Simulation Of Basal Body Deformation In Tetrahymena Thermophila

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Abstract

COMSOL® models of basal body deformation using the Beam Interface are compared to electron tomograms of Tetrahymena thermophila basal bodies high-pressure frozen while undergoing beating deformation. This approach provides insight into the nanoscale structures and internal forces generated in cilia and basal bodies.

Cilia are small, hair-like appendages that cells use to move fluid or propel themselves through fluid. The underlying structure of the cilium is the active cytoskeleton called the axoneme, which is approximately 200nm in diameter and comprises 9 outer microtubule doublets and 2 inner microtubule singlets in a Central Pair Complex (CPC). Radial spokes passively couple the CPC to the outer doublets. Outer doublets are passively inter-connected by circumferential links, and actively coupled by unidirectional shear-force generating motor proteins called dyneins, which provide the motive force for ciliary beating.

Basal bodies anchor these actively-beating cellular appendages to cells. Basal bodies consist of microtubule triplets inline with the ciliary doublets, as well as protein structures that stiffen the basal body such as the cartwheel structure and AC linkers. Striated fibers, post-ciliary microtubules, and transverse microtubules link adjacent basal bodies to each other and connect the basal body to the cellular cortex.

Much of the structure of the basal body and cilium is known by electron microscopy and tomography. However, understanding how internal forces are applied and getting values for the physical properties of these intricate nanoscale structures is an area of ongoing research. One way to try to understand these structures is through inverse modeling in COMSOL Multiphysics®. By creating a model of this complex physical system and bringing the behavior of that model into alignment with the observed behavior of cilia and basal bodies in the organism Tetrahymena thermophila, we hope to gain insight into how cilia beat and a greater understanding of basal body structures that is not possible using experimental methods alone.

A model of the cilium and basal body was created in COMSOL Multiphysics® using beam systems within the Structural Mechanics Module. First a simplified 4-doublet model was created in 2D for easy iteration. Then, a full '9+2' model was created to capture the complex system more realistically. Microtubules and radial spokes were modeled as Euler-Bernouli beams. Inter-doublet nexin links were modeled as nonlinear viscoelastic springs using the linear extrusion coupling operator. Dynein forces are modeled as follower edge loads applied in balanced pairs using extrusion couplings to average tangent vectors of adjacent doublets. Distributed moments applied using edge loads model dynein arm moments and maintain moment equilibrium in the model. Inertia is neglected in this small-scale system where viscous and elastic forces dominate.

Static studies of cilium and basal body deformation were conducted using the stationary solver with geometric nonlinearity enabled. A continuation study using an auxiliary sweep of the applied

load fraction helped ensure convergence of the large-deformation study. Deformations under time-varying loads were investigated using the time dependent solver using the BDF time stepping method.

Figures used in the abstract

Figure 1 : Electron tomogram of deformed basal body triplets and striated fiber. Heatmap shows triplet curvature.

Figure 2 : Wireframe view of 3D model of basal body and associated structures.

Figure 3 : Axial forces in 3D basal body model under deformation due to internal forces.