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Stress-based regulation of multicellular plant growth: a *finite* element modeling approach applied to planar leaf morphogenesis



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How do plant cells locally control their growth to coordinately produce macroscopic shapes?

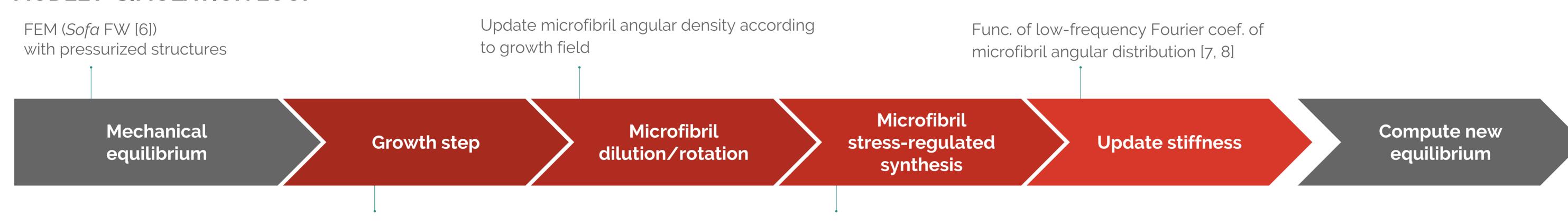
Mechanical tensions hypothetically provide cues governing local cell growth regulation [1,2].

What kind of emergent dynamical behavior can a stress-sensing tissue display?

➤ Finite element multicellular model coupling growth and stress feedback

Mechanical stress results from turgor and growth heterogeneity Cortical microtubules align in the axis of main stress [1] and regulate stiffness [2]

MODEL / SIMULATION LOOP



Update element rest state [4]: $\partial_t m{F}_{
m g} \propto (m{E} - m{E}_0)_+ \cdot m{F}_{
m g}$

Stress-dependent microfibril polym. [7] $ho^+\left(heta
ight)\propto e^{\gamma S_ heta}$

BUILDING ABSTRACT 3D CELLULAR MESHES Centroidal Voronoi Triangulation

[9]

STABILITY OF PLANT GROWTH Several typical growth modes. Can a stress feedback mechanism capture them?

SOME RESULTS

 We simulate the local dynamics of various abstract shapes (ellipsoids) mimicking flat shape (~800-cell meshes).

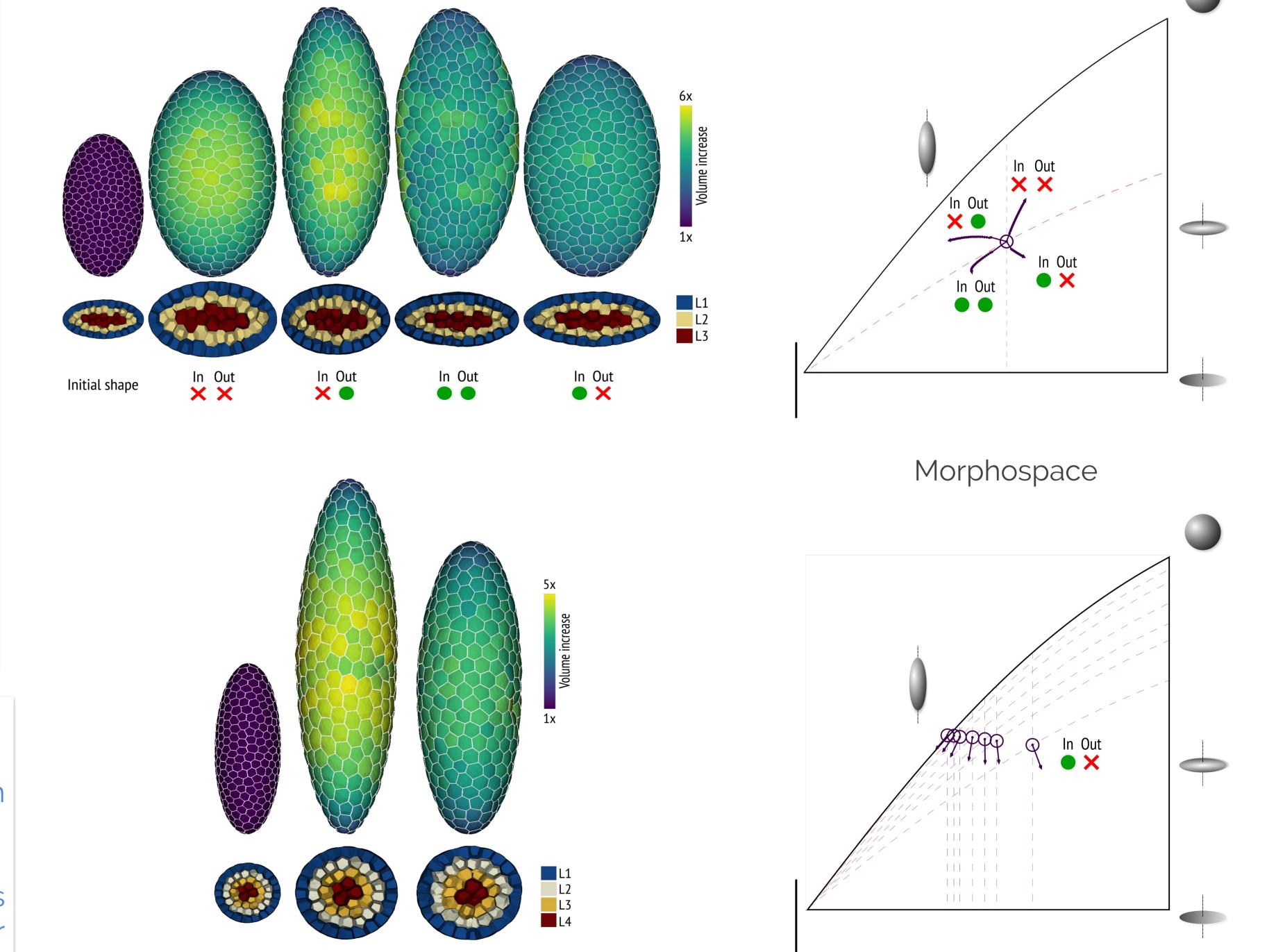
tessellation

- Epidermal feedback or inner feedback stabilize axial elongation of axisymmetric shapes.
- Flat expansion requires inner stress feedback: microtubules align in the axis of thickness to resist thickening.
- This mechanism allows amplification of organ asymmetry.
- Coupling inner and epidermal feedback leads to conflicting microtubule alignment (not shown) → possible mechanical instability?

TAKE-HOME MESSAGE

A single mechanism accounts for flat and axial expansion mode depending on initial shape.

Coupling inner and epidermal stress feedback reveals nontrivial behavior and possibly unstable regimes. \rightarrow Need for additional regulation?



References: [1] Hamant et al., 2008, Science; [2] Bozorg et al., 2014, PLOS Comp. Biol.; [3] Paredez et al., 2006, Science; [4] Boudon et al., 2015, PLOS Comp. Biol.; [5] Bozorg et al., 2016, Physical Biology; [6] Faure et al., 2012, in Soft Tissue Biomechanical Modeling for Computer Assisted Surgery. [7] Oliveri et al., 2018, J. of Mathematical Biology; [8] Cox, 1952; British J. of Applied Physics; [9] Cerutti et al., 2017, Frontiers in Plant Science.

