Symmetry Breaking of Actin Networks Governs Confinement Pressure

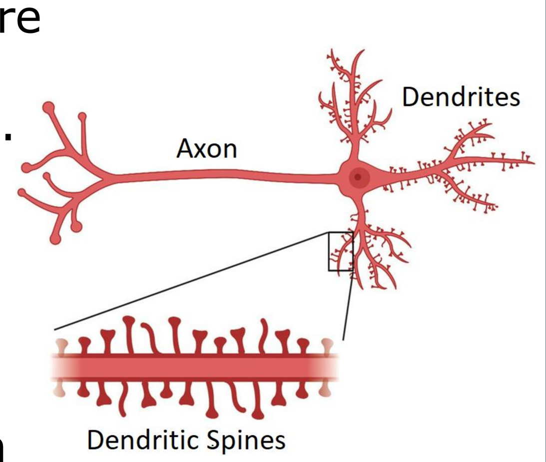
Lilly Roelofs[1,2], Andrei G. Gasic[2], Carlos Bueno[2], Peter G. Wolynes[2], Greg Morrison[2,3]

[1]Department of Biomedical Engineering, University of Houston; [2]Center for Theoretical Biological Physics, Rice University; [3]Department of Physics, University of Houston

Motivation

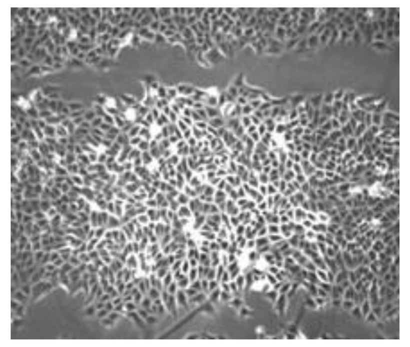
Dendritic Spine Morphology

Actin fiber networks are found in numerous biological systems, i.e. the cell cytoskeleton of dendritic spines. Characterizing the biological phenomena that modulate actin network dynamics can enhance our understanding of dendritic spine growth/shrinkage, which is known to **affect fundamental learning and memory processes**.



Active Matter

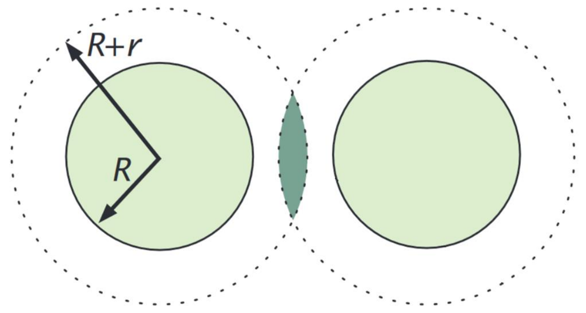
Active matter does not have a specific thermodynamic equation of state due to it's non-equilibrium nature. Thus, understanding how **pressure changes in an active system** is highly nontrivial.



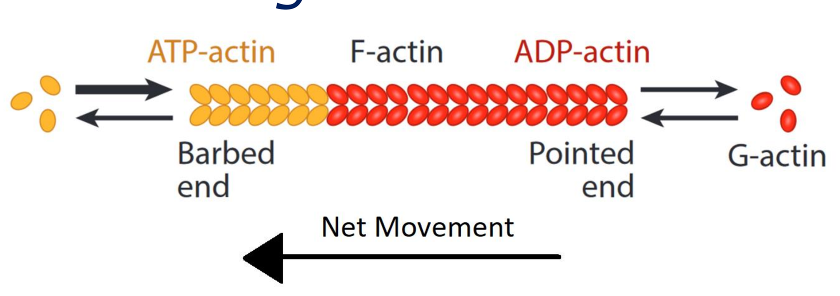
Biophysical Factors

Steric Interactions (Volume Exclusion)

Volume excluding gives rise to depletion (entropic) forces.



Treadmilling

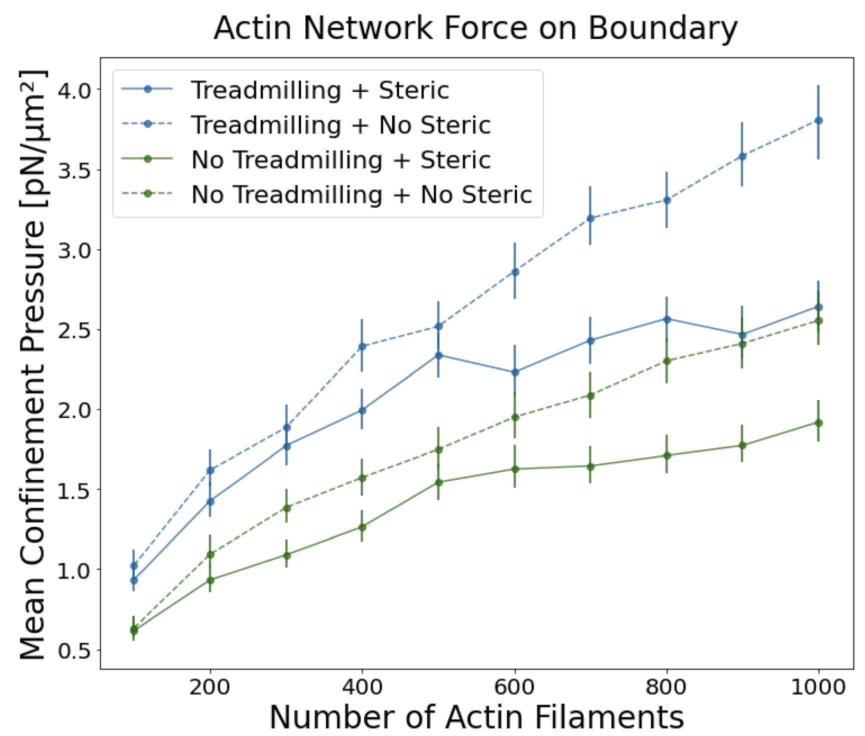


Momomer-filament association/disassociation causes filament to undergo net movement towards the plus end.

Crosslinkers

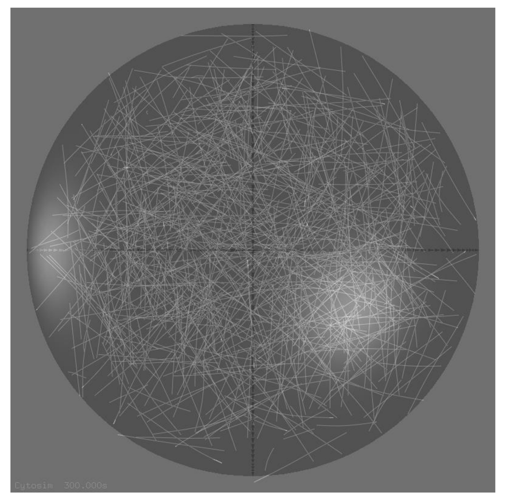
Proteins which are known to affect several physical properties of polymer systems, such as gelation and contraction.

Steric Interactions and Treadmilling Filaments Modulate the Pressure Against the Boundary

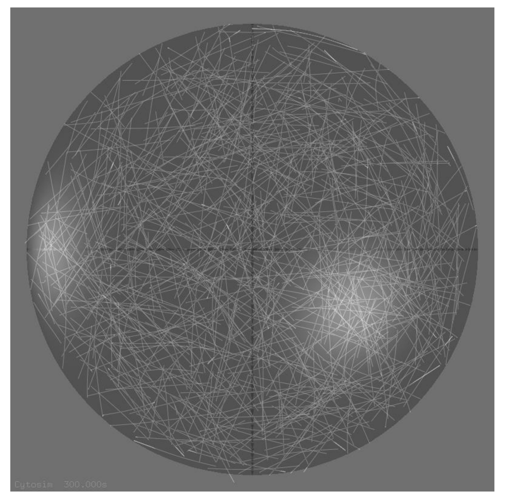


- Treadmilling applies a larger pressure to the boundary
- Depletion forces from steric interactions (volume exclusion) decreases the pressure on the boundary

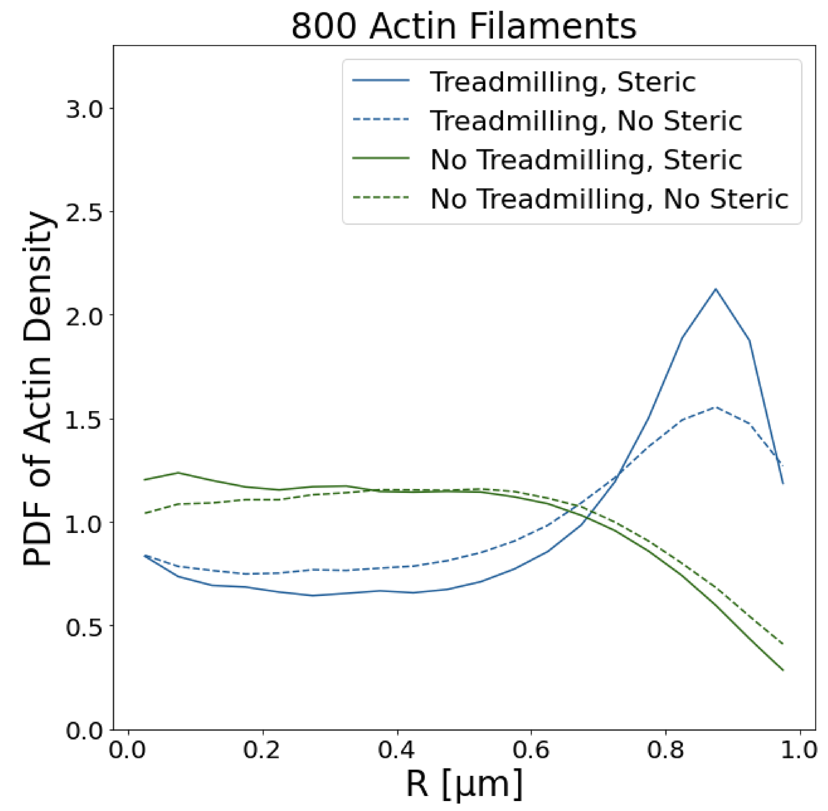
No Treadmilling, Steric, 800 Filaments

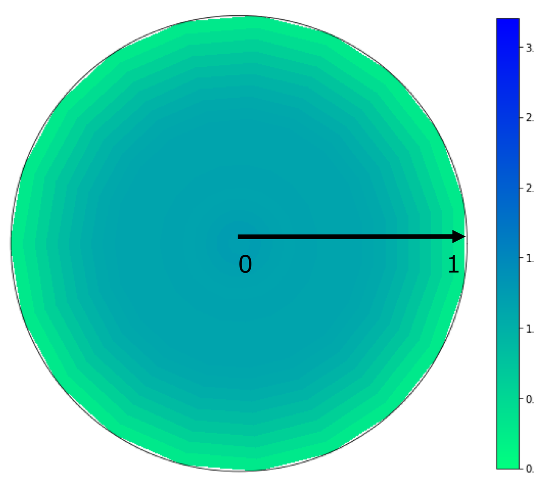


Treadmilling, No Steric, 800 Filaments

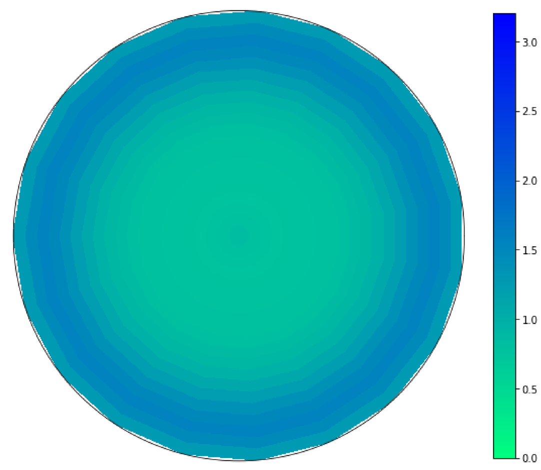


- Treadmilling induces translational symmetry breaking





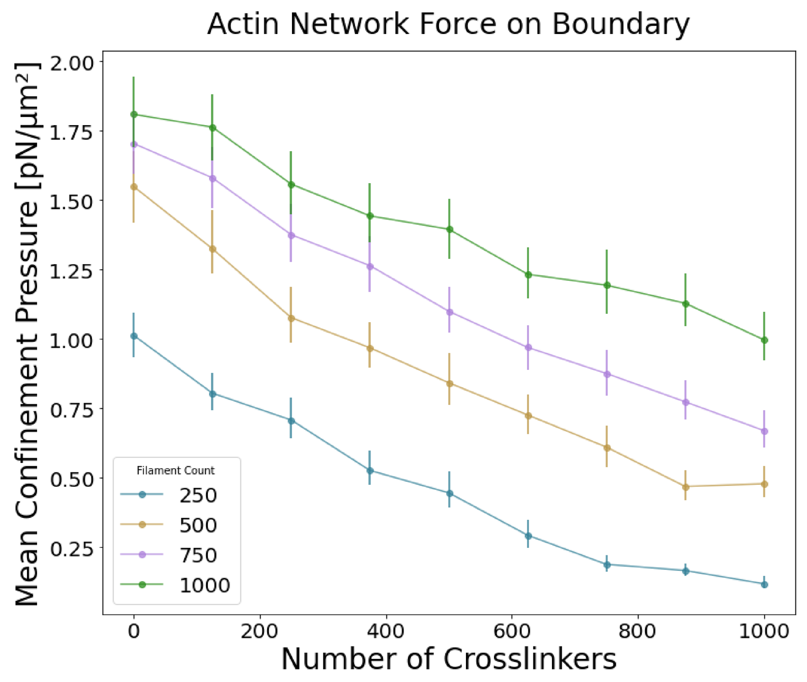
No Treadmilling, Steric, 800 Filaments



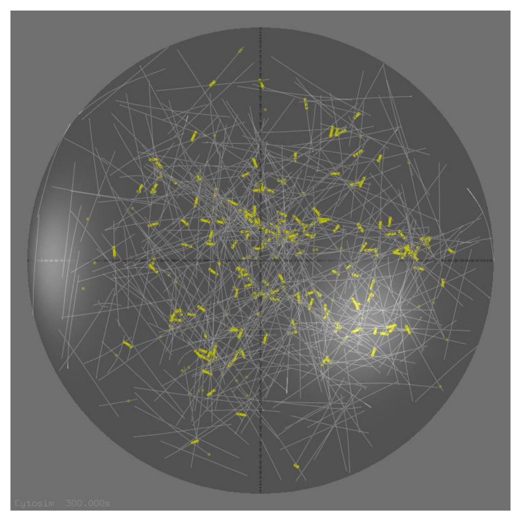
Treadmilling, No Steric, 800 Filaments

Crosslinker to Filament Ratio Regulates Cluster Formation

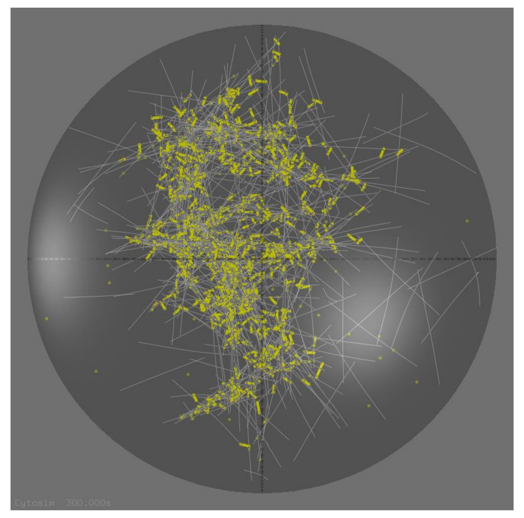
- Linear decrease of mean confinement pressure observed when increasing the number of crosslinkers

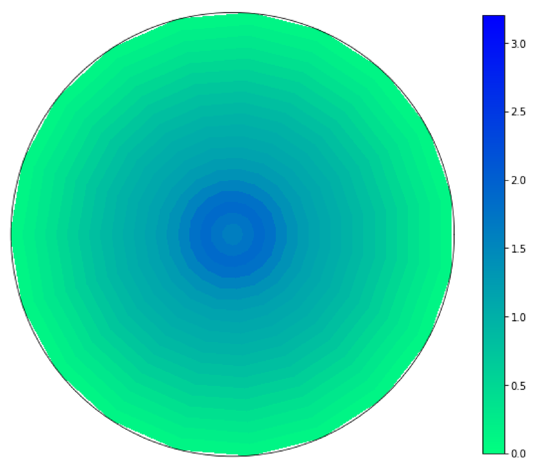


500 Filaments, 250 Crosslinkers

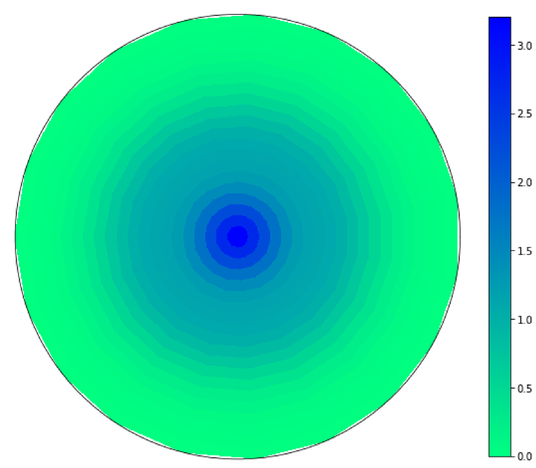


500 Filaments, 1000 Crosslinkers

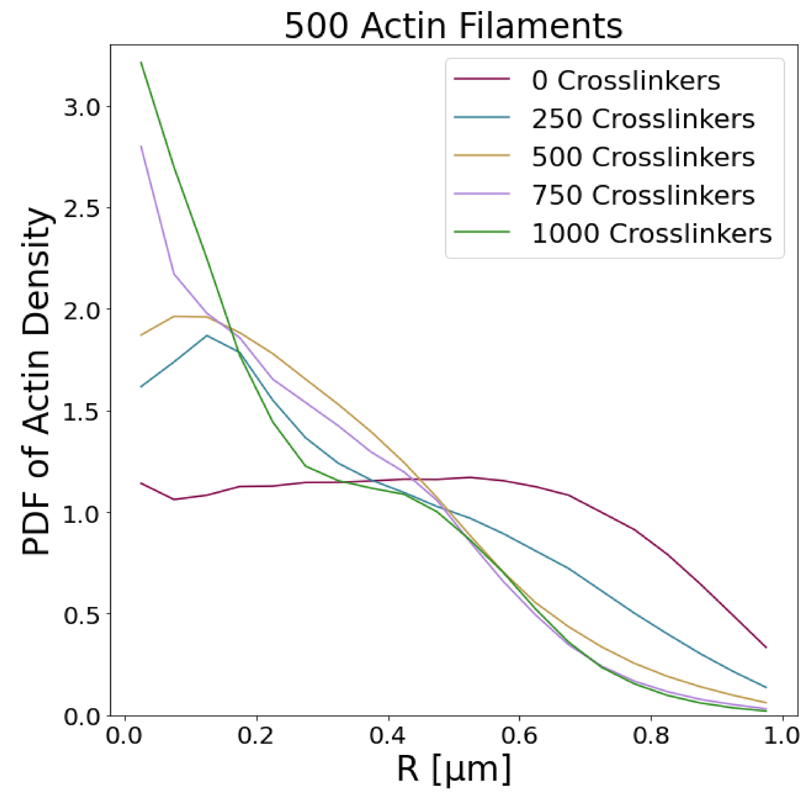




500 Filaments, 250 Crosslinkers



500 Filaments, 1000 Crosslinkers



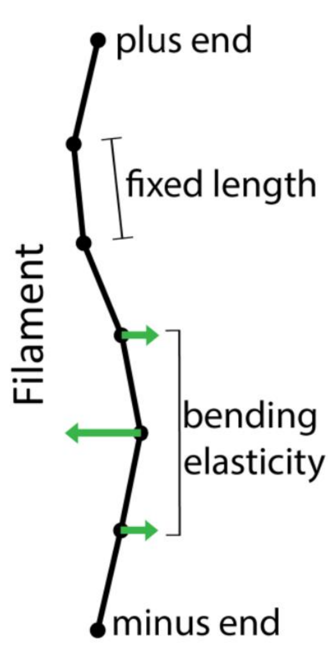
- Greater ratios of crosslinkers to filaments cause cluster formation towards the center
- After the gelation point, translation symmetry breaking occurs

Cytosim

Cytosim is used to simulate biologically-relevant cell cytoskeletons and their associated proteins. Filaments, spheres, and solids are represented by a finite number of points. *Cytosim* uses the Collective Langevin Dynamics equation of motion:

Eq. (1) $d\mathbf{x} = \mu\, F(\mathbf{x}, t)\, dt + dB(t)$

This model considers:
- μ - Mobility coefficients
- $F(\mathbf{x}, t)$ - Forces such as bending elasticity, constraints applied by the segment links, etc.
- $B(t)$ - The effect of brownian motion



Conclusion

	Confinement Pressure [pN/μm²]	PDF
Steric Interactions/ Volume Exclusion	Decrease ↓	Minor Perturbation
Treadmilling	Increase ↑	Towards Boundary →
Increasing Crosslinker: Filament Ratio	Decrease ↓	Towards Center ←

Future Work

Varying the:
- Filament length to system size ratio
- Péclet number of the system

Addition of:
- Branchers (Arp 2/3 complex)
- Motors

Acknowledgements

NSF-DMR-2137680
ORBITS funded by NSF-PHY-2019745
NOTS funded by NSF-CNS-1338099

References

[1] S. Banerjee, ML. Gardel, and US. Schwarz, *Annual Review of Condensed Matter Physics,* **11**:421–39 (2020)
[2] P. Hotulainen and CC. Hoogenraad, *Journal of Cell Biology,* **189**:619–629 (2010)
[3] M. Poujade, et. al, *Proceedings of the National Academy of Sciences*, **104**: 15988-93 (2007)
[4] RB. Phillips, et. al, Physical Biology of the Cell, (2019)
[5] Y. Eliaz, et. al, *Physical Review E*, **102**:062420-1-14 (2020)
[6] AP. Solon, et. al, *Nature Physics,* **11**:673-678 (2015)
[7] F. Nedelec and D. Foethke, *New Journal of Physics*, **9**:427 (2007)

For contact information, technical details, and simulation videos, scan: