input information about needle geometries and tissue material properties. Such a model could be used in surgical simulators for real-time haptic feedback or forces for given needle displacement. Nienhuys et al. [34] have presented a mechanics-based computational technique for estimating the reaction forces on the needle by a tissue. Wei Dong et al. [36] has developed a mechanics-based model of needle tip when it is inserted and rotated into a soft tissue. They have attempted to develop a 3D model of needle-tissue interaction, but they have not provided any experimental results for validation of their model.

Okamura et al. [19] developed a mechanics-based model to predict needle behavior using mechanical properties of tissue and geometrical properties of needle. They presented an analytical model for the load developed at needle tip based on its geometry and material properties of tissue, guided by microscopic observation of needle-tissue interactions. Also, an analytical model for calculation of deflection of needle tip in transverse direction is developed using energy-based approach. They have also validated their model with experimental observations.

2. Materials and Methods

2.1 Modelling Tissue Failure/Rupture:

Within the context of finite element modelling, the ‘energy of fracture’ approach is a very effective method of incorporating failure of an otherwise continuous mesh. In finite element software like ABAQUS, cohesive elements implement this concept through a fracture toughness parameter which is analogous to the strain energy release rate.

In 2D simulations, the cohesive elements are four-node with two ‘active’ faces. The traction–separation relationship between these two faces of the element determines whether or not the cohesive element is intact or, having failed, is removed from the simulation. To incorporate elements of zero thickness, constitutive thickness parameter (Tc) is included in the element formulation linking strain (ε) and separation (δ):

2.2 Modelling and Simulation:

To model the needle insertion phenomena, FE based 2D simulations are performed. The Poisson ratio for the tissue is kept near 0.5 to simulate the incompressible nature of tissue, and the value of the coefficient of friction between needle and tissue is kept low at 0.1, to replicate biological tissue behavior where the presence of fluid within the organs may act as a lubricant [11].

2.2.1 Material and Geometric Properties

The geometric and material properties for tissue and cohesive elements are taken from M. Oldfield et al. [3] and shown in table 3.1. The needle is modelled as a discrete rigid body, as the deformation in needle would be very small in comparison to that in tissue, hence to reduce the computational cost a rigid part type was selected instead of a deformable part type for the needle.
Needle

**Material Properties:**
Rigid Material (as the elastic deformation in needle is negligible)

**Geometrical Properties:**
- Diameter: 8 mm
- Length: 160 mm
- Tip-include angle: 50 °

Tissue

**Material Properties:**
- Young Modulus: 7 kPa
- Poisson Ratio: 0.475

**Geometrical Properties:**
- Length of each part: 80 mm
- Depth of each part: 86 mm

Cohesive Elements

**Material Properties:**
- Stiffness: \( 6.64 \times 10^{-4} \, N/mm^2 \)
- Fracture Toughness: 17.43 J/mm²

**Geometrical Properties:**
- Length: 86 mm
- Geometric Thickness: 0.001 mm
- Constitutive Thickness: 1

3-node 2D plane strain (CPE3) elements are used to mesh the tissue parts, and the cohesive layer is mesh using 4-node 2D cohesive element (COH2D4). Performing the convergence analysis, it has been found that an element size of 1.6 mm is suitable for the tissue elements. The tissue rupture parameter for the cohesive elements is modelled using traction-separation relationship as shown in figure 3.1. The value \( \delta \theta \) is set close to the needle diameter, and value of \( \delta y \) is calculated from the relation between the tissue rupture toughness parameter (\( G_c \)), tissue elasticity (\( E_T \)), and fracture separation (\( \delta \theta \)). Three sets of simulations are performed and a unique set of values of \( \delta y \) and \( \delta \theta \) are taken for each simulation as shown in figure 3.5.

2.2.2 Simulation Setup

Figure 3.3 shows the simulation setup for these FE based simulations. The tissue has been made of two parts joined together using tie constraint. The cohesive element is modelled as a thin layer of 2D cohesive elements. This cohesive layer is put between the two tissue parts and joined together using tie constraint. The needle is placed in the needle the junction of the two tissue parts, vertical overt the cohesive layer as shown in figure 3.3. To enable lateral forces across the cohesive elements two elements at the top of tissue block are removed. This enables the initial reparation across the crack surface.

2.2.3 Boundary Conditions

Appropriate boundary conditions have been applied to simulate realistic modelling as shown in figure 3.3. The sides of tissue block are pinned to replicate the presence of a container. Nodes along the bottom of the tissue block are free to move in the lateral direction (x-direction) but are prevented to move in normal direction (y-direction) to replicate the presence of container bottom. An additional constraint of equal and opposite displacement is applied to the nodes on either side of the crack axis to reduce the possibility of buckling associated with small numerical errors. The needle is given a displacement boundary condition of 25 mm along the needle shaft in y-direction to press against the tissue, to imitate the tissue rupture.
3. Results

The simulations are performed in ABAQUS/CAE (version 6.14) using an explicit solver. The deformation of tissue due to needle insertion and resulting contour plot for von-mises stress in tissue is shown in figure 3.4 for 25 mm depth of insertion of needle.

Figure 1. (a) Simulation setup for needle-insertion model; (b) Boundary conditions imposed on the needle-insertion model.

Figure 2. Contour plot for von-mises stress over deformed tissue.

Figure 3. Reaction force vs. insertion depth for different values of $\delta_0$ and $\delta_y$. 
Figure 3 shows the reaction forces acting along the needle shaft in y-direction, for different values of $\delta y$ and $\delta O$. The value $\delta O$ are kept close to the needle diameter, and value of $\delta y$ is calculated from the relation between $Gc$, $ET$, and $\delta O$. From the figure 3.5 is can be seen that small variation in the values of $\delta y$ and $\delta O$ does not make any significant change in values of reaction force and $GC$ is more important parameter of needle insertion modelling.

3.1 Verification of Insertion Model

To verify the results obtained from the FE based simulations, the reaction forces are compared with some of the previously published research work [2] and [3], as shown in figure 3.6. The plots shown in these figures are obtained from the experimental measurements for the reaction forces acting along the needle shaft during needle-insertion in soft tissue. It can be observed that trend in the results of the simulation match closely with these experimental results. The difference in the magnitude of the reaction forces is because of the fact that each research work have used different tissues.

4. Discussion

The needle-tissue interaction forces are analyzed in both palpation and insertion phenomena. To verify the results obtained from the FE based simulations performed for the needle-tissue palpation model, they are compared with the reported experimental results. Data obtained from the palpation models are used to develop a parametric model that can be implemented in a real-time surgical simulator to provide information about the tissue deformation and the reaction forces at a very high rate. Cohesive elements are used in the insertion model implements to simulate the tissue failure and crack generation phenomena. Results from the finite element-based simulation for the insertion model are compared with the reported experimental results in various other research work and a similar trend in insertion force is observed. The presence of a peak in reaction force just before the initiation of the tissue rupture, followed by a drastic reduction in the reaction forces, indicates the occurrence of tissue relaxation phenomena. Hence the implementation of cohesive element for insertion modelling is appropriate.

An analytical model is developed for the reaction forces acting on the needle during needle-insertion, the expressions for axial and transverse reaction forces in the symmetric and bevel tip needle are compared with a finite element-based simulation and both results follow the same trend. This validates the analytical model developed on the basis of local tissue deformation, compressive and frictional forces generated due to inclusion on the needle in the tissue. The constant difference in the current analytical and simulation results is due to the absence of tissue rupture toughness parameter in the analytical model. Sensitivity analyses are performed for variation in axial and transverse reaction forces with respect to tip bevel angle and tissue elasticity using FE based simulations. It is observed that the variation in reaction forces with tip bevel angle and tissue elasticity follow the same trend as the analytical model, further validating the analytical model.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: title; Table S1: title; Video S1: title.

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Appendix A

The appendix is an optional section that can contain details and data supplemental to the main text—for example, explanations of experimental details that would disrupt the flow of the main text but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data is shown in the main text can be added here if brief, or as Supplementary data. Mathematical proofs of results not central to the paper can be added as an appendix.

Appendix B

All appendix sections must be cited in the main text. In the appendices, Figures, Tables, etc. should be labeled starting with “A”—e.g., Figure A1, Figure A2, etc.

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