Finite Element Modeling of mechanical properties of plant cells in *Arabidopsis thaliana.*

Pawel Krupinski[1*], Marcus Heisler[2], Patrick Hung[3], Elliot Meyerowitz[2], Eric Mjolsness[1]

[1]Institute for Genomics and Bioinformatics: Bren School of information and Computer Sciences, University of California, Irvine, CA 92607, USA
[2]Division of Biology: California Institute of Technology, Pasadena, CA 91125 USA
[3] Center for Advanced Computing Research: California Institute of Technology, Pasadena, CA 91125 USA

Mechanical properties of plant cells, next to gene regulatory signals, are thought to be an important factor in cell growth and division[1]. These properties are in large part determined by properties of the cell walls which provide rigid structure for plant tissues. The structural strength of primary cell walls comes from the presence of a fibrous network of cellulose microfibrils, which have a tensile strength and elastic modulus comparable to steel[2]. Orientation of the fibers in the network is of major importance for the elastic properties of the cell walls. If the direction of microfibrils is random walls behave like an elastically isotropic material, whereas if microfibrils are aligned along one direction walls act as anisotropic composite material. The mechanical properties of such walls can be substantially different in directions longitudinal and transverse to the orientation of the cellulose microfibrils, forcing cells to elongate in one direction[3,4]. The orientation of the cellulose array can be dynamically controlled during the life of the cell[5], making it difficult to realistically model cell growth during longer periods of time. For that reason mechanical models of cells often simplify the task by reducing dimensionality to two dimensions, or by working with simple geometries, suitable for analytical studies[6,7]. While such approaches are valuable for developing a general understanding of the principles governing mechanical interactions within a cell, Finite Element Models (FEM) offer an attractive alternative because they are able to handle multiple cells and realistic geometries. At the same time, FEM allows the incorporation of different material models for plant walls, including anisotropic, composite array of cellulose microfibrils and viscoelastic materials. FEM also makes it possible to extract not only the global deformation of a collection of cells, but also local information about stresses and strains within each cell wall. From a modeling point of view this may be of particular importance since it is possible these quantities may contribute to the decisions cells make about the orientation of their cellulose microfibrils and division plane. .

As an example of how the results of FEM simulation can contribute to the creation of realistic and biologically inclined models we consider a cell division algorithm. The idea of the algorithm is based on the observation that the preprophase band of microtubules that defines the position of new cell walls seems to be guided by the position of tensile, transvacuolar strands of actin extending from the nucleus to the cell cortex. We model such filaments and then generate all possible division planes by grouping them into pairs. From these, we choose the combinations that produce new walls that are most perpendicular to overall direction of cell growth. Using these rules we have been able to predict the division planes of Arabidopsis embryo cells up to the 16 cell stage.

FEM is also suitable for large-scale modeling of plant tissue, in which mechanical updates are interconnected with Gene Regulatory Networks to provide spatial and topological information utilized by GRN algorithms. GRN can at the same time provide feedback to the FEM model by adjusting its parameters. Such a realization of mutual interaction between the cell's mechanics and bioprocesses under genetic control take us an important step closer to the accurate and complete simulation of living plant tissues.

FIGURES:

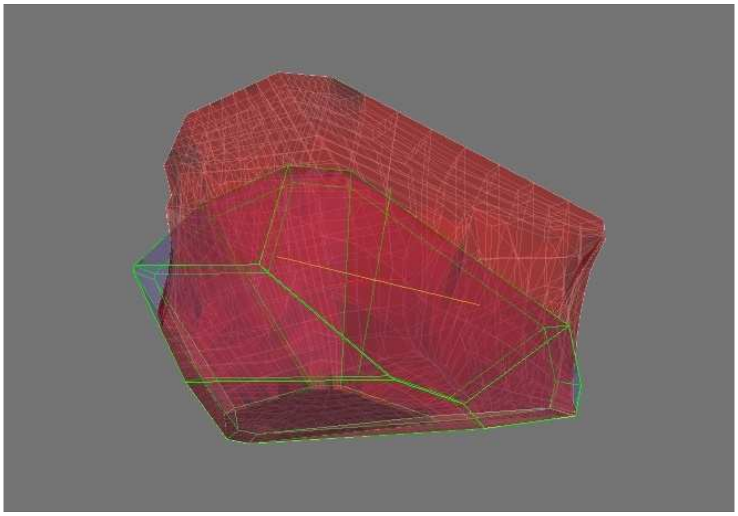

Figure 1. Example of deformation in FEM model of polyhedral cell. Original cell (green outline) was stretched and twisted 30º along vertical axis. Resulting deformation and mesh shown in red.

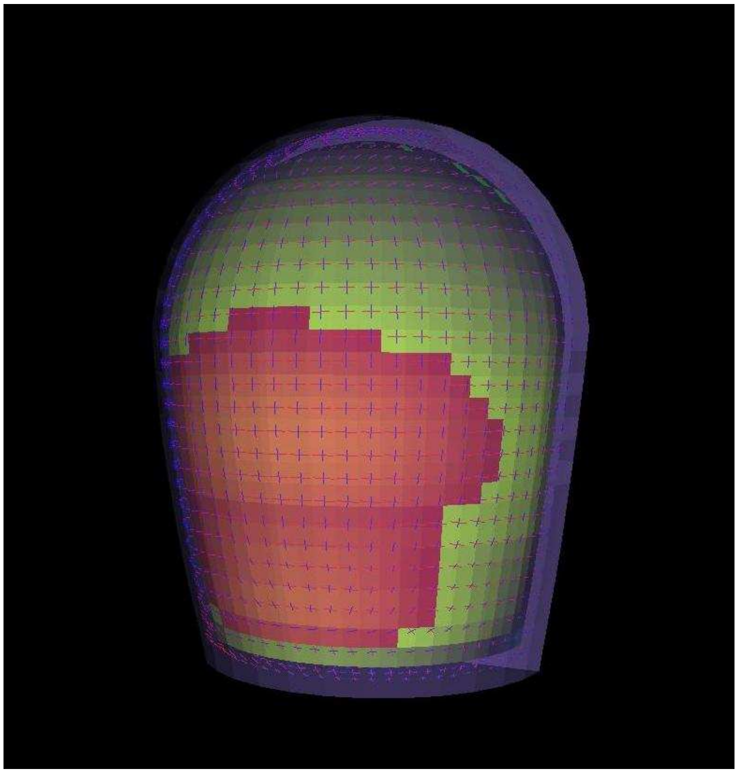

Figure 2. Stress pattern from FEM model of 2-cell Arabidopsis thaliana embryo growing under turgor pressure. Surface coloring represents value of Von Misses stress (red-high, green-low). Crosses give principal direction of surface stress.

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*pkrupins@uci.edu