A Fast Krylov Subspace-based Method for Multi-physics Modeling of Electrosurgical Cutting of Soft Tissue

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ABSTRACT

In electrosurgery radiofrequency (RF, 300 KHz—3 MHz) alternating current (AC) is used to raise intracellular temperature in order to achieve cutting or coagulation of soft tissue [1]. The type of tissue effect (e.g. cutting or coagulation) is dependent on many factors, such as activation time and electrosurgical waveform properties. Thus, modeling electrosurgical procedure in soft tissue is concerned with the behavior of deformable tissue within electromagnetic field under combined electric, thermal, or mechanical loadings. Furthermore, the Joule heating generated from the electromagnetic wave induces pressure changes on the cellular level due to evaporation of water, which leads to rupture of cellular wall resulting in very precise cutting and fragmentation of the tissue. Despite wide popularity of electrosurgery, the effects of cellular level mechanisms on the electro-thermo-mechanical damage of soft tissue have not been adequately understood.

We have developed a multi-physics model to investigate the effects of cellular level mechanisms on the electro-thermo-mechanical response of RF activated soft tissue. Cellular level micromechanical model has been incorporated into the tissue level continuum model to accurately determine the thermodynamic states such as temperature and pressure. The micromechanical model based equation of state (EOS) provides the additional pressure arising from evaporation of intracellular and cellular water by absorbing heat due to Joule heating. A linear elastic material model is used to describe the deviatoric response of the tissue. A level set approach [2] is used to capture the interfacial evolution of tissue fracture (i.e. cutting) based on Griffith's fracture criterion [3]. A multi-physics based finite element model is developed to simulate the electrosurgical cutting of soft tissue. The coupled governing equations for current, temperature, deformation, and level set parameter fields are solved iteratively using Krylov subspace based iterative solver (e.g. GMRES). Not having to explicitly compute and store the finite element stiffness matrix of the coupled system reduces storage requirements, and computational complexities and costs compared to efforts based on explicit formation of stiffness matrix. The computational efficiency of the Krylov subspace based iterative solver is enhanced using a matrix-free block-preconditioner [4]. The model is shown to capture the characteristics of RF activated soft tissue deformation, temperature and fracture interface evolution.

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