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7th Proceeding of the Plant Biomechanics International Conference

Bruno Moulia, Meriem Fournier

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HAL Authorization

7th Plant Biomechanics International Conference

Clermont-Ferrand
20-24 August 2012

Chairs

Dr Bruno Moulia

Integrative Physics & Biology of Trees, INRA, Clermont-Ferrand, France

&

Dr Meriem Fournier

LERFoB, AgroParisTech, Nancy, France



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Program

Monday 20 August 2012**08:00 Registration (Ctd)****08:30 OPENING of PlantBioMech2012 Bruno MOULIA****08:50 Opening Keynote: Lorna GIBSON** The hierarchical structure and mechanics of Plants**09:30 Session MODEL : Integrative Biomechanical Modeling****09:30 Adelin BARBACCI** Another brick in the wall**09:50 A.A. DZHURAKHALOV** Implementation of realistic cell wall mechanics in VirtualLeaf**10:10 Coffee break****10:40 John FOZARD** Modelling root elongation and gravitropic responses using multicellular models**11:00 Simon PEARCE** Extracting elastic properties from large-strain indentation of seed endosperms**11:20 Session INT-FLOW: Plant-Fluids Mechanical Interactions: Internal Fluids****11:20 Keynote: Hervé COCHARD** Xylem hydraulics and mechanics: where are the trade-offs?**12:00 Flash-Talks: MODEL, INT-FLOW and ECO-EVO****Session MODEL: Integrative Biomechanical Modeling**

- Development of the numerical model of the plant tissue using finite element method (P. M. PIECZYWEK)
- Another explanation for the origin of sunflower (*Helianthus annuus* L.) seedless fruits, or fruits with incompletely developed embryos (P. BELLÈS / Luis F. HERNÁNDEZ)
- Upscaling the Lockhart equation to tissue level uncovers the role of individual tissues in *Arabidopsis* root expansion (Oliver JENSEN)
- How biomechanical analysis of fracture helps to formalize statistical windthrow modeling (Vivien BONNESOEUR)
- **Session INT-FLOW: Plant-Fluids Mechanical Interactions: Internal Fluids**
- Cavitation in trees monitored using simultaneously acoustics and optics (Alexandre PONOMARENKO)
- Can xylem diameter changes be used as an indicator of xylem tensions in freezing temperatures? (Anna LINTUNEN)
- Poroelastic coupling in biomimetic branches (Geoffroy. GUENA)
- Determination of the hydraulic conductivity of the plant root by the pressure relaxation method: processing on the basis of a continuum model (Sergei A. LOGVENKOV)
- Modelling phloem fluxes between sources and sinks (Andre LACOINTE)

Session ECO-EVO: Ecological and Evolutionary Biomechanics

- Leaf-fracture properties correlated with nutritional traits in nine Australian seagrass species: implications for susceptibility to herbivory (Carmen BARRERAS DE LOS SANTOS)
- The Garden of Eden: at the crossroad of biodiversity and biomechanics (Tancrede ALMÉRAS - Catherine PEIX)
- Wind effect on mechanics and hydraulics traits across the canopy of cold desert shrubs (Patricia.A. IOGNA)
- Peculiar tension wood cell wall structure in genus from French Guiana previously related to the former *Flacourtiaceae* family (Julien RUELLE)
- The ecological relevance of the pomelo (*Citrus maxima*) peel acting as an effective impact protection (Marc THIELEN)
- Evolution of shrub-like growth forms in the *Aristolochia* subgenus *Isotrema* (Sarah WAGNER)
- The bending mechanics of tree stems: the key role of wood maturation stress for resisting both permanent and temporary loads (Tancrede ALMÉRAS)

12:30 Lunch

13:30 Poster session: MODEL, INT-FLOW and ECO-EVO

14:30 Session INT-FLOW: Plant-Fluids Mechanical Interactions: Internal Fluids

14:30 Eric BADEL A new good candidate for a long distance signaling of mechanical strain events: the hydraulic pulses

14:50 Jordi MARTINEZ-VILALTA Spatial distribution and packing of xylem conduits

15:10 Kaare H. JENSEN Design principles of the phloem vascular system of plants

15:30 Olivier VINCENT Dynamics of cavitation in real and artificial trees

15:50 Xavier NOBLIN Cavitation propagation in natural and artificial fern sporangia: what can we learn for xylem ?

16:10 Coffee break

16:40 Session ECO-EVO: Ecological and Evolutionary Biomechanics

16:40 Keynote: Sara PUIJALON Responses of aquatic plants to mechanical stress and disturbance: phenotypic plasticity and plant strategies

17:20 Christoph NEINHUIS Devils claws? A materials perspective

17:40 Catherine COUTAND Study of the interspecific variability of mechanosensitivity on stem growth regulation in five neotropical rainforest species

18:00 M. LARJAVAARA Why trees are of the size that they are?

18:20 Meriem FOURNIER Gravitropic movements in trees are constrained by size and growth rate and make cambial growth a carbon sink during sapling stages

Tuesday 21 August 2012**08:30 Session MORPHO: Biomechanics of Morphogenesis and Pattern Formation****08:30** Keynote: *Areski BOUDAUD* The physical basis of morphogenesis. From the shoot apex to leaves**09:10** *Agata BURIAN* On relations between growth, geometry and microtubule arrangement during morphogenesis at the shoot apex of *Arabidopsis***09:30** *Eran SHARON* Experimental study of the effect of mechanical stress on the evolution of leaf vascular system**09:50** *Frank W. TELEWSKI* Considerations on the formation of wind-induced asymmetric canopies in trees**10:10** Coffee break**10:40** *Leah BAND/ Benjamin PÉRET* Auxin regulates aquaporin function to facilitate lateral root emergence**11:00** *Wendy K. SILK / Mimi A.R. KOEHL* Ruffles or Straps**11:20 Session SENSE: Mechano- and Gravi- Sensing and Transduction****11:20** Keynote: *Elisabeth HASWELL* A feeling for the organism: mechanosensitive channels in plants**12:00 Flash-Talks: MORPHO, SENSE, ROOT-SOIL and TOOLS****Session MORPHO: Biomechanics of Morphogenesis and Pattern Formation**

- Auxin regulates aquaporin function to facilitate lateral root emergence (Benjamin PÉRET / Leah BAND)
- The coupling between microtubule orientation and cellulose deposition contributes to the maintenance of the phyllotactic patterns during stem growth in *Arabidopsis* (Benoît LANDREIN)
- Mechanical regulation of auxin-mediated growth (Naomi NAKAYAMA)
- Mechanical regulation of PIN1 in the meristem (Sarah ROBINSON)

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• **Session SENSE: Mechano- and Gravi- Sensing and Transduction**

- System Mechanobiology : The Sum-of-Strain-Sensing model S³m as an integrative mechanistic model of mechanosensing and thigmomorphogenesis in plant stems (Bruno MOULIA)
- Does transmission of a traumatic signal in aerial part of *Arabidopsis* involve mechanosensitive channels of the MSL family? (Jean-Marie FRACHISSE)
- Modelling of the frequency sensibility of mechanosensing channels (Jean-Marc ALLAIN)
- Response to gravitropic stimulation of poplar stems. Proteome analysis of apical and basal regions (Patricia ROEKEL-DREVET)
- Using uniaxial stretching to investigate single plant cell rheology and mechano-sensing (Pauline DURAND-SMET)
- Perception of gravity stress in non-statocyte plant cells (Robert PALIN/Anja GEITMANN)

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• **Session ROOT-SOIL: Plant- Soil Mechanical Interactions**

- Using a discrete model of root/soil interaction to quantify the protection of forests against shallow landslide and rockfall hazards (Franck BOURRIER)
- Root phenotyping (Ralf C. DIETRICH)
- Root Growth in 2D Wet Granular Media Modified By Intrusions (Cesare M. CEJAS)

•

• **Session TOOLS: Metrology and Softwares for Plant Biomechanics and Mechanobiology.**

- The 3D magnetic digitizing: a tool to measure 3D tree geometrical structure and its dynamics (Marc SAUDREAU)
- Terrestrial LIDAR : a tool to scan tree geometrical architecture (Thierry CONSTANT/ Mathieu DASSOT)

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16:10 Coffee break

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17:20 Evelyne KOLB Strategies of root growth facing a pore and development of root radial forces measured by photo-elasticity

17:40 Kenneth LOADES Effects of environmental stress on root biomechanics

18:00 Josette MASLE Mechanical stress on roots: an environmental cue central to root-shoot coordination and plant survival

20:30 Popular Science Evening Event “Plant BioMech 2012” (End of this document for a map)

(In collaboration with the Museum of Natural History H Lecocq, salle de l'espace municipal Georges-Conchon, 3 rue Léo-Lagrange à Clermont-Ferrand)

20:30 Keynote (in French): **George JERONIMIDIS** Des Ingénieurs à l'école des plantes: biomimétique et conception mécanique (When mechanical and civil engineers learn from plants: biomimetics and mechanical design)

Wednesday 22 August 2012**08:30 Session TREE: Trees and Wood Biomechanics****08:30** Keynote: *Thierry FOURCAUD* Is mechanics an important component of tree architecture?**09:10 B. BERGMAN / F EWERS** The effect of leaf nodes on stem biomechanics in two tree species**09:30 Christophe ELOY** Wind on trees: Is Leonardo's rule the best design?**09:50 Guillaume POT** Characterization of spatial and temporal evolutions of green wood mechanical properties during maturation**10:10 Tobias HAUSHAHN** General biomechanics and functional morphology of *Dracaena marginata***10:30** Coffee break**11:00 Joseph GRIL** Longitudinal growth stresses in trees: analytical models and functional implications**11:20 Roland ENNOS / Adam VAN CASTERON** Factors affecting the fracture properties of branches**11:40 Bruno CLAIR** Longitudinal and tangential maturation stresses in Eucalyptus plantation trees**12:00 Flash-Talks: TREE, TOOLS****Session TREE: Trees and Wood Biomechanics**

- Why do all trees break at almost the same wind speed (Alexandre PONOMARENKO)
- The bending strength of tree stems: towards a model that accounts for the pre-stress field and the post-plastic behaviour of wood (Yamina AIMENE / Tancrède ALMERAS)
- Components testing of hazel forks (Duncan SLATER)
- Detecting wind acclimation in trees in the urban forest using dendrochronology (Frank W. TELEWSKI)
- Functional branching morphology of arborescent columnar cacti (Hannes SCHWAGER)
- The role of elastic deformation in the statics of inclination angle of leaves (Loïc TADRIST)
- Gravitropic response of beech trees growing in different competitive environments (Mathieu DASSOT)
- Sclereids to structurally optimise resistance to bending stress in *Malus* peduncles (Melanie HORBENS)
- Is bending strain better than tilt angle to understand the level of growth stresses in mature trees? (Thierry CONSTANT)
- Structural sensitivity analysis and model comparisons of *Zea Mays* stalk flexibility (Douglas COOK)
- Effect of Growth Stresses on Anatomical and Physical Properties of *Fagus orientalis* L. (Kambiz POURTAHMASI)
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- CR - KinePlant toolbox (Julien DIENER)
- X Ray computer tomography: a new tool for retrospective analysis of the spatial distribution of tissues in large trees. (Meriem FOURNIER)
- Tree safety evaluation by pulling test and wind load analysis (Vincent DELLUS)

12:30 Lunch**13:30 Posters Session TREE: Trees and Wood Biomechanics**

14:30 Field Trips

- Hike up the Puy Pariou :

The Puy Pariou is the archetypical cone shaped crater (in fact a Strombolian volcano). We will climb up the crater, enjoying the wonderful view on the Chaîne des Puys as well as the changes in vegetations along the climbing. Please make sure you are fit enough to do this walk and that you have the proper equipment (shoes, hat, water ...).

Duration of the hike: 2h / Distance: 5 km / Altitudes: Maxi 1213 m Mini 977 m / cumulated climbing and descents: ~ +350 m -410 m



- Cross-sectional anatomy of a volcano: le Puy de Lemptégny :

Visit the “Puy de Lemptégny” quarry exposing the "roots of a volcano": You may see many features typical of the volcanic landscape such as volcanic chimneys, lava flows and huge volcanic bombs. You will observe the magma feeding system under and through a volcano; you will learn how volcanologists work out the reconstitution of the volcanic history of these young volcanoes. You learn about the use of volcanic rocks and you visit a local craft-shop producing "lave émaillée" (lava ceramics). Visit duration 2h30 (very easy, in English).



Thursday 23 August 2012**08:30 Session MICROMECH: Cell Wall, Cell and Tissue Micromechanics****08:30** Keynote: *Ingo BURGERT* Plant micromechanics**09:10** *Anja GEITMANN* Biochemical and biomechanical properties of fungal spore walls**09:30** *Fernanda GUEDES* Searching for polysaccharides specific to tension wood fibers**09:50** *Hiroyuki YAMAMOTO* A micromechanical analysis of interaction between cellulose microfibrils and matrix substances in wood cell wall by using the X-ray diffraction method**10:10** Coffee break**10:40** *Nicola M. EVERITT* Probing the stiffness of plant tissues: nano-indentation of germinating seeds**11:00** *Pierre CABROLIER* Wood axial mechanical properties at the tissue level in connection to sub-cell wall organization**11:20** *Tancrede ALMÉRAS* The origin of maturation stress in tension wood: using a wide range of observations and mechanical considerations to discriminate between hypothetical mechanisms**11:40 Flash-Talks: MICROMECH , MOTION, TOOLS, BIOMAT****Session: MICROMECH: Cell Wall, Cell and Tissue Micromechanics**

- Measuring mechanical properties of growing cells by combining Cellular Force Microscopy, osmotic treatments and Finite Element modeling (A. WEBER)
- Functional micro-mechanics of plant tissues: assessing the contribution of cellulose to the mechanical behaviour of wood (Arthur GRONVOLD)
- *Medicago truncatula* seed germination and radicle growth: A microstructural NMR clarification (M. LAHAYE)
- Fungal degradation of Scots Pine (*Pinus sylvestris* L.) wood: micromechanical and microstructural characterization at the cell wall level (Leopold WAGNER)
- Mechanical properties of epidermal cells of whole living roots of *Arabidopsis thaliana*: An atomic force microscopy study (Nicola M. EVERITT)
- Enzymatic investigation of plant cell wall mechanical properties (Pauline VIDECOQ)
- Deposition and organisation of cell wall polymers during tension wood cell wall maturation as studied by FTIR microspectroscopy (Shanshan CHANG)
- Biomechanical aspects of seed germination: endosperm weakening of *Lepidium sativum* (garden cress) and *Nicotiana tabacum* (tobacco) (Tina STEINBRECHER)
- Nanoindentation-based methods for quantifying the mechanical response of living plant cells *in vivo* (Joseph A. TURNER)

Session MOTION: Plant Motions and Plant Tribology

- The ultrafast fern sporangium catapult (Coraline LLORENS)
- Growth dynamics of an avocado tree leaf (Julien DERR)
- Exploring the attachment mechanisms of *Peperomia* fruits (*Piperaceae*) (Lena FRENZKE)
- Mechanism of active closure of the Venus flytrap : pressure probe measurements at the cellular level (Mathieu COLOMBANI)
- Regulation of shape and position of the stem during two consecutive years after tilting in maritime pine (*Pinus pinaster* Ait.) (Rosario SIERRA-DE-GRADO)
- Fast plant movements (Simon POPPINGA)
- Foliar disease transmission: Insights from fluid dynamics (Tristan GILET)
- Hygroscopic movement in *geraniaceae* - diversity, structure and evolution (Yael ABRAHAM)

Session TOOLS: Metrology and Softwares for Plant Biomechanics and Mechanobiology.

- The benefits of Atomic Force Microscopy for characterizing topography and mechanical properties of plant tissues (Torsten MÜLLER)
- JRobust: an open - source application for analysis of AFM force curves (Hermanowicz PAWE)

Session BIOMAT (Cntd): Applied Biomachanics for Material Sciences and Engineering

- Preparation of Poplar wood plastic reinforced composites: influence of Tension and Normal wood fibers on defibrization and mechanical properties (Bruno Clair)
- The effect of Ca²⁺ and cellular structure on apple firmness and acoustic emission (Artur Zdunek)
- Respective effects of lignins and of extractives on the dynamic mechanical behaviour of wood (Iris Brémaud)

- Sorting the timber by a musician VS acoustical indexes (Maryam Ghorbani / Mehran Roohnia)
- Vibrational based nondestructive testing of wood: an acoustical approach from lumber to small beams (Mehran Roohnia)

12:30 Lunch

13:30 Poster Session: MICROMECH, MOTION, TOOLS, BIOMAT

14:50 Session MOTION: Plant Motions and Plant Tribology

14:50 Keynote: *Yoel FORTERRE* Moving fast without muscle: Lessons from the Venus flytrap

15:30 *Jesse SILVERBERG* Helical buckling of plant roots: mechanics and morphology

15:50 *Marc JOYEUX* To buckle or not to buckle

16:10 Coffee break

16:40 *Renaud BASTIEN* A universal dynamic modelling of aerial gravitropism

17:00 *Rivka ELBAUM* Hygroscopic coiling movement of the seed dispersal unit of stork's bill

17:20 *Jiro SAKAMOTO* Mechanical analysis of bursting fruit of *Vicia angustifolia* (*Vicia sativa* subsp. *nigra*) with spiral motion

17:40 *Mark RUDNICKI* Branch motion of mature decurrent crowns: experimental and theoretical analysis

19:30 Gala Dinner

Friday 24 August 2012**08:30 Session GROWTH: Biophysics of Growth****08:30** Keynote: *Tobias BASKIN* Anisotropic expansion of higher plants

09:10 Anne-Lise ROUTIER-KIERZKOWSKA New methods for probing cell mechanics in growing plant tissues

09:30 Antje VOEGELE Embryo growth, endosperm weakening and testa permeability are major targets for the inhibition of *Lepidium sativum* seed germination by myriganone A

09:50 A. BRAYBROOK The mechanics of hypocotyl elongation in the dark: A study of anisotropic cell expansion Siobhan

10:10 D. S. THOMPSON Investigation of the interaction between wall hydration and mechanical behaviour using composites of cell wall polysaccharides with bacterial cellulose

10:30 Coffee break

11:00 Herman HOFTE Control of cell wall integrity during plant growth

11:20 Mahsa NAGHAVI Invasive cellular growth in pollen tubes

11:40 Rosemary DYSON A model of crosslink kinetics in the expanding plant cell wall: yield stress and enzyme action

12:00 Flash-Talks: GROWTH and BIOMIM**Session: GROWTH: Biophysics of Growth**

- Kinematic analysis and regulation of TIP1 aquaporins expression in the growing root apex of poplar under osmotic stress (M-B. BOGEAT-TRIBOULOT)
- Growth of plants under dynamical stimulation (Christelle DER LOUGHIAN)
- Epidermal cell growth is quantised into cell periphery portions at contacts with different neighbours? A case study of arabidopsis puzzle-shaped cells (Dorota KWIATKOWSKA)
- Biophysical modelling of cambial activity and wood formation in conifers (Félix HARTMANN)
- *In vivo* analysis of local wall stiffness at the shoot apical meristem in *Arabidopsis* using atomic force microscopy (Pascale MILANI)
- Understanding the dynamic changes that occur at the cell periphery during morphogenesis in the shoot apical meristem (Raymond WIGHTMAN)
- A midline model for gravitropic root bending (S.A. SMITHEMAN / Oliver JENSEN)
- Cell wall mechanical properties of *Arabidopsis* hypocotyls in connection with growth and gravitropism: effects of xyloglucan endotransglucosylase / hydrolases, expansin-like proteins and brassinosteroids (Dimitry SUSLOV)
- A qualitative model of symplastic and intrusive growth of the vascular cambium of broadleaved trees? A biomechanical perspective (Pawel KOJS)

Session BIOMIM: Plant Biomechanics for Biomimetics

- Functional anatomy and biomechanics of papaya stems (Andreas KEMPE)
- Thinking tools in biomechanics and the 45° degree angle (R. KAPPEL)
- Walking and jumping spores (Philippe MARMOTTANT)
- Cross sectional organization of supporting tissues and vascular bundles in perennial plants as concept generator for biomimetic construction principles (Ruwen KAMINSKI)
- The flower of *Strelitzia reginae* as concept generator for the development of a technical deformation system for architectural purposes (Tom MASSELTTER)
- An analytic model of the self-sealing mechanism of the succulent plant *Delosperma cooperi* (Wilfried KONRAD)

12:30 Lunch**13:30 Poster Session: GROWTH and BIOMIM****14:30 Session BIOMIM: Plant Biomechanics for Biomimetics**

14:30 Keynote: *Peter FRATZL* Plant cells as inspiration for adaptive composites and actuators

15:10 *Benoit THECKES* A tree-inspired damping mechanism in flexible structures: damping-by-branching

15:30 *H.F. BOHN* Biomechanics of permanent attachment in self-clinging climbing plants

15:50 *Iwiza TESARI* How to understand root plates of trees

16:10 Coffee break

16:40 *Olga SPECK* Self-healing processes in plants as concept generators for biomimetic self-repairing materials

17:00 *Thomas SPECK* Self-healing elastomers? Learning from Nature's solutions

17:20 Closing Session / Announcement of PlantBioMech 2015 *Meriem FOURNIER*

SUMMARY PROGRAM

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
16h30-18h30 Registration	8h-8h30 Registration	8h30-10h10 Session MORPHO	8h30-10h30 Session TREE	8h30-10h10 Session MICROMECHANICS	8h30-10h30 Session GROWTH
	8h30-8h50 Opening				
	8h50-9h30 Opening Keynote				
	9h30-10h10 Session MODEL				
	10h10-10h40 Coffee break	10h10-10h40 Coffee break	10h30-11h Coffee break	10h10-10h40 Coffee break	10h30-11h Coffee break
	10h40-11h20 Session MODEL	10h40-11h20 Session MORPHO	11h-12h Session TREE	10h40-11h40 Session MICROMECHANICS	11h-12h Session GROWTH
	11h20-12h Session INT-FLOW	11h20-12h Session SENSE			
	12h-12h30 Flash-Talks	12h-12h30 Flash-Talks	12h-12h30 Flash-Talks	11h40-12h30 Flash-Talks	12h-12h30 Flash-Talks
	12h30-13h30 Lunch	12h30-13h30 Lunch	12h30-13h30 Lunch	12h30-13h30 Lunch	12h30-13h30 Lunch
	13h30-14h30 Posters	13h30-14h30 Posters	13h30-14h30 Posters	13h30-14h50 Posters	13h30-14h30 Posters
	14h30-16h10 Session INT-FLOW	14h30-16h10 Session SENSE	14h30 Field Trip	14h50-16h10 Session MOTION	14h30-16h10 Session BIOMIM
	16h10-16h40 Coffee break	16h10-16h40 Coffee break		16h10-16h40 Coffee break	16h10-16h40 Coffee break
	16h40-18h20 Session ECO-EVO	16h40-18h Session ROOT-SOIL		16h40-17h40 Session MOTION	16h40-17h20 Session BIOMIM
					19h15 Gala Diner

Introduction

What is Plant Biomechanics?

Plant Biomechanics is the study of the **structures and functions of biological systems from the plant phylum (*Plantae*) with the help of concepts and methods of mechanics** [1-5].

These methods may involve continuum mechanics, solid and fluid mechanics, kinematics, statics, dynamics, mechanism analysis, structural analysis, rheology, strength of material, hydraulics, thermo- and electro-elasticity, tribology, mechanical metrology, modeling.... And example of key concepts are velocity, deformation and conformational changes, strain, force, moment, stress, pressure, tension, shear, elasticity, viscosity, plasticity, surface tension, vibration, resonance, wave, sound, collision, mechanical energy, work, instabilities, strength, toughness, resilience, rupture. ... They can apply to both the inner solids and fluids of the plant organs and cells, as well as to the interactions with fluids and solids in the environment (e.g. wind, aquatic currents and waves, contacts, impacts, adhesion, penetration, interactions with animals and pathogens). And they are **combined with the concepts and methods from the biological sub-discipline under concern** (e.g. genomics, biochemistry, molecular and cellular physiology, electrophysiology, ecophysiology, ecology, paleobotany...) **to yield meaningful knowledge.**

The biological systems under concern range from molecular and cellular structures (e.g. DNA, stretch-activated channels, wall associated proteins, cytoskeleton, cell membranes, nuclei, cell wall...) up to entire communities (e.g. forests, grassland) and landscapes, including the plant body, organs and tissues.

Examples of biological functions that are being studied from a biomechanical perspective include mechano-sensing, mechano-transduction and gene regulations (e.g. [5-8], this is sometime referred to as mechanobiology), growth (cell expansion, division, wall synthesis and exocytosis, water influxes e.g. [9-13]), cell and tissue differentiation, pattern formation and morphogenesis (e.g. [3, 14,15]), sap and internal fluid circulations (e.g. [2,5,16,17]), motricity (e.g.[18,19]), tropism, nasties and twining (e.g.[19,20]), posture control (e.g. [21]), penetration in soils and in tissues (e.g. [22-24]), anchorage and drag resistance (e.g. [4,25-29]), biomechanical acclimations (osmoregulation, thigmomorphogenesis, e.g. [5-8]), fast motions and seed dispersal (e.g. [2,27,30]), resistance to biotic injuries (as herbivory or pathogens, e.g. [22-32]), metabolic ecology and scaling laws (e.g. [2, 33-36]), ecological strategies (e.g. [37,38]), evolutionary biomechanical adaptations, and inference of extinct plant stature and biomechanical functions from paleobotanical records (e.g. [38-39])....

The reason for studying plant biomechanics can be **biological fundamental knowledge**. In this case the purpose is to understand a function per se. For example, mechanobiology refers to the studies of the way plants sense and respond to external and internal mechanical loads [5-8].

But they may be also related to **concerns in forestry and crop sciences**, for example to cope with the problem of wind-throw and crop lodging [4, 25-27]. It may also come from material scientists studying processes involving **material derived from plants which properties relates to the biomechanical history of the material in the plant before harvest** (fruits and vegetables, wood, bamboo, e.g. [40-43]). For example the problems set to the wood transformation industry by pre-stresses and by the heterogeneity between reaction and normal wood in wood logs have fostered active biomechanical research in the differentiation of the secondary cell wall (e.g. [42,43,44]) as well as in plant tropisms and posture control (e.g. [19,21,37,43]).

More recently, concerns from researchers in mechanical engineering and technology to learn from the Evolution of plant mechanical structures and to be trained to different types of solutions for the mechanical design of structures (e.g. soft and anisotropic matter, deformable and foldable structures, smart materials) has lead to biomechanical studies from the a **biomimetical point of view** (e.g. [44-46]).

And there are so many other works that could be cited (the references here are just a few recent illustrations and reviews sampling the whole field). But you will see the most recent outcomes of this **expanding interdisciplinary field, at the interfaces of biology, mechanics, physics and engineering, at the 7th Plant BioMechanics International Conference.**

Welcome!

B. Moulia and M Fournier, Nov 2011

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Sessions

1. **MicroMech**: Cell Wall, Cell and Tissue Micromechanics.

chairing: **Dr B Clair / Pr A Geitmann**

2. **Tree**: Trees and Wood Biomechanics.

chairing : **Dr C Coutand / Pr H. Yamamoto**

3. **Sense**: Mechano- and Gravi- Sensing and Transduction.

organizer : **Dr N Leblanc-Fournier / Dr M T Morita**

4. **Growth**: Biophysics of Growth.

chairing: **Dr O Hamant / Pr W K Silk**

5. **Morpho**: Biomechanics of Morphogenesis (and pattern formation).

chairing: **Dr A Barbacci / Pr D Kwiatkowska**

6. Ext-Flow: Plant - Fluids Mechanical Interactions I- external flows. (not opened)

7. **Int-Flow**: Plant-Fluids Mechanical Interactions II internal fluids.

chairing: **Dr E Badel / Pr F Ewers**

8. **Root-Soil**: Plant- Soil Mechanical Interactions.

chairing: **Dr N Everitt / Pr R Ennos**

9. **Motion**: Plant Motions and Plant Tribology.

chairing : **Dr R Bastien / Pr JL Julien**

10. **Eco-Evo**: Ecological and Evolutionary Biomechanics.

chairing: **Pr P Roeckel-Drevet / Pr F Telewski**

11. **Model**: Integrative Biomechanical Modelling.

chairing : **Dr T Almeras / Pr G Jeronimidis**

12. **Tools**: Metrology and Softwares for Plant Biomechanics and Mechanobiology.

chairing : **MSc J Franchel / Dr T Constant / Dr M Rudnicki**

13. **BioMim**: Plant Biomechanics for Biomimetics.

chairing : **Dr T Masselter / Pr T Speck**

14. **BioMat**: Applied Biomechanics for Material Sciences and Engineering.

chairing : **Dr D Julien-Pierre / Dr B Thibaut**

15. Misc: Miscellaneous = Other topics. (not opened)

Contents

Session Model

Integrative Biomechanical Modeling

Another Brick In The Wall

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Abstract

Growth of plant cell is conditioned by the cell wall (CW) ability to extend irreversibly. Two conditions are required for CW extension. The first one is a tensile stress, which is function of the coupling effects between turgor pressure, CW mechanical properties and enzymatic activity. The second condition is the cell capacity to synthetize, export and assemble new polysaccharides to the existing CW. This condition depends on turgor pressure, enzymatic activity and temperature. Thus, cell growth results from a complex and dynamical interplay between the microstructure, the mechanical properties and the environment of the CW.

The aim of this communication is to present, on different examples, the potential of a theoretical framework allowing the development of models. These are able to account explicitly for the rearrangement of the microstructure and the associated change of mechanical properties under fluctuant temperature and turgor pressure. The framework is based on two hypothesis. The first one, due to Callen, stipulates the existence of a potential function, called internal energy, containing all the information on the system and depending *a priori* on all independent extensive variables necessary to describe the system. The second assumption, due to Cunat, extends the validity of the first assumption for non-equilibrium situations.

From these assumptions, generic constitutive equations of the growing CW were established. This set of differential equations is depending on three kinds of energy (mechanical, chemical and thermal) and their couplings implied in the growth process. The Gibbs-Duhem relationships also inherit to these assumptions and allow moving the constitutive equations towards a chemical or a mechanical point of view, which is a convenient way to design a model that can be tested by pertinent measures. These relationships make it possible to explicitly formulate the dependency of the bulk modulus or the “right dilatation tensor” to microstructure. To complete the constitutive equations, kinetics equations relative to the polysaccharides assembling are written for the most general case. From this theoretical framework, models is tested using literature example. It depicts the volumetric growth of the alga *Chara corallina* cell triggered by pressure and temperature.

The design of the experimental approach relative to this modeling approach has been presented by P. Videcoq in growth session for poster presentation.

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Keywords

Cell Wall, Growth, Irreversible thermodynamics, Non-linear effect, Modeling

Implementation of realistic cell wall mechanics in VirtualLeaf

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Abstract

The mechanical properties of the cell wall play an important role in the plant growth process. They regulate the size and shape of cells and this should be taken into account and correctly described in the modeling of growth dynamics. In the cell-based computational modeling framework VirtualLeaf, the two-dimensional cell tissue is represented by polygons with a set of elastic cell wall elements. The balance between turgor pressure and cell wall resistance is described by the surface energy of cells and an elastic energy of cell walls. Though this model can regulate the cell size, it does not contain an explicit cell wall mechanics.

To better describe the cell wall mechanics we developed a viscoelastic model suggested by Maxwell in which the deformation of wall is determined by the combination of Hooke_'s law and Newton_'s law. This model describes the balance between turgor pressure and cell wall yielding by an elastic energy and pressure potential energy of the system. Another difference with VirtualLeaf is that in this new approach the rest length (which corresponds to the absence of turgor pressure) of each wall element and the turgor pressure in each cell are updated by solving an ordinary differential equation. As the whole dynamic process of the system includes cell growth and cell division accompanied by formation of new walls, wall elements and cells, significant modifications and extensions have been made to VirtualLeaf.

Implementation of the viscoelastic model in VirtualLeaf extends the capabilities of the platform to study the mechanical basis of growth in plant organs such as leaves and roots. We will present some case studies on the regulation of cell cycle, cell expansion and auxin regulated growth in Arabidopsis using this new implemented cell wall mechanics.

Keywords

cell wall mechanics, viscoelastic model, cell growth, cell division

Modelling root elongation and gravitropic responses using multicellular models

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Abstract

Multicellular models provide an ideal framework in which to integrate processes occurring at cell and tissue scales. We describe a vertex-based model for plant tissue in which anisotropic viscous wall properties control the growth of the cells. The geometrical representation is two-dimensional, and the mechanical properties of cell walls in the plane of the simulation are discretized using finite elements. This is combined with models for cell division, polar auxin transport in the root apex, auxin responses, and other gene regulatory networks (encoded in Systems Biology Modelling Language). Cell scale geometrical data is acquired from confocal imaging and used to provide the initial state of the tissue. The simulation is implemented in a combination of Python and C++, within the OpenAlea framework, in a modular fashion which allows multiple sub-models to be readily combined. The mechanical and transport models give large systems of differential equations for the evolution of the tissue state; these are solved numerically, with the sparsity of the Jacobian matrix being exploited for efficient computation.

We also describe a hybrid vertex-midline model, which provide a computationally efficient and highly robust method of describing uniaxial growth, whilst still explicitly including cell-level detail which is important, e.g. for auxin transport in the root apex. The extension of this approach to fully three-dimensional models is also discussed.

We show how both these models may be used to investigate root elongation and the bending of a root during a gravitropic response.

Keywords

Multicellular, Multiscale, Gravitropism, Simulation

Extracting elastic properties from large-strain indentation of seed endosperms

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Abstract

Experimentally measuring the elastic properties of a thin-walled flexible biological membrane or shell is not trivial, particularly when the initial shape of the surface is not flat. Elastic properties are necessary as an input into mathematical simulations, as well as enabling a meaningful comparison between tissues of different shapes and sizes. Previous mathematical studies of the large-strain indentation of elastic surfaces have assumed that the surface is initially flat, which is often not the case for biological membranes. The surface is modelled as isotropic, incompressible and hyperelastic. It is found that for highly curved surfaces a higher-order shell theory rather than the membrane theory must be used, ensuring that bending of the surface requires energy and preventing wrinkling from occurring. Once all geometric properties of the initial surface are known, it is only two elastic moduli corresponding to stretching and bending and the large-strain elastic behaviour which require fitting to the data.

Our particular interest is seed germination, particularly the stretching and rupture of the endosperm by the radicle in the species *Lepidium sativum* (garden cress), where the endosperm is a highly-curved single-cell layer surrounding the embryo. Experiments consisting of pushing a needle through excised endosperms and recording the resulting force and displacement generate the data with which we may fit our model to, allowing elastic moduli to be extracted. These elastic moduli enable us to compare the results from the indentation of different shapes and sizes of endosperm, determining changes caused by cell wall remodifying enzymes.

Keywords

Modelling, Elasticity, Endosperm, Indentation

Development of the numerical model of the plant tissue using finite element method

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Abstract

The relation between stress and strain of plant materials has been a subject of many research studies. However, due to complex geometry, hierarchical structure and interplay between cell walls and cell interiors, the problem of plant tissue mechanics still remains not fully understood. Unlikely to most engineering materials, the properties of plant tissues are the result of their micro-scale morphological features. Mechanical properties of fruit and vegetable tissues are strongly related to the spatial arrangement and shape of cells, the number of intercellular spaces, turgor pressure, the nano-composition of cell walls and the degree of degradation of the middle lamellae.

In this studies we were using the finite element method (FEM) to simulate the behavior of cellular structure under various mechanical load conditions. The goal of this research was to create a computational model that incorporates micro-scale geometrical features of plant tissue, and which will provide qualitative and quantitative predictions of mechanical properties. The onion epidermis was used as a basic mechanical system, which then had to be reconstructed in a virtual environment. Since our approach was based on the reconstruction of the geometry of plant tissue we used the confocal scanning laser microscopy for the acquisition of images in order to have basic geometrical features of the each cell within an image. Data from images was used for reconstruction of plant tissue microstructure for computational virtual environments by means of the tessellation algorithms. Cell walls and cell interiors were modelled as separated bodies with individual material properties. The boundaries of each cells interior were obtained by offset of cell wall boundaries by desired value of wall thickness. The geometry of model was transferred into ANSYS 11 (ANSYS Inc., U.S.A.) computational environment by protocol developed in Matlab R2010a (MathWorks, U.S.A.). The FEM model of tissue, was completed by definitions of finite element types, real constants, material properties, loads and supports. Virtual model was used to simulate uniaxial tensile tests. Simulation results were compared with experimental data. For this purpose thin strips of onion epidermis tissue were mounted into miniature tensile stage and tested for uniaxial tension within the limits of non-destructive deformation.

The developed model showed good, qualitative agreement with experimental results. Model was able to simulate the nonlinearity arising from the changes of turgor or cell wall properties. Quantitative predictions of plant tissue behavior under mechanical load requires further model sensitivity analysis and modifications of initial parameters.

Keywords

finite element method, tissue geometry modelling, micro-mechanics

Another explanation for the origin of sunflower (*Helianthus annuus* L.) seedless fruits, or fruits with incompletely developed embryos.

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Abstract

Fruits with absent or underdeveloped embryos cause major yield losses in the sunflower crop. Among the most common causes of the origin of these fruits are pollination or fertilization failures and physiological defects in the ovary and embryo, genotypic or induced by environmental stresses. Mechanical stress never has been included in this scenario. We have previously determined that a 2-3 day fertilization shift can occur between neighboring florets into the sunflower capitulum. Being the ovaries so closed packed in the receptacle, this work then proposes that ovaries with advanced fertilization can exert significant radial and axial tensions on those ovaries with delayed fertilization. This would be able to generate a mechanical stimulus larger enough to trigger the synthesis of endogenous regulators that could alter, for example, pollen tube growth or decrease the import of water and photoassimilates into the embryo.

A FE model of a young sunflower ovary was built and a Mechanical Event Simulation was performed using the software ALGOR (v.16.0). Shear stresses generated by the friction of neighboring ovaries, fertilized 3 days earlier, in contact with the model were then calculated. Ovary expansion rate (radial, tangential and axial) with regard of receptacle radial expansion rate was also considered. In vivo tests were also made, isolating ovaries by removing the adjacent flowers and brushing them during 1 day (force $N = 1-3$) using a micromanipulator. In other isolated flowers a solution of Ethrel (100 mg/L) was injected (10 μ l) into the ovary base with a microsyringe. Total peroxidases in treated and untreated ovaries, isolated and not isolated were also determined. The vonMises stresses calculated in the FE model after the simulation, showed values (6.5 to 11.6 $N.m^{-2}$) that exceed the maximum resistance of the constituent tissues located near the site of attachment of the ovary with the receptacle. The computed magnitude, higher than 2 N, can be considered higher enough to induce a thigmomorphogenic response. The results emerging from the model suggests that a tensile stress at that site could exert physical alterations of vascular tissue and/or trigger the induction of biochemical responses. Total peroxidase levels (DELTA Abs₄₇₀ min.g fresh weight)⁻¹ rose from 22 in control ovaries to 72 and 107 in brushed and ethrel-treated ovaries respectively. From these findings we hypothesize the negative effect of intra capitulum mechanical stresses on the sunflower seed development.

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Keywords

Helianthus annuus, finite element, fruit growth, sunflower

Upscaling the Lockhart equation to tissue level uncovers the role of individual tissues in Arabidopsis root expansion

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Abstract

Root elongation and bending require the coordinated expansion of multiple cells of different types. These processes are regulated by the action of hormones that target different cell layers (in Arabidopsis, for example, auxin targets the epidermis while gibberellin targets the endodermis). A systems-level description of a process such as root gravitropism calls for new multiscale models that can connect the action of enzymes on specific molecular components of composite cell walls to shape changes at the organ level. An important task in this effort is to connect the properties of individual cell walls to properties of the tissue as a whole. We undertake this using variants of the Lockhart equation, which provides a simple constitutive framework for describing both cell and tissue deformation, assigning yield and extensibility parameters to materials at different lengthscales. Exploiting the highly organised structure of the elongation zone of the Arabidopsis root, we integrate from cell to tissue level using a simple homogenization approach. Exploiting detailed measurements of cell turgor, cell geometries and wall thicknesses, we express tissue-level effective extensibilities and yield in terms of geometric factors and mechanical properties of individual cell layers. Our analysis quantifies the contributions of different cell layers to tissue-level extensibility and yield, demonstrating for example highest sensitivity to properties of the epidermis (and hence to the action of auxin). We use kinematic data to infer tissue-level and cell-level mechanical parameters as a function of distance along the elongation zone. Our approach also gives insight into the generation of residual stresses in the root and is readily extended to quantify the role of heterogeneous cell-wall softening in driving root bending.

Keywords

elongation, bending, extensibility, yield, gravitropism

How biomechanical analysis of fracture helps to formalise statistical windthrow modelling

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Abstract

To assess the risk of windthrow, statistical studies establish relations between the damage rates observed after a gale and the available site, stand and tree variables. Simple deterministic concepts of biomechanics are then used to discuss the encountered results. However, individual windthrow should be considered as a biomechanical problem of fracture all along the process modelling including wind forces related to wind velocity and tree morphology, tree strength, with stochastic considerations. The goal of this presentation is to discuss how formalising *a priori* statistical windthrow models with biomechanical concepts. It will be illustrated by the case study of *Fagus sylvatica* stands (88 plots and 660 dominant trees, representing a wide range of site conditions and silvicultures) in French Lorraine highly damaged by storm Lothar in 1999. The model was based on the Weibull “weakest link model” of fracture and the computation of a simplified wind-induced bending moment which was reduced to the product of square tree height by crown diameter. As no reliable data on local wind velocities were available, lack of independence between the trees within a plot was treated using random effect at the plot level. We compared this model with a multiple logistic regression often used in statistical windthrow modelling. Introducing a random effect was very beneficial for the model quality and may represent among other effects, the local wind conditions during the storm. The wind induced bending moment was a good indicator to predict windthrow for a large range of tree size and morphology. Soil depth defined by appearance of very stony layers and not rooting depth was the best site factor. Weibull theory appeared to be delicate to implement in the case of the root-soil plate fracture of uprooted trees while it is more interesting to model trunk breakage. The use of meaningful mechanical predictors may be a good approach to improve robustness of statistical models.

Keywords

Statistical windthrow modelling, *Fagus sylvatica*, wind loading, stand structure

Session INT-FLOW

Plant-Fluids Mechanical Interactions: Internal Fluids

Xylem hydraulics and mechanics are the trade-offs?

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Abstract

The xylem is a complex tissue that covers different key functions in woody plants: 1) it transports water throughout the plant to replace water lost during leaf transpiration, 2) it confers to trunk and branches their stiffness and flexibility, and 3) it stores water, nutrients and carbohydrates. These functions have set contrasted selective pressures on this tissue and shaped its structure during evolution. Understanding how xylem functions relate to xylem anatomy is a challenging issue. Each function is associated to a set of xylem characteristics that can be antagonistic across functions. It is therefore important to identify the tradeoffs between xylem functions. We will focus here on the tradeoffs between hydraulic traits (efficiency versus safety) and the tradeoffs between hydraulic and mechanical traits. A better understanding of the structural and genomic determinants of each function and the exploration of their genetic variability within and across species has recently brought new light on these questions.

Keywords

xylem

A new good candidate for a long distance signaling of mechanical strain events: the hydraulic pulses

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Abstract

Wind is known to increase water stresses by increasing evaporation rates, but a possible additional negative effect of wind sways mechanically impairing water conductivity has remained disputed. Coupling flow-meters and pressure sensors with a mechanical testing device, we investigated the hydraulic effects of mechanical deformation of saturated branches and stems. Experiments have been carried out on isolated branch segments of several angiosperm and gymnosperm species or *in planta* on a stem of a living tree (poplar). Permanent bending generates only a negligible effect on conductivity, even with very large deformations. This indicates that there are no major changes in the anatomical structure, i.e. mainly the vessel lumens (angiosperms) or tracheids (gymnosperms) dimensions, that could lead to a loss of efficiency of the vascular system.

Nevertheless, for the first time, we display that bending strains generate a transient high pressure variation that is able to propagate rapidly along the water conduits. We quantified these pressure pulses and we observed i) that living cells were not involved in the phenomenon, ii) an high inter-specific variability of its magnitude, iii) a proportional relationship of this magnitude with the strained volume. We hypothesize that the origin of this hydraulic pulse is the poroelastic behavior of the saturated wood material and we proposed a first modelling to explain the mechanism: during deformation of the conduits the incompressible water contained in lumens and cell walls moves in the conduits with no contribution of the living parenchyma cells. This generates a local transient overpressure in the conduit that propagates in the vascular system.

In planta experiments confirmed that hydraulic pulses propagate along the vascular system of the xylem symmetrically to the upper and lower regions of the stem. As a signaling process, this hydraulic behavior could be an efficient for a fast long distance signal transporting mecanobiological information to the extreme organs as leaves, roots and apices.

Keywords

bending, strain, hydraulic, pressure, wood, trees, poroelasticity, signaling

Spatial distribution and packing of xylem conduits

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Abstract

The hydraulic properties of the xylem determine the ability of plants to transport liquid water from the soil to the leaves and to cope with important stress factors, such as frost and drought. Hydraulic properties have usually been studied as a function of the anatomy of xylem conduits and the pits interconnecting them. However, recent studies have proposed that system-level properties, related to the topology of the xylem network, may also play an important role. In this contribution we study the effect of the spatial arrangement of conduits in xylem cross-sections on the relationship between mean conduit lumen area and conduit density (packing function) across species. Point pattern analysis was used to describe the spatial distribution of xylem conduits in cross-sections from 97 temperate woody species (Mencuccini et al. 2010). The effect of conduit aggregation on the packing function was tested using phylogenetic generalised least squares (PGLS). A hydraulic model with an explicit description of the topology of the xylem network, based on Loepfe et al. (2007), was used to interpret the functional significance of our findings. Our results showed that the spatial arrangement of conduits affected the packing function across species, so that species with aggregated distributions tended to have lower conduit lumen fractions and lower conduit densities for a given conduit size. These effects remained significant after accounting for the different wood type of the studied species (conifer, diffuse-porous, semi ring-porous or ring-porous) and the phylogenetic structure of the data. According to our modelling results, the higher conduit-to-conduit connectivity of species with aggregated spatial distributions allows them to achieve higher hydraulic conductivity. At the same time, however, species with aggregated conduits pay a cost in terms of increased vulnerability to embolism. In conclusion, our results imply that the spatial arrangement of conduits affects the fundamental structural and functional attributes of the xylem and should be taken into account in future studies of ecological wood anatomy.

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Keywords

cavitation; embolism; hydraulic conductivity; network connectivity; packing; water transport; xylem anatomy

Design Principles of the Phloem Vascular System of Plants

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Abstract

Plants require effective vascular systems for the transport of water and dissolved molecules between distal regions. Their survival depends on the ability to transport sugars from the leaves where they are produced to sites of active growth. In this talk, we describe how the phloem vasculature have evolved into a highly optimized microfluidic system, and which basic physical principles govern the flow.

Applying a generalization of Murray_'s law to the phloem vascular system, we find a simple relation between the characteristic sizes of the plant organs which optimizes the efficiency of energy transfer [1,2]. We further consider the optimal sugar concentration for phloem flow, analogous to the optimal hematocrit in animals. We find that two optimum concentrations exist, depending on the sugar and ion loading mechanisms employed by the plant.

We compare these predictions to experiments performed on plants and in artificial microfluidic biomimicking systems with good results. Our findings show that the phloem is a highly optimized microfluidic system, and provides a new framework for investigating the physical principles governing the morphological diversity of plants.

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Keywords

Phloem, sugar transport, vascular transport, optimality, scaling analysis

Dynamics of cavitation in real and artificial trees

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Abstract

In a tree, water is transported from the roots to the leaves by the xylem structure composed of conducting elements (tracheids in gymnosperms and vessels in angiosperms). This is achieved by evaporation in the leaves which pulls the whole water column up, that is under tension (or negative pressure). Despite being a very efficient and passive way to create fluxes, this mechanism has an important drawback: water under tension is metastable and bubbles can spontaneously appear inside it, leading to embolism due to the subsequent expansion of these bubbles. This harmful process is called cavitation.

There has been a lot of effort in the past decades to understand how cavitation happens, propagate, or can be repaired. One of the main limitations to the study of cavitation is that it is virtually impossible to directly observe events in wood. As a result, most investigations use indirect techniques such as ultrasound emissions, the origin of which is still debated.

We developed a method to observe cavitation events optically, by cutting tangential slices of pinewood that are thin enough (50-100 μm) to let light pass through and to contain at least one intact tracheid in the radial direction. These wood slices are completely embedded in a hydrogel to prevent any direct air entry. Negative pressure is generated in the tracheids by drying the extremities of the samples at ambient conditions or in a controlled humidity chamber. Cavitation events can either be triggered by a laser or appear spontaneously after a sufficient drying time.

We discovered that individual cavitation bubbles have a two steps expansion process. In the first extremely fast step, a bubble appears at a microsecond timescale and reaches a transiently stable volume. The second step immediately follows: the bubble expands until filling the whole tracheid. We will show that if this filling process follows a diffusive dynamics in $t^{1/2}$, the global drying (or “embolism”) front in the wood samples grows linearly in time. We will present a simple physical modelling that explains this particular dynamics.

We will conclude by showing that we can get some insight in the previous dynamics by the study of “artificial trees” made of microfluidic channels embedded in a hydrogel. In particular, we found that the ultra-fast birth of the bubble presents volume oscillations. We expect these oscillations to play a role in the acoustic emissions detected during cavitation, and this study should help interpreting the recorded signals.

Keywords

Cavitation, Xylem, Tree, Artificial tree, Flow, Tracheid, Water, Sap, Fast Dynamics, Hydrogel

Cavitation propagation in natural and artificial fern sporangia: what can we learn for xylem?

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Abstract

Fern sporangia are surrounded by a row of cells called the annulus. The volume decrease of each cells, along with the cohesive forces induced, lead to a change in curvature of the annulus. Tension builds in each cell and when the negative pressure is too high to be sustained, cavitation bubbles are nucleated. This releases the tension in the cells and lead to a very fast motion of the sporangium that springs back at 10 m/s (1). we focused here on cavitation bubbles nucleation and propagation, either in the natural sporangia or artificial devices.

First we present a study of cavitation in natural sporangia (observations, measurements, modeling). We could observe that several bubbles are nucleated, almost at the same time in several annulus cells. The question is how do these cells cavitate almost at the same moment?

Then we present our study on artificial microfluidic devices that mimics the fern sporangium using hydrogels devices or synthetic trees (2). These devices are made of water cavities in the gels matrix that are analogous to neighboring cells in the sporangium. We could observe a very analogous behavior as in the natural sporangium system: several bubbles can be nucleated almost at the same time in neighboring cells. We present our measurements, interpret this new way of cavitation propagation between cells and discuss the possible implications for xylem embolism.

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- (2) Wheeler and Stroock, *Nature*, 455, p. 208-212 (2008)

Keywords

cavitation, fern sporangium, bubbles, microfluidics, synthetic trees, xylem

Cavitation in trees monitored using simultaneously acoustics and optics

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Abstract

Under hydric stress, the water column in trees, which is under tension in the conducting element (vessels or tracheids resp. for angiosperms and gymnosperms); can cavitate: bubbles appear and eventually cause an embolism in the circulation. It has been shown that cavitation is associated with short acoustic emissions, and they can be recorded in the ultrasound range. However the precise origin of each acoustic emission is still not clear. In particular, the acoustic emissions could be not only the consequence of cavitation, but also of the collapse of xylem conduits, or of fractures in the wood.

Here we present an original set-up where we can simultaneously record (i) the acoustic emissions, (ii) the location of cavitation events, by imaging the sap channels under light transmission microscopy. We are then able to correlate the sounds to the visible changes in channels, such as the appearance of cavitation bubbles. For fast phenomena, we can use a high-speed camera in the optical set-up, so as to resolve the dynamics of propagation of cavitation events.

We consider two types of sap channels: biomimetic ones made of hydrogel, and real wood xylem conduits embedded in hydrogel. The hydrogel is set into a low humidity atmosphere so as to generate negative pressures in the liquid filled cavities. The biomimetic channels will be helpful to calibrate the acoustic and optical set-up, and to resolve temporally cavitation events. The real xylem conduits will be tested so as to obtain the acoustic signature of each cavitation event, and try to discriminate it from other events.

We hope the results of the present study might help to better understand the acoustic signals emitted by trees, and to obtain further information in the evolution of wood under dry stress conditions.

Keywords

acoustics, ultrasound, cavitation, xylem, dry stress

Can xylem diameter changes be used as an indicator of xylem tensions in freezing temperatures?

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Abstract

Pinus sylvestris experience large seasonal variations in temperature at the northern limits of its distribution in Northern Scandinavia (70°N). In summer, stem diameter changes because of the variation in stem water status [1, 2]. Due to the elasticity of the living tissue, the changes are clearly higher in bark, but occur also in xylem [2]. Bark diameter in trees is known to shrink also at freezing temperatures [3, 4]. This is explained by extracellular freezing, which protects the living cells from intracellular freezing and cell death [5]. In extracellular freezing, the osmotic concentration inside the living cells increases as extracellular ice creates a water vapour deficit that draws cell water out of the elastic cells [5]. This leads to shrinkage of the cells. When the bark has been autoclaved, no shrinking has occurred but swelling instead due to the larger volume of ice compared to liquid water [3].

Also xylem diameter is known to shrink due to freezing, although to clearly lesser extent in comparison to bark [3, 4]. It has been suggested that diameter changes in xylem during freezing and thawing is based on changes in xylem water status consistently with summer diameter changes [3]. Are xylem diameter changes an indicator of the water potential differences between the proceeding ice front and remaining liquid water inside a freezing wood and can the phenomenon be used in freeze-induced cavitation study?

We measured 9 cold acclimated branches of Scots pine that were cut from adult trees. In 6 of the samples the living parenchyma in the xylem was killed by wrapping the sample with plastic film and insulation tape and heating the sample in 60°C for an hour. After this, the respiration was measured to make sure that most of the cells were not functioning. The freezing was conducted in a weather chamber. The ambient temperature was decreased from approximately 20°C to -10°C in approximately two hours. Thermocouples were measuring the xylem- and ambient temperatures and two diameter sensors were recording the diameter changes during freezing.

The preliminary results show that the xylem shrinks upon freezing unless the living parenchyma cells in xylem are killed. After the heating treatment the diameter swelled suggesting that the shrinking of xylem in freezing cannot be used as measure of xylem tensions, but is result from shrinking of the living parenchyma due to extracellular freezing.

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Keywords

freezing, *Pinus sylvestris*, water potential, xylem diameter

Poroelastic coupling in biomimetic branches

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Abstract

Plants are constantly subjected to external mechanical loads such as wind, rain or even neighbours. These stimuli are known to affect the growth of the plants, a process called thigmomorphogenesis. Interestingly, plants physiological responses to these external loads is sometimes observed far from the stimulated area, which suggests the transportation of information through the plant. Among the different hypothesis found in the literature to account for this long-distance transport (electrical signal, hormone transport), it has been proposed that local mechanical stimuli (bending) could generate an hydraulic pulse that moves through the xylem. This appealing idea seems to be supported by recent experiments made in the PIAF laboratory on cut branches or whole plants, showing that the rapid bending of a branch is associated to transient overpressure in the xylem.

In this work, we address this question from a physical perspective and investigate the coupling between mechanical bending and hydraulic response in biomimetic branches. The branches consists in transparent elastomeric (PDMS) beams drilled with longitudinal micro-channels and filled with a viscous fluid. We precisely measure the hydraulic response (pressure amplitude, propagation velocity, decay time) as function of the different control parameters of the system (bending amplitude, micro-channel density, macroscopic rigidity, hydraulic conductivity) and compare with typical responses obtained on real plants. This study enable to better understand the physical mechanisms at play in the long-distance transport of information in plants.

Keywords

poroelasticity, growth

Determination of the hydraulic conductivity of the plant root by the pressure relaxation method: processing on the basis of a continuum model

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Abstract

The coefficient of hydraulic conductivity of the root is a key parameter controlling the water flow across the root. For measuring the integral coefficient of hydraulic conductivity a method of pressure relaxation is now widely used. This technique is based on a disturbance of the steady state in which the water flow across the root is stopped. The root pressure relaxation in response to a small change in the water-driving force is measured. The processing of the relaxation curve yields two characteristic times from the smaller of which, using the representation of the root as a membrane, a parameter identified with the hydraulic conductivity of the root is commonly calculated.

However, using the membrane model in processing the measurement results totally ignores the organization of the radial flow at both micro- and macrolevel, which is related with the anatomical structure of the root.

In this study, we determine the hydraulic conductivity of the root as the partial derivative of the flow-rate with respect to the hydrostatic pressure difference between the xylem vessels and the environment at a fixed difference in osmotic pressure. The water and solute transport across the root between the environment and the xylem is investigated on the basis of multiphase continuum mechanics. A mathematical model which treats the process as two-phase fluid flow through a solid framework is developed [1]. Two fluid phases containing a solute are identified with the intra- and extracellular fluids that fill the symplast and apoplast, respectively. The interphase mass exchange is regulated by membrane-type relations taking into account active solute transport, interface permeability to solute and water, and osmotic water transfer. Solving a boundary problem, we obtain the dependence of the flow-rate on the difference in hydrostatic pressure. Numerically differentiating this curve, we find the theoretical coefficient of conductivity. We apply our model of transport in roots to simulating the relaxation experiments described in the literature.

The results of processing based on the membrane and continuum models are compared. It is demonstrated that the coefficient of hydraulic conductivity of the root can be determined only if the slow, not rapid, segment of the experimental relaxation curve is used.

This work was supported by the Russian Foundation for Basic Research (project No. 11-01-00774).

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Keywords

hydraulic conductivity of the root, pressure relaxation method

Modelling phloem fluxes between sources and sinks

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Abstract

In plants, photoassimilates are transported from sources to sinks in sieve tubes by a mass flow of phloem sap down an axial hydrostatic pressure gradient. That gradient is generated by an osmotic gradient, maintained by lateral phloem loading / unloading in different areas within the plant. This very simple mechanism, as formulated by Münch (1928) after a famous experiment, is now accepted by all plant physiologists with minor variations. However, its translation from a qualitative principle into a quantitative model has not been straightforward. In the classical approach, the pathway is considered as spatially continuous. Several one-dimensional (1-D) models, simulating translocation from one source to one sink, have been elaborated with increasing biophysical refinements, leading to very detailed 1-D models like Thompson and Holbrook (2003). However, more realistic architectures involving several sources or sinks have long remained out of the reach of these models due to calculation difficulty. In 1993, Minchin *et al.* designed the first model of assimilate allocation within a 'moderately complex' architecture involving one source and two sinks, at the cost of an oversimplified, hardly realistic description of biophysical processes.

The antagonism between architectural complexity and biophysical realism can be overcome by a modular approach as proposed by Daudet *et al.* (2002) and further developed by Lacoïnte and Minchin (2008). That approach gives control on both qualitative complexity (phloem loading / unloading functions in relation to local tissue metabolism and xylem fluxes) and quantitative complexity (spatial resolution and network topology). The model yields the same simulation results as the best 1-D theoretical models available with very good accuracy; it is further able to simulate assimilate translocation within more realistic vascular and tissue topologies with similar accuracy, which reference 1-D continuous models cannot. Thus, in the '1 source, 2 sinks' case, it reproduces the results of Minchin *et al.* (1993) qualitatively, further pointing out extra, little known phenomena like the impact of transpiration on assimilate allocation. The explanatory and predictive capacities of the model are exemplified and validated by an experiment using ^{14}C labelling (Thorpe *et al.*, 2011)

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Keywords

phloem, assimilate, transport, allocation, source, sink, Münch, mass flow, model

Session ECO-EVO

Ecological and Evolutionary Biomechanics

Responses of aquatic plants to mechanical stress and disturbance

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Abstract

External mechanical forces resulting from the pressure exerted by wind or water movement are a major stress factor for plants and may cause regular disturbances in many ecosystems. A plant's ability to resist these forces relies on several strategies, as minimization of the forces encountered by the plant or maximization of its mechanical resistance to breakage. Aquatic vegetation is submitted to mechanical factors differing from terrestrial one: aquatic plants experience reduced gravitational forces due to buoyant nature of water, but important hydrodynamic forces induced by water movement (current, waves, floods). Moreover, in certain habitats, aquatic plants are also submitted to temporary dewatering, which results in a drastic change in mechanical forces that they encounter, particularly in increased gravitational forces. Aquatic plants are characterized by some specific anatomical traits (e.g. small amount of strengthening tissues or presence of large lacunar systems) and generally a high level of phenotypic plasticity that participate to adaptation to various abiotic factors. This talk aims to present the strategies and adaptations of aquatic plants to these mechanical factors: hydrodynamic forces induced by current and floods and gravitational forces induced by dewatering.

Keywords
phenotypic

Devils claws - a materials perspective

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Abstract

Proboscidea louisianica and *Ibicella lutea* (Martyniaceae) are both annual herbs of tropical and subtropical America. Apart from large and attractive flowers, the plants are characterised by sticky glands, sometimes interpreted as preadaptation to insectivory as well as eye-catching fruits. These fruits consist of a thick parenchymatous exo- and mesocarp while the endocarp differentiates into a sclerenchymatous capsule. Upon ripening, the fleshy fruit wall is shed releasing the capsule. During development, the short style elongates and differentiates into two horn like structures that are able to hook into the ankles or fur of animals. The two halves of the style split along their axis and separate due to desiccation. As a result the capsule splits open at the base of the style allowing seeds to be dispersed. However, to release the seeds the capsule needs to be treated mechanically forcing the seeds through the narrow opening, i.e. the capsules are subject to forces such as bending, compression and torsion. Fruits of *Proboscidea louisianica* were harvested in regular intervals during the summer growth season to study fruit development and tissue differentiation. The tissues of the capsule, especially the hornlike extensions were mechanically tested in three point bending and uniaxial tensions. The endocarp differentiates into a complex arrangement of sclerenchymatous fibres that on the one hand are arranged parallel to the outer shape of the horns while on the other hand fibres grow perpendicular to the latter forming a kind of sleeve around individual longitudinal fibre bundles. The biomechanical consequences of this specific fibre arrangement will be presented and discussed.

Keywords

Proboscidea, capsule, tissue differentiation, biomechanics

Study of the interspecific variability of mechanosensitivity on stem growth regulation in five neotropical rainforest species

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Abstract

In rain forests, saplings of shade-intolerant species are involved in a very challenging competition for height growth and access to light within the canopy. Indeed they are submitted to harsh photosynthetic constraints due to under-storey deep shade, and the stretch to the canopy is among the largest on Land.

Shade-intolerant species have thus to grow in height as fast as possible while avoiding stem buckling or breakage. Their survival thus depends on the regulation of the slenderness (height/diameter ratio) and stability of their saplings.

Different growth habits and biomechanical strategies have been observed among shade intolerant woody species. Trees display different amount of slenderness and buckling risks, whereas lianas overreach their buckling length while relying on other species for their support.

Mechanosensing of bending strains under chronic winds or self-weight, and consequent thigmomorphogenesis, were found crucial to control trunk size and slenderness according to the bending rigidity of the trunk and the loads it is been submitted to..

The present study investigates whether five different neotropical species with contrasting slendernesses and biomechanical strategies (*Eperua falcata*, *E. grandiflora*, *Tachigali melinonii*, *Symphonia globulifera* and *Bauhinia guianensis*) exhibit differences in mechanosensitivity

Defining quantitative and relevant thigmomorphogenetic traits requires a proper analysis of load distribution and biological signal integration within the stem, given that the species can display differences in size. This can be achieved through the Sum-of-Strain-Sensing model (S³m) that has been validated on molecular and growth responses. The parameters of the dose-response curve between the applied sum of bending strains and the growth response define the mechanosensitivity of the plant in a size-independent manner.

Saplings were subjected to a regimen of controlled mechanical bending over a period of 2 months. Mechanical loading was controlled in terms of strains so that the species were subjected to the same range of sum of strains. Dose–response curves were then compared between tested species

Only one trait, the mechanosensing threshold displayed clear interspecific variation, with two clusters of species. Interestingly, the liana species *B. guianensis* exhibited a higher threshold than other Leguminosae species tested. This study provides a conceptual framework to study variability in plant mechanosensing and demonstrated interspecific variability in mechanosensing

Keywords

mechanosensitivity, trees, thigmomorphogenesis, growth strategies

Why trees are of the size that they are?

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Abstract

Tall trees are able to place their leaves at higher light levels, are able to overshadow their neighbours, spread their wind dispersed pollen or seeds further, survive better surface fires and escape colonization of climbers better. On the other hand, taller trees are at a greater risk of being hit by lightning, have greater difficulty in transporting water up to the crown and can be easier toppled over by their own weight or wind. Because the risk of being hit by lightning is low in most ecosystems either hydraulics or mechanics of trunks limit tree height. Most dominant trees in the world are short relative to hydraulically maximal heights and the huge investment that trees make to build heart wood indicate the importance of mechanical limits of height as heart wood is functional for staying erect but not to transport water. To stay erect trees need to resist static loads caused by their own weight and e.g. snow. However, normally static loads are far from being able to bend large trees. On the other hand being toppled over by wind is common and usually fatal and seems to be the main factor limiting tree height. Trees could avoid toppling over by building a fatter trunk. Why don't they do that?

Trees cannot consume more energy than they produce. Most of the consumption occurs in leaves, branches and roots but the interest here is the small portion of total occurring in the sapwood and especially on the surface of the trunk which has been shown empirically to cause most of the trunk maintenance cost. The value of high wood density, the classic self-thinning law, the rarity of buttresses and aerial roots and global variation in humid old-growth forest biomass can be understood based on the importance of trunk surface in energetics and by assuming that trees try to be as tall as they can without taking excessive risk of being toppled over by wind.

Keywords

tree size, wind drag, biomass

Gravitropic movements in trees are constrained by size and growth rate and make cambial growth a carbon sink during sapling stages

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Abstract

Trees are gigantic and long living organisms where gravitropic movements are governed by cambial growth spread along organs. By confronting simple biomechanical models to observations and experiments, we will try to synthesize how size and time constrain the ability of trees to control their posture. Basic dimensional effects of length and diameter will be stated using a now widely used model describing how stem curvature changes with time. This model suggests that diameter and cambial growth strongly limit the curvature rate. Previous investigations in greenhouse experiments where a strong initial perturbation of lean was applied will be used to discuss how the capacity of gravitropic response differs between individuals according to species autecology, growth conditions and ontogenic stage. Then, we will present new results about movements of saplings observed in natural conditions and try to demonstrate that i) the posture control is a relevant ecological process contributing to explain how saplings respond to the disturbance of their environment, ii) this biomechanical function could be a reason why resource allocation is preferentially directed to cambial growth after gap opening. We will also investigate the scaling of curvature changes among a wide range of size and competition environments in a beech silvicultural experiment, and show that the control of reaction wood formation does not balance dimensional effects. Lastly we will discuss how allometric relationships between diameter and height, modified by environment and ontogeny, could be derived from these considerations. The conclusion emphasizes that allometric laws of posture control must be discussed with respect to other constraints such as the self-weight and long-term consequences on the tree development over its whole life.

Keywords

Gravitropism, Ecological strategies, Integrative mechanical modelling, Tree saplings, Tropical rainforests, Beech

Leaf-fracture properties correlated with nutritional traits in nine Australian seagrass species: potential implications for susceptibility to herbivory

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Abstract

Seagrasses are exposed to constant risk of structural damage due to abiotic factors, such as waves and currents, and biotic factors, e.g. herbivory. Leaf mechanical resistance is therefore, essential in protecting plants from structural failure and may also have ecological consequences. For example, mechanical traits of seagrass leaves may play an important role on plant-herbivore interactions and food-preferences of herbivores in these ecosystems, as widely reported for terrestrial plants. However, little is known about leaf mechanical resistance against structural damage in seagrasses and how it varies with other traits such as their nutritional value. We analysed on seagrass leaves the correlation between fracture properties relevant to herbivory and their nutritional value, testing the general assumption that species that invest heavily in mechanical resistance (toughening of the leaves) will present low nitrogen and high carbon and fibre contents. Direct measurements of leaf traits were conducted on nine seagrass species from south-western Australia: i) leaf-fracture properties from shearing and tearing tests, ii) nutritional values (carbon to nitrogen ratio and fibre content), and iii) morphological and structural traits (specific leaf area and leaf thickness). Results showed that leaf-fracture properties in seagrasses were tightly correlated to C:N ratio, which reflects their nutritional value, thus supporting the general assumption that C investment is inversely correlated to N content. This close correlation suggested that patterns of seagrass consumption may be influenced not only by C:N ratio but also the leaf-fracture properties. Among co-existing seagrasses, we found a continuous spectrum of mechanical and nutritional traits across species, which provide fundamental information of species assembly, herbivore behaviour and ecosystem functions.

Keywords

Biomechanics, Herbivory, Nitrogen, Nutritional trait, Leaf toughness, Mechanical resistance

The Garden of Eden: at the crossroad of biodiversity and biomechanics

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Abstract

In the piedmont of the Tian Shan mountain (located at the border between Kazakhstan and China), natural forests of wild apples trees *Malus sieversii* extend along 2000 kilometres. They were first discovered at the beginning of the 20th century by the great Russian evolutionist Nicolai Vavilov and extensively studied by his fellow Pr. Aymak Djangaliev. This discovery remained ignored by most western scientists until Catherine Peix, a scientist and filmmaker, recently made a documentary film aiming at informing the scientific community about the extraordinary particularities of these forests and the urge to protect them as a world's heritage. Until now only agronomists and geneticists studied them, focusing on the fruits' natural resistance against fungal diseases. Vavilov's intuition that these forests are at the origin of the domesticated apple tree *M. domestica* was recently confirmed using molecular biology.

The diversity of sexual and vegetative characters of *M. sieversii* is outstanding and should attract attention of scientists from many disciplines, including forest ecology and plant biomechanics. Within a single population, the size of fruits varies from that of a cherry to that of a commercial apple. The size of some trees can reach 30 m in height and more than 150 cm in diameter. Moreover, the shape of trees is also tremendously variable: erected, opening, spreading, dropping and even weeping habits are found within a single site. Furthermore, this diversity is found in populations from habitats that drastically differ in elevation, rain, soil quality and depth.

These observations raise several questions of high relevance to biomechanical ecology: why does this species exhibit such a within-population diversity in shape? Why do we find this diversity in such a wide range of environmental conditions? These questions challenge the almost paradigmatic idea that natural selection results in an adaptation of tree shape to its environment.

The presentation will illustrate the above-mentioned characteristics of the biomechanical ecology of *M. sieversii*. Hypotheses will be formulated to explain the cause of the within-population diversity in shape. These putative explanations are based on previous works dealing with, on one hand, the contribution of biomechanical traits to the biodiversity in tropical rainforests, and, on the other hand, the modelling of (domesticated) fruit trees biomechanics.

Keywords

Malus sieversii, biodiversity, tree shape, fruit trees

Wind effect on mechanics and hydraulics traits across the canopy of cold desert shrubs

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Abstract

Wind is an environmental factor that affects plant development. Stems within the canopy exposed to different wind intensities could express different phenotypes in relation to hydraulics and mechanical traits. Wood density has been related with vessel anatomical properties, and in accordance with the Hagen-Poiseuille law, with the water transport efficiency. The objective was to evaluate the relationship between the hydraulic characteristics and the mechanical resistance of stems within the plant under the influence of wind stress. Four dominant patagonian steppe shrubs were chosen: *Colliguaja integerrima*, *Berberis microphylla*, *Acantholippia seriphioides* and *Fabiana patagonica*. Vessel diameter and density, hydraulic conductivity (ks), wood density and flexural rigidity (FR) of stems naturally exposed to wind within the same individual (windward and leeward) were measured.

In all species FR was higher at windward, indicating that stems more exposed to wind are stiffer than protected stems. This suggests that this mechanical trait exhibits intraindividual phenotypic plasticity induced by wind across the studied Patagonian shrubs. However wood density only showed significant changes between exposures in *C. integerrima*, being exposed stems denser.

There was no specific pattern in the response of ks to wind exposure across species. Two species (*C. integerrima* and *A. seriphioides*) had lower ks at windward than at leeward. While in *A. seriphioides* lower ks was consistent with the lower vessel diameter ($P < 0.01$) and density, in *C. integerrima* low ks was correlated with the lower vessel density ($P < 0.1$) of higher diameter. These results put in evidence a “tradeoff” between mechanical safety and hydraulic efficiency where stems under wind stress give priority to rigid instead of efficient water transport systems.

On the other hand, *F. patagonica* exhibited higher ks at windward than leeward, which was related to a higher density ($P < 0.01$) of smaller vessels ($P < 0.01$) and *B. microphylla* had higher ks at windward as a result of an increase in vessel diameter ($P < 0.01$) despite the decrease in vessel density. At difference of *C. integerrima* and *A. seriphioides*, these species did not exhibit a “tradeoff” between conductivity and mechanical resistance due to stems with higher hydraulic capacity showed also higher resistance to bend with the wind at windward. A possible explanation could be that a small change in vessel traits that would affect hydraulic conductivity have no effects on stiffness of the stems.

Keywords

wind, hydraulics, mechanics, ecophysiology, tradeoff

Peculiar tension wood cell wall structure in genus from French Guiana previously related to the former Flacourtiaceae family

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Abstract

In order to restore their verticality after accidental leaning, to maintain the branch at a given angle or to change axis orientation for better access to light trees are able to bend progressively their trunk or branches by an active mechanical action driven by cambial activity. This reorientation is associated with the formation of a peculiar type of wood, called reaction wood. In angiosperm species it is formed on the upper side of the axis (tension wood). Among angiosperms, diversity in the form of reaction wood fibres has long been recognized. The most typical form of angiosperm tension wood is characterized by the development of a so-called gelatinous layer (G-layer). However, several species do not develop G-layer, while showing evidence of tension wood production. During an exploration of biomechanical strategies of tropical rainforest species, trees from *Laetia procera* and *Casearia javitensis* species, neo-tropical forest species previously related to the former Flacourtiaceae family, showed a peculiar secondary wall structure, with an alternance of thick and thin layers, while opposite wood of this species has a typical secondary wall structure. The observation of this peculiar structure in these two species led us to the questioning of a common anatomical feature in tension wood fibres at the family level.

Ten trees among 10 species and 7 genera were chosen with the aim to screen most species previously related to the Flacourtiaceae family that can be found in French Guyana. Those trees, with diameter at breast height ranging between 19 and 28 cm, were exhibiting a reorientation process after some accidental inclination. This was verified *in situ* by mechanical estimation of maturation strain (MS). Samples for the study of secondary wall structure were taken at the measurement point and observations were made in transverse plane with a colour 3D laser scanning microscope. MS observed in tension wood of all the studied trees were in the upper range of reported values. Among the ten observed trees, 8 trees belonging to 6 genera showed a polylaminate structure in their tension wood although 2 trees, belonging to the *Lacistema* genus, did not show any difference between tension and opposite or lateral wood. These results will be discussed within the context of angiosperm phylogeny and evolution of tension wood morphology, especially in the frame of the reaggregation of species and genera that used to be related to the former Flacourtiaceae family into the Lacistemataceae and the Salicaceae family.

Keywords

Tension wood • Tropical rainforest species • Flacourtiaceae • Polylaminate secondary wall

The ecological relevance of the pomelo (*Citrus maxima*) peel acting as an effective impact protection

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Abstract

Pomelos are the largest and heaviest fruits among the genus *Citrus*. Beside the mandarin (*C. reticulata*) and the citron (*C. medica*), the pomelo (*C. maxima*) is one of the three 'true' citrus species originating from south-east asia. The extraordinary thick peel of the pomelo thus must not be seen as an artifact resulting from cultivation or cross-breeding, and therefore gives rise to the question of its ecological relevance. Regarding the tree height of up to 15m and the increasing weight of these fruits during maturation, they have to cope with large amounts of kinetic energy when impacting on the ground after being shed. Shed, mature citrus fruits serve as propagation units as they will be consumed by animals (e.g. bears, monkeys and fruitivorous bats) and consequently the seeds are dispersed by these vectors. For the plant it is therefore crucial to produce fruits that stay attractive for the vectors over a sufficient period of time. This can only be provided if the fruits peel stays intact as otherwise the fruit would quickly be contaminated by the ubiquitous mold spores. The latter not only render the fruits unattractive for potential vectors, they additionally affect the germination capacity of the enclosed seeds. To analyze the influence of the peel's state (intact or bruised) on the fruit's decay progress, we conducted a series of free fall tests by dropping pomelos from different heights onto a natural and pliable ground (lawn) and subsequently placing them into a greenhouse. These humid and warm conditions were chosen in order to simulate the subtropical climate prevailing in the region of origin of the pomelo. After 12 days first traces of mould became visible in case of the pomelo that split open during impact (drop height = 21.7 m). The pomelos that did not split open (drop height = 13.7 m) as well as a control showed no sign of decay until the 32nd day after impact. These results and the fact that the peel is a light weight tissue ($\rho_{\text{peel}} \sim 370 \text{ kg m}^{-3}$ compared to $\rho_{\text{pulp}} \sim 980 \text{ kg m}^{-3}$ and $\rho_{\text{fruit}} = 710 \text{ kg m}^{-3}$) suggest that the peel constitutes a highly effective natural impact protection.

Keywords

Biomechanics, *Citrus maxima*, Impact protection

Evolution of shrub-like growth forms in the *Aristolochia* subgenus *Isotrema*

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Abstract

The genus *Aristolochia* (c. 500 species) is a predominantly tropical and subtropical genus that extends to Mediterranean and temperate zones worldwide, and has highest species richness in the New World (Wanke et al., 2006). The climbing habit is characteristic for the genus *Aristolochia* (Gentry, 1991), but interestingly a handful of Mexican and Central American species are known to grow as shrub-like forms (Pfeifer, 1966). Climbing plants can be highly specialized and adapted to live with dependence on other plants for mechanical support. Of particular interest is whether clades that become specialized as climbers become “developmentally locked” into their specialized growth form or whether they can diversify further into other growth forms such as self-supporting shrubs and trees. We are investigating the evolution of the rare self-supporting growth form within the genus *Aristolochia*, only known from the subgenus *Isotrema*, by studying biomechanical properties and anatomy in a phylogenetic context. The study indicates that shrub-like species in *Isotrema* are restricted to the monophyletic Central American lineage, which also contains climbing species. Our results including recent field work at their natural sites of growth show that recorded shrubby species are indeed not climbing but not fully self-supporting; they develop a more or less upright growth with their branches leaning on the surrounding vegetation. Comparison of biomechanical properties reveals a clear difference between species growing as lianas, and species exhibiting this shrub-like habit. Stems of shrub-like species show an increase in Young’s modulus from young to mature phases, and retain stable values after a certain stage of development, whereas values of climbers progressively decrease during development. Interestingly, some kind of intermediate forms between typical lianas and shrub-like forms have been identified. These species develop a climbing habit, but show less flexible mature stems compared to the typical *Aristolochia* lianas, and share several anatomical properties with the shrub-like forms. Anatomical studies have detected, that even the shrub-like, more or less upright species, have retained some lianoid stem characters that are known to promote flexibility including ray parenchyma and a thick periderm. Thus, our study suggests that while growth forms within the genus *Aristolochia* might have partly escaped from the constraints of life as lianas, they do not develop a height, size and stability typical of self-supporting shrubs and trees.

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Keywords

Aristolochia, Anatomy, Biomechanics, Evolution, Growth Form, Phylogeny

The bending mechanics of tree stems: the key role of wood maturation stress for resisting both permanent and temporary loads

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Abstract

The mechanical design of trees and wood is suited to face two types of mechanical loads: permanent loads related to the increase in self-weight, and temporary loads due to external actions such as wind. In angiosperms, a tensile longitudinal stress is always generated around the tree periphery during wood formation. This maturation stress plays a key role in terms of biomechanical adaptation of the tree to its environment: it provides the stem with a motor system allowing the postural control of the tree (i.e. compensating for the effect of permanent loads) and, eventually, the reorientation of stems and branches in response to disturbance. Another important function of this tensile pre-stress located at the periphery is to improve the bending resistance of stems against temporary loads, by compensating for the relatively low compressive strength of green wood.

As consequence of maturation stress production, compressive growth stress accumulates in the core of the trunk. A numerical model was formulated and implemented to compute the field of longitudinal growth stress across a growing cross-section, and to calculate ecologically relevant parameters defined as the “performance of the motor system” and the “safety against temporary bending”. The model is general enough to account for any cross-section shape, growth eccentricity, viscoelastic behavior of wood and heterogeneity of wood mechanical properties (stiffness and maturation stress). Simulations were performed to evaluate the influence of these parameters on the growth stress pattern, motor performance, and safety against temporary bending. Results show that in some situations, the growth stress pattern can have a negative impact on the bending safety. A sensitivity analysis was performed and evidences that, in some case, the motor performance can be only improved at the expense of a lower safety against bending loads.

Conclusions emphasize the fact that the value of biomechanical parameters mediates a trade-off between the motor performance of the stem and its safety against temporary loads, and that the range of real value of biomechanical parameters is close to optimal regarding this trade-off.

Keywords

gravitropism; stem bending strength; functional trade-off; growth stresses; juvenile wood; eccentricity

Session Morpho

Biomechanics of morphogenesis and pattern formation

The physical basics of morphogenesis

From the shoot apex to leaves

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Abstract

Morphogenesis is the remarkable process by which a developing organism acquires its shape. As morphogenesis entails dynamic changes in the structural elements (mostly cell walls) that define shape, it is essential to investigate the role of the mechanical properties of these elements in an organismal context. Does cell differentiation lead to modifications in mechanical properties? Do these mechanical properties predict shape changes? More generally, what are the principles behind morphogenesis? In this talk, I will present our approaches to tackle these questions, focussing on organogenesis at the shoot apex and on leaf morphogenesis.

Keywords

biophysics

On relations between growth, geometry and microtubule arrangement during morphogenesis at the shoot apex of *Arabidopsis*

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Abstract

An important issue in plant development studies is how organ pattern is generated. Plant organs are formed at the shoot apical meristem, which is a complex and dynamic structure consisting of continuously growing and dividing cells. Morphogenesis at the shoot apex is intrinsically related with cyclic changes of meristem geometry. In case of *Arabidopsis*, a new organ first appears as a bulge at the meristem surface. Later on a saddle-shaped crease is formed between the bulging primodium and the meristem, and consequently becomes an adaxial boundary that separates the new organ from the meristem. New organs are positioned in a very regular pattern called phyllotaxis. Many hypotheses have been put forward, from those which account for biomechanical mechanisms for the pattern generation (P.B. Green's hypothesis), to those which consider a biochemical factor as a key determinant of phyllotaxis. While currently auxin has been established as a key biochemical regulator of phyllotaxis, the contribution of microtubules, which affect the cell wall structure and thus cell expansion and divisions, is just beginning to be rediscovered.

We search for relations between microtubule arrangement, cell growth and meristem surface geometry. We use dissected inflorescence shoot apices of transgenic line of *Arabidopsis GFP-MBD* (*Microtubule Binding Domain*) growing *in vitro*. Live imaging by confocal microscopy is combined with sequential replica technique. The former is used for visualization of cortical microtubules under outer periclinal walls of meristem L1 cells (surface cell layer). A tool for measurement of fluorescent signal enables quantification of microtubule orientation and array anisotropy at different time intervals. The replica technique is used for quantification of areal growth rate and growth anisotropy for individual cells as well as the local curvature of the meristem surface.

This combined confocal-replica protocol provides a unique possibility to study spatial and temporal relations between microtubule arrangement, cell growth and geometry, their anisotropy in particular, at the same regions of individual meristems. We use geometry parameters, namely Gaussian curvature and principal directions of curvature, as a landmark of developmental stage of meristem and emerging primordia, and as a quantity related with pattern of mechanical stresses. Furthermore, quantitative data on microtubule arrangement are combined with parameters of cell growth, i.e. areal growth rate and growth anisotropy (especially the direction of maximal growth rate), and related with organ initiation and further development represented by geometry changes.

Keywords

microtubules, shoot apical meristem, cell growth, meristem geometry

Experimental Study of the Effect of Mechanical Stress on the Evolution of Leaf's Vascular System

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Abstract

I will present a combined experimental and numerical study of the effect of mechanical stresses on leaf growth. In particular, we study the effect of externally applied stress on the evolving geometry of leaf's vascular system. In the experiments we stretch the margins of a growing Bay-Leaves leaves, while imaging their vein system. We find a clear measurable effect of stress on the evolution of the system: Growth is enhanced along the stretching direction and as a result the vascular network is "deformed" compared to an un-stretched network. The measured deformation fields are compared to fields generated by a theoretical model. The model assumes that mechanical loads (pressure/stress) within a leaf are carried by the vascular network, which responds as a visco-elastic material. We show good qualitative agreement between experimental data and model predictions.

Keywords

leaves veins stress growth morphogenesis

Considerations on the formation of wind-induced asymmetric canopies in trees

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Abstract

The action of a strong and persistent unidirectional wind on tree crowns is known to alter crown morphology creating a more streamlined or asymmetric architecture providing mechanical advantage to the tree by reducing mechanical loading of the stem via reduced drag. The appearance of the streamlined growth form can be induced by two mechanisms. The first is a simple physical damage mechanism in which branches and foliage are physically broken, resulting in damage to the tree. The second is a more gradual process of wind force induced bending of the branches and foliage into a sweeping growth form devoid of physical damage. The mechanism of this second process is less clearly understood and the subject of this talk. How does a tree obtain and maintain the streamlined or windswept growth form? Telewski (2012) addressed two hypotheses regarding biological control of streamlined canopy formation; a physiological thigmotropic mechanism and a biophysical/biomechanical mechanism. If mechanoreception and subsequent physiological growth response are responsible, then evidence should exist in the tree structure to support this hypothesis. The asymmetric growth form is consistent with a negative thigmotropic growth response. However, anatomical evidence does not support such a mechanism. Contrary to maintaining a curved morphology away from the prevailing wind direction, compression wood has been reported to form on the leeward side of branches and displaced leaders. This position of compression wood should push the displaced branches back into the wind.

Evidence may support the biophysical/biomechanical mechanism. Branch junctions have been reported to exhibit low stiffness and strength, but increased flexibility and toughness (Fäber et al. 2001, Burgert and Jungnikl 2004). An increase in flexibility permits easier branch deflection, but what maintains the deflection once the applied force of the wind is removed? The slip-stick or Velcro hypothesis (Spatz et al. 1999, Keckes et al. 2003) could account for the repositioning and subsequent maintenance of branch displacement after the wind load has been removed. However, this hypothesis was observed in compression wood under tensile strain. The compression wood in windswept branches is under compression during wind loading. A recent analysis of greenwood biomechanical properties revealed a possible relationship between wood properties and the degree of asymmetry obtained under similar loading conditions (Telewski 2012). Trees most sensitive to permanent crown deformation tend to have stronger, denser wood. Clearly, asymmetrical wind pressure induces branch and stem deflection. However, the mechanism for maintaining deformation is still not completely understood.

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Keywords

crown asymmetry, thigmotropism, wind-swept, compression wood

Auxin regulates aquaporin function to facilitate lateral root emergence

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Abstract

Aquaporins are membrane channels that facilitate water movement across cell membranes. Here, we establish a new link between aquaporin-dependent tissue hydraulics and auxin-regulated root development in *Arabidopsis thaliana*. We report that most aquaporin genes are repressed during lateral root formation and that exogenous auxin treatment represses aquaporin genes and reduces root hydraulic conductivity both at the cell and whole organ levels. Expression studies revealed that the highly expressed aquaporin PIP2;1 is progressively excluded from the site of the auxin response maximum in lateral root primordia whilst being maintained at their base and in the underlying vascular tissues.

To understand how lateral root emergence is affected by the spatial distribution of auxin and PIP2;1, we developed a mathematical model of the cross-section of the root, which simulates water fluxes between stele, primordium and overlaying tissues, and shows how the resulting variations in pressure can drive expansion of the primordium. Simulations revealed that the build up of auxin within the primordium and overlaying tissue promotes emergence, and that positive and negative perturbations of PIP2;1 expression slow emergence. Consistent with these predictions, we found that *pip2;1* mutants and constitutive *PIP2;1* overexpressing lines exhibit delayed emergence. We conclude that auxin promotes lateral root emergence by regulating the spatial and temporal distribution of aquaporin-dependent root tissue water transport.

Keywords

Lateral root development, Aquaporins, Auxin, Modelling,

Ruffles or Straps

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Abstract

Curved and twisted structures are common in Nature and are produced by several different mechanisms. We used the giant bull kelp, *Nereocystis luetkeana*, to investigate how the kinematics of blade growth produces different morphologies in response to the mechanical loads on the blades. Like other genera of marine macroalgae, *Nereocystis* has strap-like blades in habitats exposed to rapid water currents, but ruffled blades at sites with slowly flowing water. In this study marking experiments were analyzed to find the temporal and spatial patterns of growth producing the ruffled and flat morphologies for blades growing in different ambient currents or subjected to mechanical loads simulating the drag force on blades at different sites. It is known that ruffles develop by elastic buckling when the blade is wide and, across the width of the blade, the rate of longitudinal growth at the margin has exceeded that of the interior tissue. The same individuals grow flat, strap-like blades when exposed to rapidly flowing water, as a consequence of small transverse growth rates and rates of longitudinal growth uniform across the width of the blade. Blades exposed to various flow regimes or mechanical loads were marked with a grid of holes punched at increments of five cm throughout the putative growth zone at the proximal end of the blade. After six days of growth the blades were harvested, and the final position of the holes was measured. The fields of growth velocity and strain rate were calculated. Growth trajectories (plots of positions of tissue particles versus time) were computed by integrating the velocity following the tissue particles during their growth displacements. The shapes of the material elements of tissue could then be seen as a function of time and position on the blade. During steady state growth of ruffled blades, the ratio of the segment length at the margin to segment length along the midline increases during displacement over 25 cm corresponding to 12 days of growth. In contrast, flat blades maintain similar growth strain rates at the margin and interior. A numerical sensitivity analysis shows the ruffled morphology can be produced by a small increase in growth strain rate at the margin near the base of the blade. The pattern of growth strains occurs whether the morphology is induced by ocean currents or weights added to produce equivalent drag.

Keywords

tidal currents, morphogenesis, mechanical drag, *Nereocystis luetkeana*, curvature

The coupling between microtubule orientation and cellulose deposition contributes to the maintenance of the phyllotactic patterns during stem growth in Arabidopsis

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Abstract

In plants, organs are arranged along the stem in a regular and stereotypical pattern called phyllotaxis. New organs are emerging at the shoot apical meristem, and the dominant role of auxin transport in directing this initial pattern is now well documented. However, the role of post-meristematic growth in phyllotaxis remains elusive. Along the stem, cells are experiencing a phase of high anisotropic growth and patterns of phyllotaxis that are initiated in the meristems are surprisingly well maintained as stem elongates. In particular, it has been proposed that the stem, when compared to a fiber-reinforced growing cylinder, should not passively maintain a straight growth, but should instead become twisted. In this scenario, the maintenance of the meristematic phyllotactic angles during stem elongation would require a tight control of cell growth. Here we tested the contribution of cellulose deposition in this process. Cellulose deposition in parallel microfibrils generally depends on the orientation of the microtubules at the cell cortex. Recently, the *POM2/CSI-1* protein has been shown to establish a physical link between cortical microtubules and the cellulose synthase complexes. In particular, cellulose deposition becomes uncoupled from microtubule orientation in *pom2/csi-1* mutant hypocotyls. We observed phyllotaxis defects in the *pom2/csi-1* mutant; two main types of phyllotaxis were displayed on the mutant stems, an alternate phyllotaxis (i.e. 180° between successive siliques) and a 90° spiral phyllotaxis. Interestingly, phyllotaxis in the *pom2/csi-1* mutant meristem was normal, showing that organ initiation in the meristem was not affected. We showed that the observed alterations of phyllotaxis were the consequences of a right-hand torsion of the stem, thus impacting the angle value between successive siliques during stem growth. Similar defects were also observed in the *spiral2* mutant, which exhibits oblique cortical microtubules orientations and a twisted stem. Based on these data, and the previously described fiber reinforced fluid model of anisotropic growth, we propose that microtubules constantly prevent the natural tendency of cellulose deposition to reorient during cell growth by maintaining newly synthesized cellulose fiber strictly parallel to the main axis of growth, thus avoiding stem torsion and allowing a strict conservation of the phyllotactic pattern prescribed in the meristem.

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Keywords

Phyllotaxis, Cellulose synthesis, Microtubules, CESA, POM-POM2, Cellulose Synthase Interacting 1, Stem twisting-

Mechanical regulation of auxin-mediated growth

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Abstract

The phytohormone auxin is a primary regulator of growth and developmental pattern formation in plants [1]. Auxin gathers at specific sites (for example, organ primordia) and induces localized growth within a tissue. Auxin also mediates developmental responses to intrinsic and external physical stimuli [2, 3]; however, exactly how mechanics influences auxin distribution is unknown.

We show that mechanical strain can regulate auxin transport and accumulation in the tomato shoot apex, where new leaves emerge and rapidly grow. Modification of turgor pressure, external force application, and artificial growth induction collectively show that the amount and intracellular localization of the auxin efflux carrier PIN1 are sensitive to mechanical alterations. In general, the more strained the tissue was, the more PIN1 was present per cell and localized to the plasma membrane. Modulation of the membrane properties alone was sufficient for most of the mechanical effects.

Our experiments support the hypothesis that the plasma membrane acts as a sensor of tissue mechanics that translates the cell wall strain into cellular responses, such as intracellular localization of membrane-embedded proteins and mechano-transduction. One implication of this fundamental mechanism is mechanical enhancement of auxin-mediated growth in young organ primordia. Growth-induced mechanical strain up-regulates PIN1 function and auxin accumulation, thereby promoting further growth, in a robust positive feedback loop.

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Keywords

auxin, PIN1, external force application, mechanical strain, shoot apex, growth

Mechanical regulation of PIN1 in the meristem

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Abstract

Initiation of new organs is the major determinant of plant form and typically occurs in a precise geometric pattern known as phyllotaxis. Organ initiation requires carefully coordinated gene expression to determine the pattern and identity of the new organs. Feedback regulation between the plant hormone auxin and one of its transporters PIN1 provides a plausible model for phyllotaxis. However, gene expression must also be coupled with mechanical changes in order to generate a physical outgrowth. Recent work suggests the orientation of PIN1 is sensitive to mechanical stimulation, opening the possibility for mechanical regulation of gene expression in plant cells. We have also observed changes in PIN1 localization in response to osmotic stress and application of large forces in the tomato shoot apex. To further investigate the mechanism behind these discoveries it is necessary to quantify gene expression and mechanical forces in the genetically tractable model organism *Arabidopsis*. To minimize the damage caused by applying mechanical forces it is necessary to be able to work with small local forces and analyze small changes in gene expression or protein localization. This can be done using Cellular Force Microscopy (CFM), a micro-indentation technique we have developed for in-vivo stiffness measurements of individual cells. With CFM, a large range of forces and displacements are possible, making it suitable for taking precise measurements and applying forces locally. We have also developed MorphoGraphX a 3D image analysis software, enabling visualization and quantification of cell sizes and protein localization. We are currently working to combine CFM and MorphoGraphX with genetic tools and molecular markers to dissect the mechanism for the PIN1 response to mechanical stimulation.

Keywords

mechanics, meristem, PIN1, auxin, *Arabidopsis*

Patterns produced by nucleation and aggregation in biopolymers

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Abstract

Nucleation and growth reactions between biopolymer (such as plant starches) solutions or gels and gas vapors diffusing into them lead to a wide variety of patterns, from ripples to polygonal lattice to less organized structures. We build a mathematical model based on nucleation, growth, and aggregation. Applying mechanical stresses to the gels changes the patterns. This system together with the model thus provides a simple way of using patterns to probe the influence of mechanical stresses on biochemical interactions.

Keywords

pattern formation, nucleation and growth

Phyllotaxis: a crystallographic solution from Botany to packing efficiency, elasticity and growth in radial symmetry

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Abstract

Phyllotaxis describes the arrangement of florets, scales or leaves in composite flowers or plants (daisy, aster, sunflower, pinecone, pineapple...). Mathematically, it is the most homogeneous and densest covering of a large disk by Voronoi cells (the florets). The Voronoi cell (or Dirichlet domain) associated with a point is defined as the region of space nearer to it than to any other point in the set. Points placed regularly on a generative spiral constitute a spiral lattice, and phyllotaxis is the tiling by the Voronoi cells of the spiral lattice. The number of points on the generative spiral increase as the flower grow, and the azimuthal angle between two successive points on the spiral is $2\pi/\tau$, where $\tau = (1+\sqrt{5})/2$ is the golden ratio.

If the generative spiral is equiangular (Bernoulli), the phyllotaxis is a conformal (single) crystal, with only hexagonal florets (outside a central core of < 30 cells) and zero shear strain. But the size of the florets increases radially outwards.

Florets of equal size are generated by points on a Fermat spiral. But the florets are not all hexagonal: There are annular crystalline grains of hexagonal florets (traversed by three visible reticular lines in the form of spirals, called parastichies) separated by grain boundaries that are circles of dislocations (d: dipole pentagon/heptagon) and square-shaped topological hexagons (t: squares with two adjacent vertices truncated). The sequence dtdtdt... is quasiperiodic, and Fibonacci numbers $f_i = 2, 3, 5, 8, 13, 21, 34, 55, 89, \dots$ are pervasive: It contains $f_i - 1$ d, f_{i-2} t, f_{i+1} cells, and separates two grains with (f_i, f_{i-1}, f_{i-2}) and (f_{i+1}, f_i, f_{i-1}) parastichies. The two main parastichies cross at right angle through the grain boundaries. A shear strain develops between two grain boundaries. It is actually a Poisson shear, associated with radial compression between two circles of fixed, but different length. Thus, elastic and plastic shear can be readily absorbed by a polycrystalline phyllotactic structure described by several successive Fibonacci numbers.

This solves the packing efficiency problem: One grain boundary constitutes a perfect circular boundary for the disk into which objects are to be packed.

Grain boundaries can be rotated (dislocation glide) and translated easily by local neighbor exchanges (phason flips in quasicrystals), radially inwards if the gaussian curvature of the substrate becomes more negative. In that way, the phyllotactic structure responds easily, locally and naturally to an external force that is expressed in the curvature of the substrate. The same structure of Fibonacci numbers of parastichies, with the same circular boundaries persists for curved substrate. But a grain bounded by two boundaries of fixed length and quasicrystalline topology, is depleted as the curvature becomes more negative. Eventually, the innermost grain empties out, and the two boundaries overlap into a more complicated structure, not observed in plants as far as we are aware.

Another application of phyllotaxis to growth can be seen in the agave. Structurally, the agave spends almost its entire life (25 years, approx.) as a single grain spherical (13,8,5) phyllotaxis, a conventional cactus of radius 0.3 m. During the last six month of its life, it sprouts a huge (2.5 m) mast in a cylindrical (5,3,2) phyllotaxis (through two grain boundaries), terminating (through one grain boundary) as seeds-loaded branches arranged in the (3,2,1) phyllotaxis, the final topological state before physical death.

The topological constraint of circular symmetry imposes an inflation-deflation symmetry that takes the place of the translational and rotational symmetries of classical crystallography

Keywords

Phyllotaxis, spiral lattice, grain boundary, conformal crystal, elasticity

Session SENSE

Mechano-and Gravi-sensing and transduction

A feeling for the organism: Mechanosensitive channels in Plants

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Abstract

My group is interested in the molecular mechanisms by which molecules, cellular structures, and organisms perceive mechanical force. Our current research program includes the structural and functional analysis of a family of ten mechanosensitive (MS) ion channels in the model plant *Arabidopsis thaliana*. This family of MS channels was identified on the basis of their similarity to a bacterial MS channel, MscS, which contributes to survival of extreme osmotic downshock in *Escherichia coli*. I will describe 1) our recent electrophysiological characterizations of these MscS-Like (MSL) channels; and 2) the results of our molecular and genetic analysis of their varied roles in plant growth and development.

Keywords

mechanosensitive

Mechanosensitive Ca²⁺ Channel Candidates MCA1 and MCA2 in Arabidopsis

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Abstract

We have been studying mechanosensitive Ca²⁺ channel candidates, MCA1 and MCA2, in *Arabidopsis thaliana*. Both candidates have no homology to known ion channels in amino acid sequence. Our recent work using a yeast expression system has shown that the N-terminal region that corresponds to approximately 40% of the total length is necessary and sufficient for Ca²⁺ influx. We have also shown that this region has a putative transmembrane segment that has an Asp residue responsible to Ca²⁺ influx. Physiologically, MCA1 is involved in sensing/transducing touch stimulus and both proteins are required for the hypoosmotic shock response. We will discuss the structure-function relationships of MCA1 and MCA2 and the role of the two proteins in mechanosensing and mechanotransduction

Keywords

mechanosensitive Ca²⁺ channels, mechanosensing, osmotic response

Exploitation of genes involved in gravity perception and signaling in gravitropism of Arabidopsis

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Abstract

Gravitropism is a form of plant movement that is under continuous control with regard to the orientation and juxtaposition of the various parts of the plant body in response to gravity. In higher plants, the relative directional change of gravity is mainly suspected in specialized cells called statocytes, followed by signal conversion from physical information into physiological information within the statocytes. The signal is subsequently transmitted to neighboring cells and other tissues, which leads to differential cell growth between the lower and upper flanks of the responsive organ.

We have studied the early process of shoot gravitropism, gravity sensing and signaling process, mainly by molecular genetic approach. In Arabidopsis shoot, statocytes are the endodermal cells. *sgr1/scarcrow (scr)* and *sgr7/short-root (shr)* mutants fail to form the endodermis and to respond to gravity in their inflorescence stems. In addition, *eal1 (endodermal-amyloplast less 1)*, which exhibits no gravitropism in inflorescence stem but retains ability to form endodermis, is a hypomorphic allele of *sgr7/shr*. Take advantage of these mutants, we performed DNA microarray analysis and compared gene expression profiles between wild type and the mutants. We found that approx. 40 genes were commonly down-regulated in these mutants and termed them *DGE (DOWN-REGULATED GENE IN EAL1)* genes.

DGE1 has sequence similarity to *Oryza sativa LAZY1* that is involved in shoot gravitropism of rice. *DGE2* has a short region homologous to *DGE1*. *DTL (DGE TWO-LIKE)* that has 54% identity to *DGE2* is found in Arabidopsis genome. All three genes are conserved in angiosperm but have no known functional domains or motifs. We analyzed T-DNA insertion mutants for these genes in single or multiple combinations. In *dge1 dge2 dtl* triple mutant, gravitropic response of shoot, hypocotyl and root were dramatically reduced. All three genes are expressed in the shoot statocytes, while *DGE2* and *DTL* are expressed in the root statocytes. Thus, *DGE1*, *DGE2*, and *DTL* are novel genes that synergistically contribute to gravitropism not only in shoot, but also in root.

Keywords

statocyte, Arabidopsis

Accommodation of physiological and molecular responses to successive mechanical bendings in poplar

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Abstract

In their natural environment, plants are continuously exposed to highly variable wind loads, and in particular to the days-to-week scale alternation of windy and quiet periods. In response to a single mechanical load, plants usually exhibit a dramatic growth response (thigmomorphogenesis) and genes involved are being characterized. However, molecular mechanisms involved in plant acclimation to recurring and successive mechanical loadings are not well characterized. More specifically how plants avoid over-responding in to continuously changing wind conditions is unknown. Through the analysis of the short-time effects of quantified stem bending on young poplars, we demonstrated the rapid induction of *PtaZFP2* expression, a gene encoding a putative C2H2 zinc finger transcription factor. The *PtaZFP2* transcripts accumulate 10 min after a single bending and the relative abundance of *PtaZFP2* transcripts was linearly correlated with the amount of applied mechanical solicitation (Martin *et al.*, 2009; Coutand *et al.*, 2009). To test the effect of successive bending, young trees were submitted either to one transient bending per day for several days or to two bendings, 1–14 days apart. Our results indicate that both diameter growth and gene expression responses are reduced after several bendings. In particular, *PtaZFP2* mRNA accumulated to a lesser extent after two bendings than after a single one. The minimum rest period between two successive loadings necessary to recover a response similar to that observed after a single bending, was 5 days. This response was observed for three other early mechano-responsive genes having different functions in the plant mechanosensing pathway, such as calcium signalling or wall modifications. These results clearly show a partial desensitization of plants to recurrent successive bendings, indicating a day-scale acclimation of sensitivity (accommodation) (Martin *et al.*, 2010). Our objectives are now to identify molecular actors involved in such mechanism by studying the regulation of early responsive gene such as *PtaZFP2* (Gourcilleau *et al.*, 2011).

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Keywords

Mechanical signals, accommodation, C2H2 transcription factor, poplar

Sense and sensitivity: role of DEK1 in mechanosensing

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Abstract

Sense and sensitivity: role of DEK1 in mechanosensing

Mechanical stimulation in plants has been widely studied for more than a century. This type of stress causes developmental alterations such as stunting, thickened stems and differential cell wall composition, as seen in several species. These responses are very likely to be triggered at a subcellular level, driven by transcriptional changes. The molecular mechanisms through which mechanical signals are transduced into intracellular responses still remain unknown.

Plants that constitutively overexpress the cytoplasmic calpain domain of the membrane anchored protein Defective Kernel 1 (DEK1) show a phenotype that resembles that of mechanically stressed plants. The calpain domain of DEK1 shows a very high homology with animal calpains; a class of calcium-dependent Cys proteases. These proteins undergo a calpain domain-releasing autolytic cleavage event during activation, a phenomenon which we have also observed in DEK1. Calpain domain overexpressing plants show an increase in cellulose content and increased lignification of stems. Transcriptional analysis of these plants shows that overexpression of the active calpain domain leads to a deregulation of genes encoding cell wall modifying enzymes. Other characteristics of mechanically stimulated plants which can be seen in calpain overexpressing lines include late flowering, petiole shortening and thickened stems. Therefore, we believe that the calpain domain of DEK1 could act as an effector which is normally activated by mechanical stimulation.

Calpain overexpressing lines were generated in a *dek1* background. According to our proposal these plants should not only behave as if responding constitutively to mechanical stimulation, but should also lack appropriate responses to applied mechanical stimuli due to lack of the proposed mechanosensory integral membrane domain of DEK1. We present results confirming that the absence of the transmembrane domains of DEK1 is indeed translated into a lack of response to mechanical stimulation in comparison to wild type plants. Thus, the transmembrane domains of DEK1 are involved in sensing mechanical stimulation.

We propose that Defective Kernel 1 (DEK1) acts both as a mechanosensor component, and as the first effector of the cascade in response to mechanical stimulation via an autolytic activation in response to mechanical stress.

References

Keywords

DEK1, calpain, mechanosensing, cell wall

Spinning plants: an efficient way to probe the gravitropic response of shoots

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Abstract

Gravity perception by plants plays a key role in their development and adaptation to environmental change (gravitropism), from the direction of seed germination to the control of the final posture. In this study, we investigate how shoots respond to change in gravity direction and/or intensity. To this aim, an original setup consisting in a rotating table has been designed, on which a row of plants can be positioned. Thanks to the continuous variation of the centrifugal force across the table, the entire response function of the plants over a large range of inclination angles and gravity intensity can be obtained, providing a new tool for a quantitative phenotyping. Results on wheat coleoptiles will be presented, and the classical sinus law found in the literature (Iino et al 1996), which stipulates that the response is proportional to the sinus of the inclination angle will be revisited. Inspired by the biomechanical model proposed by Bastien et al. (2011) and based on kinematic consideration of the growing process, a new way of defining the gravitropic response curve using dimensionless quantities will be proposed and tested against the experimental measurements.

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Keywords

gravitropism, growth

System Mechanobiology: The Sum-of-Strain-Sensing model S³m as an integrative mechanistic model of mechanosensing and thigmomorphogenesis in plant stems

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Abstract

Mechanosensitive control of plant growth (thigmomorphogenesis) is a major process shaping how terrestrial plants acclimate to the mechanical challenges set by wind, selfweight, and autostresses [1,2,3]. However it is a complex process that involves an interaction between the loads and the mechanical, mechanosensitive and meristematic structures of the plant. Loads acting on the plant are distributed down to the tissues, following continuum mechanics. Mechanosensing, though, occurs within each living cell, building up into integrated signals that modulate the growth activity of the growing tissues. And the response of plant depends on the amount of load, on the sensitivity of cells mechanotransduction, but also on the size and geometry of the different tissues involved (load bearing tissues, mechanosensitive tissues and growing tissues). Yet the studies on mechanosensing tend to address macroscopic and molecular responses, ignoring the biomechanical aspects of load distribution to tissues and reducing biological signal integration to a “mean plant cell. Recently a mechanistic and integrative biomechanical and mechanobiological model of thigmomorphogenesis, the *Sum of Strain Sensing model* S³m has been developed [1]. Mechanical loads due to wind drag acting on the plant are distributed down to the tissues, following structure mechanics. Mechanosensing, then occurs within the cells, building up into integrated signals travelling to the meristems and triggering growth responses. As a mechanistic model, S³m has been validated in its sensing mechanism (through quantitative gene expression [4]) as well as on its growth outputs in controlled experiments [4,5]. A major asset of S³m is that it can be coupled with mechanical models to analyze the effects of the static and dynamic strains produced by wind-induced vibrations in plants [6]. But as S³m also handles growth responses to wind, it may also be coupled with structure-function growth model. Last but not least, it remains a quite simple model, with only 4 parameters, and can be used to define quantitative ecological traits [2] as well as to phenotype mechanotransduction mutants

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Keywords

mechanosensing, system mechanobiology, thigmomorphogenesis wind

Does transmission of a traumatic signal in aerial part of *Arabidopsis* involve mechanosensitive channels of the MSL family?

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Abstract

In bacterial and animal systems, mechanosensitive (MS) ion channels are thought to mediate the perception of pressure, touch, and sound. Although plants respond to a wide variety of mechanical stimuli, and many mechanosensitive channel activities have been characterized in plant membranes using the patch-clamp method, the molecular nature of mechanoperception in plant systems has remained elusive [1]. It is only recently that gene cloning and knockout strategies combine with the patch clamp technique resulted in the identification of MSL mechanogated channels in *Arabidopsis*, relative of the *E. coli* Mechanosensitive channel of Small conductance [2] [3].

Using GUS reporter gene and quantitative PCR we have studied the pattern and the expression of MSL4, MSL5, MSL6, MSL9 and MSL10 in response to mechanical stimulation of the rosette leaves. Our results show that the expression of the MSL5 and MSL10 is enhanced by a wounding stimulation. This response is restricted to the wounded leave. We have also analysed whether the expression of putative mechanosensitive candidate genes is under the dependence of MSLs channels. Preliminary results obtained on wild type and on MSLs knock out plants indicate a systemic activation of some candidate genes, only in the presence of MSLs channels. Finally, an electrophysiological characterisation of MSL10 reveal new informations in term of biophysical properties of this channel.

Based on these results, we argue on the physiological role of MSLs in aerial part of the plant.

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Keywords

mechanosensitive channel, mechanotransduction, *Arabidopsis*

Modelling of the frequency sensibility of mechanosensing channels

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Abstract

Plants are subjected to a variety of mechanical stimuli such as wind, rains or obstacles encountered during their growth. These macroscopic mechanical loadings are transmitted through the plant motion to the cell membrane. In most of the cases, the resulting cell deformations lead to the activation of mechanosensitive (MS) channels, which in turn transform the mechanical signal into an electrochemical one. Therefore, MS channels are likely to participate into the mechanical sensitivity of the plants.

Classical approaches have focussed on the static case, linking the current generated by the MS channel to a constant membrane tension. Temporal aspects have been used to characterize the different existing states and their transition rates. Models of such system are build on the idea that the different rate constants are modified by the membrane tension. Using this approach, it is possible to reproduce the Boltzmann law of the opening probability of the MS channel with the membrane tension.

However plants may experience dynamical loadings, it is important to understand the dynamical response of MS channels. To investigate this problem, we consider the case of a membrane tension oscillating around an average static tension. We predict the number of open channels (and thus the current) versus the frequency of the tension oscillation.

We will first do the simpler case, where the MS has only two possible states: open and close, with a dependence of the chemical rates with the membrane tension. The response is strongly non-linear with an increase of the current as the frequency increases. This analysis predicts a modification of the sensitivity to the loading rate with the amplitude of the loading. This simple case will be extended to the real case of MsL10 channels, which requests more possible states. The model parameters will be adjusted on data at a given frequency. Then we will investigate in detail the response of the channel to the frequency and we will compare our results with experimental data.

Keywords

mechano-sensitive channels, frequency, model

Response to gravitropic stimulation of poplar stems. Proteome analysis of apical and basal regions

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Abstract

Gravity is a constant force guiding the direction of plant growth. In young poplar stem, reorientation of the apical region is mainly obtained by differential growth of elongating primary tissues. At the base, where elongation is achieved but where the cambium is active, reorientation is due to asymmetrical formation of reaction wood. After 45 min of gravistimulation, the stem showed no reorientation, but one week later, reaction wood was observed at the base of the stem. To determine the molecular mechanisms taking place at the top and base of the stem, after 45 min or one week of inclination, the changes induced in protein accumulation were studied by 2D-PAGE and quantitatively analyzed using image analysis software. Around 300 protein spots were reproducibly detected and analyzed. Forty percent of these proteins showed significant changes after inclination. Mass spectrometry analysis of 135 spots led to the identification of 60 proteins involved in a wide range of activities and metabolisms. Very different patterns of protein expression were obtained according to conditions tested, highlighting the complexity of gravitropic responses. Our results suggest that primary and secondary tissues present specific mechanisms to sense reorientation and to respond to inclination.

Keywords

gravitropism - poplar - proteomics

Using uniaxial stretching to investigate single plant cell rheology and mecano-sensing

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Abstract

Mechanical signals are contributing to many developmental processes in animals and in plants. Plant cell displays very specific mechanical features, notably because of the presence of stiff pecto-cellulosic walls. The anisotropic rigidity of the cell walls, under turgor pressure, allows each cell to grow in a defined direction, thus impacting plant shape and architecture. This mechanical anisotropy seems to be related to the cortical microtubules which are known to serve as tracks for the cellulose synthesis complexes at the plasma membrane. Recent studies have shown that cortical microtubules orientations are correlated with maximal stress direction in plant tissue. However, the qualitative aspect of those initial studies does not allow to investigate further the mechanisms involved in plant cell response to mechanical stress.

Our goal is to investigate quantitatively the process developed by plant cells to adapt to their mechanical environment.

First, we characterize the rheological properties of a single plant cell using a single cell uniaxial stretching device. This setup allows us to determine the rheological properties at the whole cell scale by performing dynamical oscillation tests. First results show a simple relationship between young moduli and viscosity, suggesting that an *Arabidopsis Thaliana* Col0 single cell behaves as a Kelvin Voigt solid.

In parallel to rheometry, we are investigating the effect of externally applied stress on the orientation of microtubules. To this end, an original setup coupling the uniaxial stretching device with total internal reflection fluorescence microscope (TIRFM) allows us to monitor the dynamics of cortical microtubules within a single plant cell when subjected to a calibrated stress.

Keywords

single cell, rheology, mechanical stress, microtubules

Perception of gravity stress in non-statocyte plant cells

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Abstract

Plants are able to perceive gravity stimulation and to respond to this trigger. Several mechanisms have been invoked to explain how plant cells perceive the direction and strength of the gravity vector and statolith based perception is well characterized. However, most plant cells are not equipped with statoliths and it is poorly understood, how they perceive and are able to respond to gravity related signals. Modulation in the synthesis and deposition of the cell wall is a common response to gravity-induced stress in plant cells, and this response is particularly pertinent as it is directed to mechanically counteract the effect of the gravity-induced compression or bending load. To understand how increased gravity acts on cell wall assembly proper we investigated one of the most rapidly growing plant cells, the pollen tube. This cellular protuberance is formed by the pollen grain to deliver the sperm cells to the ovules for fertilization and it can easily be cultivated in vitro. The main metabolic activity of the pollen tube is the synthesis and the deposition of cell wall precursors. Cell wall assembly in this cell is spatially confined to its tip and occurs at extremely high rates allowing for short term experiments. We monitored the effect of hyper-gravity on pollen tube growth, cell wall assembly, and intracellular transport using brightfield and epi-fluorescence illumination. Live cell imaging was enabled by placing the remote controlled microscope in the Large Diameter Centrifuge facility operated at the labs of the European Space Agency.

Sense

Keywords

gravity stress, gravity response, cell expansion, pollen tube

Session ROOT-SOIL

Plant-Soil Mechanical Interactions

How do roots penetrate strong soils?

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Abstract

Soil provides water and nutrients for plant growth, but these can only be exploited if roots can effectively proliferate within the soil profile. Before considering penetration strategies of roots, it may be helpful to briefly consider the soil physical characteristics which challenge root elongation. While much research has been conducted on the effects of water stress, it is mechanical strength in soil that more commonly restricts root elongation. Soils which are dry or have been compacted are mechanically strong and this severely restricts root elongation. It is not widely appreciated that very little soil drying is needed to increase the strength of soil to the point where very little elongation can occur. When this happens roots are thought to rely on structural macropores within the soil.

Roots need to generate a growth pressure to elongate in soil and the measurement of growth pressure is described. It was once thought that differences in growth pressure could explain differences in the abilities of roots of different species or cultivars to penetrate strong soil, however, this is now known to be untrue. Nevertheless, measurements of growth pressure as a function of water stress and temperature have taught us much about the development of growth pressure. The simultaneous measurement of growth pressure and cell turgor has highlighted the role of cell wall loosening in allowing cell turgor to be converted into growth pressure.

Interestingly, the elongation of roots in uniformly strong soil is poor at discrimination between the root penetration ability of different rice cultivars. This has led to the use of wax layer root screens to provide a rapid laboratory assay for root penetration ability. In this test the number of roots that can penetrate a strong layer in comparison with a weak layer is used as an index to compare the ability of different cultivars or species to penetrate strong soil layers. The use of this assay with mapping populations in rice has identified QTLs for root penetration. There is even a commercial rice cultivar that has been bred for its ability to penetrate strong layers. One of the main root factors which confer good root penetration ability on roots is a high bending stiffness which is primarily determined by root diameter. The wax layer assay is a blunt tool and root penetration is also affected by fine scale gradients in soil strength as well as the angle of root penetration. Both of these geometrical factors can have a greater effect on root penetration than genotype. In wheat genotypic differences in root penetration are only expressed when the angle of root incidence is near vertical. In rice if the strength increases with distance over a few millimetres, root penetration is much higher in comparison with an abrupt increase in strength.

Finally, the relative importance of the factors discussed in the presentation is put into a wider context. Root proliferation is triggered by nutrient availability, although the availability of immobile nutrients is affected by soil strength. There is also conflicting evidence on the effect of soil structure on plant growth which is possibly explained by different types of crop management. It is possible that soil structure may be less important for winter crops grown in the UK compared to spring sown crops.

Keywords : root, soil, soil strength, QTL, cereals

Strategies of root growth facing a pore and development of root radial forces measured by photoelasticity

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Abstract

The growth of roots largely affects and reorganizes the porous or crack networks of soils and substrates in natural and urban environments. Though, if axial root growth was well studied, not much data exists on the impact of radial root growth. Yet, all this data is necessary for developing accurate models of soil/root interactions.

To study such coupling we designed an original technique based on photoelasticity. By using a time lapse approach, we examined root penetration of heterogeneous medium in a model system made of a single pore between two photoelastic disks. Root growth was laterally impeded by modifying the gap width between disks (d in mm), thus simulating the impact of soil pore size. Moreover, as the disks became optically birefringent when submitted to a mechanical loading, we could infer from the development and locations of black fringes in the photoelastic disks the radial forces exerted by the root entering the gap. In the experiments we used primary roots of chick pea (*Cicer arietinum* L.) seedlings and imposed d comparable to the root's diameter and ranging from 0.5 to 2.3 mm. Changes in morphology and forces were recorded by time-lapse imaging every 24 minutes up to 5 days.

The probability of root entering the gap depended on the gap size but was also affected by circumnutation. Indeed, contrary to most experiments, our set up was designed to radially impede the root and to avoid blocking the axial root growth. Then, the root was free to reorient in a way very similar to what is observed in nature in textured soils as well as in artificial environments (roots growing inside cracks and fissure, along pipes, etc.). Sometimes the root did not even enter the gap though large and was experiencing negative gravitropism. For roots passing through the gap, morphological parameters were not affected by the radial constraint. In particular, mean values of diameters outside the gap zone and growth rate were the same as for control roots but their variance increased. Inside the gap zone, outer cortex cells were compressed but the central cylinder was unaffected. Radial forces were increasing with time but no force levelling was observed even after 5 days. The radial force was related to the root strain in the gap and an estimation of radial stress gave a value comparable to turgor pressure.

Root-soil

Keywords

radial force development, root growth, photoelasticity, mechanical stress, *Cicer arietinum* L. (chick-pea)

Effects of environmental stress on root biomechanics

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Abstract

Increasing interest in the contribution of roots to stabilising soils has necessitated an increase in knowledge of the mechanisms and processes by which roots interact with soils within differing environments. It is known that soil structure and other soil physical properties impact root growth, less is understood on how abiotic stresses affect the root biomechanical properties such as strength and elasticity. Civil engineers are increasingly looking for 'green' alternatives for the stabilisation of soils but the adoption of eco-engineering approaches is hindered without the availability of accurate models to predict plant root contributions to soil stabilisation. Current models use root strength and, more recently, root stiffness (elasticity).

The physical environment is known to elicit responses in plant roots, waterlogging for instance increases air spaces within roots through the development of aerenchyma whilst in compacted soils root elongation rates are slowed and root diameter increases. From an engineering perspective such changes will influence both the depth within the soil that roots may penetrate and also the contribution of the roots to soil stabilisation. Seminal root length of barley (*Hordeum vulgare*) grown in compacted soil and waterlogged soil was reduced by 70% and 42% respectively with nodal root length increasing in waterlogged soil by 291% when compared to plants grown in optimum conditions. Predictions of root strength were also significantly improved when the relationship between root diameter and strength was predicted for each root type, typically root strength models are derived from a random sample of roots without reference to the type of root. Currently work is underway to investigate the effects of aerenchyma on root strength and elasticity, results from this study will be discussed in the presentation.

Data presented highlights the importance of increasing our knowledge of the effects of abiotic stresses on root biomechanics. It is key to understand the contributions of internal root structures on strength and elasticity of roots to improve existing reinforcement models and increase both the adoption and uptake of eco-engineering strategies to control natural soils.

Keywords

roots, soil, abiotic stress, biomechanics, aerenchyma

Mechanical stress on roots: an environmental cue central to root: shoot coordination and plant survival

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Abstract

Roots anchor plants to soils and forage for nutrients and water. They also act as exquisite mechanical sensors. Roots are extremely sensitive to the mechanical resistance they need to overcome to push their way through the soil, with its constant variations due to soil drying and re-wetting, or of course compaction. The perception of increased mechanical resistances at the root tip triggers a local signalling that causes roots to elongate more slowly, change path and shape, and alters cellular function. It also triggers a very fast and effective systemic signalling to aerial meristems and leaves, and notably stomata, causing conservative growth and water use. Remarkably these aerial responses occur within minutes and even in the presence of still plentiful water and nutrients. This led us to propose root mechanical stress as a cue to plants of impending drought and restriction of soil resources.

We are investigating the genetic determinants of the perception, signalling and short-term responses to root mechanical stress. We will present some of the results from this work and highlight components that appear central to the coordinated development and function of roots and leaves and are likely to play a key role in their fine-tuning to exogenous mechanical stimuli.

Keywords

Root mechanical stress Perception Signalling Genetic determinants Root: shoot coordination Root development Stomata

Using a discrete model of root_soil interaction to quantify the protection of forests against shallow landslide and rockfall hazards

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Abstract

In mountainous areas, forests may hold a protection function against natural hazards. The presence of trees may prevent the hazards to happen or reduce their magnitude. Quantifying this protective effect is a complex task for forest managers given the variability of the physical processes governing the interaction between the trees and the different natural hazards. To evaluate the influence of tree anchorage in these processes, a model of tree root system/soil interactions under static and dynamic mechanical loadings has been developed. The model has been used to analyze the influence of tree anchorage on the protection against landslide and rockfall hazard.

For shallow landslides, the roots system provides additional resistance to the shear loading of the soil potentially inducing a shallow landslide. For rockfall hazard, the energy of a rock before the impact on a tree is significantly dissipated by plastic and frictional processes in the tree anchorage. A numerical model of root system/soil interactions, based on the Discrete Element Method (DEM), has been developed to identify the physical processes involved for both hazards. The DEM is an efficient approach extensively used in the field of soil mechanics. The soil is modelled as an assembly of rigid locally deformable spheres interacting at their contact points. The roots are either modelled as deformable cylindrical elements embedded into the soil for structural roots or by additional cohesive contact forces between the soil particles for fine roots. This approach allows integrating the main local physical processes between the roots and the soil. Indeed, the roots and soil particle being able to move independently one to the others, the soil additional resistance due to roots tensile and bending strains as well as to root soil cohesive and frictional interaction forces are integrated.

For shallow landslides, direct shear tests of rooted and non-rooted soils were modelled to identify the processes involved into roots reinforcement depending on the soil type and the architecture of the root system. For rockfall hazard, the energy dissipated by the impact was assessed by measuring the difference in the impacting rock kinetic energy before and after impact on the tree trunk. The role played by root anchorage was analyzed by comparing the energy dissipated during the impact of a rock on a rigidly anchored trunk or on a trunk anchored to a model root system embedded into the soil.

Keywords

root system, roots/soil interaction, natural hazards

Root phenotyping

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Abstract

Can the size of a root system be estimated by its electrical capacitance?

There is much interest in the use of capacitance measurement to estimate the size of intact root systems. The equipment required is cheap and easy to apply in field and laboratory studies. Many studies have reported good correlations between capacitance and root mass, and a linear relationship between these variables is predicted by a model that has been proposed by Dalton (1995). Two studies were conducted to test the model on hydroponically grown barley (*Hordeum vulgare* L. cv. Optic) and on barley grown in soil, respectively. In the first study a range of treatments was used that included: raising whole roots out of solution; cutting roots below the solution surface; and varying the distance between plant electrode and solution surface. In the second study the plants were left to dry before the soil containing the top or bottom of the root system was selectively wetted. Good correlations were found between capacitance and mass for whole root systems in solution and in soil. However, excision of submerged root parts had negligible effects on the observed capacitance. Overall, capacitance correlated better with the root dimensions at the solution surface, than with root mass. Good correlations were also achieved between capacitance and the sum of shoot circumferences at the soil surface but only after moistening. The capacitance was lower and the correlations poorer and when the top soil was dry. In both studies the bulk of the root system did not influence the capacitance. These findings indicate that previously observed correlations between root mass and capacitance are circumstantial. They arise because plant dimensions at the soil surface are correlated with total root mass. A new model is proposed.

Root-soil

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Keywords

phenotyping, root, soil, root growth, capacitance, barley, electrical circuit

Root Growth in 2D Wet Granular Media Modified By Intrusions

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Abstract

Plants, like all living things, require water to survive. In the context of soil-water retention, methods like particularly the use of superabsorbent hydrogels as additives are common techniques. Although the effects of these chemical additives on hydraulic properties in wet granular media have already been extensively studied, so far little has been understood particularly on its direct relation to root growth. While also much has also been known about water flow in soil, there has been limited understanding of the coupling of roots with fluxes such as evaporation. Using a controlled visual set-up of a 2D model system consisting of monolayer glass beads, experimental investigations on the physics of real root systems have been undertaken particularly on the growth of roots in a model soil subjected to various physical and chemical treatment conditions. Root penetration in granular media responds to changes in water distribution. Preliminary results have shown that solid physical intrusions (e.g. a square rod) added into the medium generates a root interaction response as the roots actively find the intrusion. This eventually induces preferential tropism of roots deeper into more saturated regions in the soil for greater efficient access to water that results to a more robust lifetime. These results are a first step in gaining an understanding of both complex water transport phenomenon and its effect on root growth mechanisms.

Root-soil

Keywords

intrusions, water retention, root growth, granular media, tropism

Session TOOLS

Metrology and Softwares for plant biomechanics and
mechanobiology

The 3D magnetic digitizing: a tool to measure 3D tree structure and its dynamics

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Abstract

The 3D structure of a plant results from its life history and could be related to its physiology and its interaction with environmental physical factors (wind, temperature, and irradiation) and available resources (light, water). Thus assessing the 3D plant structure could give relevant information about the way a plant responds to long-term and short term external environmental fluctuations. The 3D digitizing associated with a dedicated software (PiafDigit) developed in our lab enable to measure plant architecture (geometry, topology, typology) associated with any organ properties (for instance: color, size, etc ...). This device was successfully applied in plant ecophysiology to assess, using 3D virtual plants, the relationships between tree structure and spatial variability in light interception by leaves (Willaume et al, 2004), in tree transpiration and photosynthesis (Sinoquet et al., 2001), and in fruit temperature dynamics (Saudreau et al., 2011). More recently it was used to describe accurately the 3D mechanical structure of complex trees as an input to mechanical calculations using the Finite Element Method (Rodriguez M. de Langre E, Moulia B. 2008). As 3D digitizers can be used in tracking mode to provide 3D location of organ at different time, this tool was more recently used and adapted to measure plant structure dynamics in relation to plant-wind interactions (Rudnicki, M., and Burns, D., 2006, de Langre et al., 2012). Based on practical 3D static and dynamic structures measurements; this communication aims at showing the device: a 3D Polhemus Fastrack Long Range (Colchester,Vt., USA), which generates a 3D magnetic field and then allow to determine locations of sensors in the 3D-space field, its advantages and drawbacks.

Tools

References

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Keywords

3D Digitizing, Plant, Architecture, Dynamics, Mock-up

Terrestrial LIDAR: a tool to scan tree geometrical architecture

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Abstract

Terrestrial-LiDAR scanners are instruments that enable the non-destructive, rapid and precise digitisation of physical scenes into three-dimensional (3D) point clouds. Historically, T-LiDAR technology has been used for industrial and civil engineering applications, for example to digitise the external surface of buildings and archaeological sites. More recently T-LiDAR has been applied to forest inventory measurements (plot cartography, species recognition, diameter at breast height, tree height, stem density, basal area and plot-level wood volume estimates) and canopy characterisation (virtual projections, gap fraction and three-dimensional foliage distribution) (see [1] for a review). In our group these techniques have been extended to the assessment of the structure of a plot of adult standing trees, for the purpose of biomechanical studies in forest.

T-LiDAR scanners provide non-destructive, accurate and extensive information about forest structure that is difficult or impossible to obtain using traditional methods. An example of the 3D scanning and reconstruction of a small plot of trees in a forest will be given, providing valuable information about the structure of neighbouring trees, as well as their crown interactions.

During PlantBioMech2012, a demonstration of the use of our terrestrial LiDAR scanner (FARO Photon 120) will be given.

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Keywords

3D Digitizing, Tree, Forest, Architecture, Mock—up, Demo

A Robust and non-intrusive method for velocimetry fields measurement.

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Abstract

There is a crucial need of non intrusive methods to describe and quantify the complex motion of plant structure induced by fluid flow. Image analysis methods constituted elegant tools to measure the spatio-temporal vector field of the velocimetry of the motion of the different plants parts.

The aim of this poster is to present two image analysis methods which have been compared on the interaction between tree and wind in open field condition. Some advantages and drawbacks have been associated to each methods. The Particule Image Velocimetry method (PIV) is a block matching method since it is based on the computation of the cross-correlation between image patches. PIV allow to access to dense velocimetry fields but displays some peak locking value when the pixelisation of the image is important compare to the patch dimensions. This method is often used, in fluid mechanics, with artificial markers seeding in the flow field and controlled laser lightning. For plant motion, the use of natural foliage texture as marker has ever been used with success to study honami phenomenon. PIV method needs important computation time essentially dedicated to filter vector fields. The other method proposed by Kanade, Lukas and Tomasi (ST+KLT) is a much faster method because of the linearization of the matching equation. However, the linearization produces critical instabilities when image texture is poor. Thus, Shi and Tomasi have introduced pre-treatment algorithm to select “good features to track” making ST+KLT not 100% dense.

The metrology of both methods has been tested for different foliage texture (dense, Intermediate, null) and wind intensity (High, Intermediate, Inertial). The ST+KLT method proved to be more accurate and robust than PIV one. Moreover, the metrological assessment of ST+KLT method is independent of foliage texture, wind velocimetry and light gradient intrinsic to outdoor scene.

Thus, ST+KLT method constitute a good quantitative image analysis method to measure velocimetry fields induced by fluid flow on complex structures such as trees.

The user-friendly versatile software Kineplant-CRToolbox coded by J. Diener is now freely available at : <http://sites.google.com/site/crtoolbox>

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Keywords

wind, PIV, tracking method, biomechanics, motion

CR - KinePlant toolbox

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Abstract

There is a crucial need of non intrusive methods to study the complex motion of plant structure induced by fluid flow. Image analysis methods constituted elegant tools to measure the spatio-temporal vector field of the velocimetry of the motion of the different plants parts.

We present here the CR - KinePlant toolbox for Matlab® which provides a set of standard algorithms to process experimental image data on plant-wind interaction. This toolbox is designed with a scientific workflow approach: The whole data processing is organised as a series of algorithmic manipulations. Each tool configuration is independent from its computation, and the workflow is considered as a processing protocol, allowing sharing and reproduction.

This toolbox is organised around two main concepts: data and tools. Data can be of several kinds for which the toolbox provides reading and writing interface. The main handled types are images, videos, optical flow sequences and their modal decomposition. Tools are algorithms which produce output data from input data, using a specific parameters set. The main tools are:

- PIV (Particle Image Velocimetry): uses the free MatPIV toolbox which compute video motion flow using image correlation
- KLT: the Lucas-Kanade tracker associated to the Tomasi-Kanade features detector
- BOD (Bi-Orthogonal Decomposition): computes the spatial and temporal modes of motion sequences (obtained using either KLT or PIV).

Tools

PIV and KLT are complementary methods to estimate motion data from video. The first, used in fluid mechanic with complex experimental protocol, computes dense velocimetry field. However, the required data quality might not be accessible in practical condition when studying plants dynamics. KLT, by first selecting the most suitable features to track, provides robust motion estimates, but required an interpolation step to produce dense flow field. The workflow is organised through a project mechanism, relating data and configured tools. It provides a complete set of user interfaces: intuitive configuration panels for all tools and a player interface that allows visualization of the input video together with all computed data.

The CR-KinePlant Toolbox is freely available at: <http://sites.google.com/site/crtoolbox>

Keywords

PIV, tracking method, Workflow, Toolbox

X Ray computer tomography: a new tool for retrospective analysis of the spatial distribution of tissues in large trees.

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Abstract

Tree biomechanics studies often require the analysis of tissue distribution – sapwood versus heartwood, branching patterns, reaction wood, tree ring – related to biophysical and growth processes (sap conduction, support of weights in a branching system, motion by gravitropism, primary and cambial growth). In natural forest conditions and mature trees, analyses need specific tools to acquire data with quite high throughput along large stems and wide number of trees according to natural variability.

This poster aims at presenting the facility of X Ray computer tomography developed in our research group on wood quality. X-ray computer tomography (CT) is a powerful methodology which enables to compute 3D maps of objects based on X-ray attenuation. The linear attenuation value of each voxel belonging to the object is computed from X-ray projections through the object, in several directions. Our device is a 4-slice medical X-ray scanner (BrightSpeed Excel by GE Healthcare) acquired in 2007 and designed for medical purposes. It is capable of processing 1.50 m-long pieces with a diameter of up to 50 cm and a maximal weight of 180 kg, in one pass. The system almost instantaneously delivers a volumetric reconstruction of the sample in the form of a stack of 512 x 512 pixel slices (i.e. * 0.6 mm-wide pixels for a 30 cm-diameter piece) with a slice thickness of 0.6–10 mm. It has been calibrated to measure accurately variations of wood density [1]. It is currently used for several applications, with appropriate softwares of image analysis developed in our group : heartwood versus sapwood extension [2], primary growth reconstruction from pith density analysis [3], branching pattern analysis including rameal traces in broadleaf trees [4]. Work in progress concerns the automatic detection of tree rings. Cartography of reaction wood is also a promising further application. However, these last applications are not yet operational in a wide range of species.

Tools

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Keywords

wood, tissue, large trees, X ray computer

The benefits of Atomic Force Microscopy for characterizing topography and mechanical properties of plant tissues

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JPK Instruments AG

Abstract

In the recent years, advances in Atomic Force Microscopy (AFM) under biological conditions have opened this technique to the field of life sciences. AFM is a multipurpose technology which is capable of much more than simply 3D imaging. Interaction forces ranging from single molecule unbinding to cell adhesion and analysis of surface and mechanical properties make AFM a key technology in life sciences (e.g. review [1]). Due to the findings that topography, roughness and mechanical properties of the extracellular matrix are crucial parameters influencing cell adhesion/motility, morphology and mechanics as well as the development of stem/progenitor cells, nano-mechanical analysis of cells increasingly gains in importance in different fields in cell biology, like cancer research [e.g. 2-4] and developmental biology [5]. The growing acceptance of AFM as a unique tool to quantify all these biophysical characteristics of animal cells and tissues can also be found in the field of plant development (e.g. [6,7]).

We provide a tailor-made AFM platform with an extended vertical range (100 microns) that meets the spatial requirement for comprehensive investigation of living cells and tissues. Combining these remarkable abilities with advanced optical techniques allows for complementary characterization of a variety of biological samples.

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Keywords

biomaterials, atomic force microscopy, life sciences

JRobust: an open - source application for analysis of AFM force curves

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Abstract

The Atomic Force Microscope (AFM) is a versatile tool for investigation of the topography and elastic properties of biomaterials. Typically, elastic properties are not measured directly, but calculated from force curves. Analysis of force curves poses significant challenges, affecting its efficiency and reliability. The key obstacles stem from limited applicability of simple contact mechanics models to biomaterials. The most commonly employed Hertz model of indentation requires that the sample is thick, linear elastic and homogenous, assumptions that are rarely satisfied for cells or organelles. Biological samples often exhibit nonhertzian behavior, which hinders determination of the contact point and extraction of Young's modulus (Lin et al 2007). In consequence, researchers are forced to rely on the manual method. The manual method, however, suffers from poor repeatability. It is also time-consuming, which makes it impractical for all but moderately-sized datasets. Because large sets of curves are collected in AFM experiments, it is crucial to develop and implement a fast, automated method, suitable for analysis of curves exhibiting pronounced deviations from the contact models.

We propose a new approach to automated analysis of force curves, employing High Breakdown Estimators, robust regression estimators, developed for analysis of data contaminated by observations grossly deviating from the assumed model (Rousseeuw 1984, Hawkins and Olive 1999). The procedure allows to obtain accurate estimations of Young's modulus from curves recorded on thin or inhomogeneous samples, as well as samples that exhibit strain stiffening. Its accuracy is demonstrated for sets of force curves recorded on isolated chloroplasts and prostate cancer cells. The procedure was implemented as part of JRobust, our free, open – source Java application for analysis of force curves. The application provides a convenient graphical interface and can be used both for manual and automatic processing of multiple curves. It calculates Young's modulus, pointwise Young's modulus (Costa et al 2006), the linear elastic range and the adhesion force. JRobust features a number of preprocessing tools, including several smoothing filters. Force – indentation and pointwise Young's modulus - indentation plots are reported to the user after each computation. Style of plots can be customized in an easy, interactive way. The numerical results can be shown in histograms and analyzed statistically. JRobust is a concurrent program, so it can make the most of multicore and multiprocessor computers, allowing for fast processing of large datasets. It can be run on all popular operating systems, including Windows, Linux and Macintosh.

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Keywords

atomic force microscopy, force curve, elasticity, automatization

Session TREE

Trees and Wood Biomechanics

Is mechanics an important component of tree architecture?

T. FOURCAUD

Tree biomechanics, AMAP, Cirad, Montpellier, France

Abstract

The complex structure of trees results from its growth and developmental history (referred to as ontogeny) driven by both endo- and exogenic processes. From the several external constraints that can affect tree form, we will make the focus on mechanical loading, e.g. gravity forces and aerodynamic drag. This talk will include three parts. We will first give a definition of tree architecture and provide the fundamental elements that are used to represent, analyze and model tree growth. In a second part we will present some recent advances in tree structural mechanics that aims to study the influence of tree structure (at a given developmental stage) on its mechanical response to external loads, including crown sway in the wind and root anchorage. In the last part, we will present the main concepts of the biomechanics of tree growth, which considers the feedback between tree architecture (i.e. the time evolution of tree structure) and its mechanical history, and draw some research perspectives in this topic.

Keywords

tree, architecture, structural mechanics, modeling, wind, anchorage

The effect of leaf nodes on stem biomechanics in two tree species

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Abstract

The effect of leaf nodes on stem biomechanics was examined in two woody species, *Juglans californica* and *Cercis occidentalis*, the former with spiral phyllotaxy and the latter with distichous (2-ranked) phyllotaxy. Bud and leaf gaps represent interruptions in the stele that are associated with vascular traces that lead to the bud and leaf. Because the parenchyma cells in the bud gap are very thin walled, it was expected that they would lower the xylem density and reduce flexural stiffness, modulus of elasticity (MOE) and modulus of rupture (MOR). To test this, fresh 8 mm diameter stem segments, with highly variable node frequencies, and of average age 3.44 years, were cut to 160 mm length for mechanical tests. We did 4-point bending tests using an Instron Mechanical Testing Device (Model 3342; Instron, Canton, Ma., USA). Density of xylem tissue samples was measured by displacement. In *Juglans*, the MOE and MOR were inversely proportional to node frequency per mm, as expected. However, these relationships were even stronger for density-specific MOE and density-specific MOR. Remarkably, xylem density was positively correlated to node frequency per mm. Comparisons were made between branch stems of adult trees and resprouting stems following wildfire. Adult stems had significantly greater node frequency and lower MOE and MOR than stems of resprouts. No significant difference occurred in the MOE when parenchyma cells in gaps were removed by drilling with a 3 mm drill bit. Artificial nodes were also created by drilling new 3 mm holes through the stele of the 160 mm stem segments, in a manner mimicking the spiral phyllotaxy of *Juglans*. This treatment had only a slight effect on MOE, much less than the impact of real nodes. In *Cercis*, which has 2 ranks of leaves on opposite sides of the stem, the flexural stiffness and MOE was much greater in the plane perpendicular to the nodes than in the plane parallel to the nodes. Sub-segments of the stem xylem containing the node had significantly greater density than either the sub-segment opposite the node or the internode sub-segment. Based upon anatomical analyses of both species, the xylem fibers surrounding the gaps were highly convoluted and compact, resulting in greater xylem density but allowing for high flexibility. Thus both the placement (phyllotaxy) and frequency of nodes on a woody stem have a dramatic impact on stem biomechanics at least several years after the leaves have been shed from the plant.

Tree

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Keywords

node, xylem density, Young_modulus, phyllotaxy

Wind on trees: Is Leonardo's rule the best design?

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Abstract

In his notebooks, Leonardo da Vinci observed that “*all the branches of a tree at every stage of its height when put together are equal in thickness to the trunk*”, which means that the cross-sectional area of branches is conserved across branching nodes. The usual explanation for this rule involves optimal transport of sap, but this argument is questionable because the portion of wood devoted to sap transport varies across species and can be as low as 5% in the biggest branches.

It is proposed here that Leonardo's rule is a consequence of the tree skeleton having a self-similar structure and the branch diameters being adjusted to resist wind-induced loads. To address this problem, a continuous model is first considered by neglecting the geometrical details of branching and wind incident angles. The robustness of this analytical model is then assessed with numerical simulations on tree skeletons generated with a simple branching rule producing self-similar structures (determinist or stochastic). These two models give identical results and agree with the rule first stated by Leonardo da Vinci.

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Keywords

Leonardo_rule, Fractal, Constant-stress model

Characterization of spatial and temporal evolutions of green wood mechanical properties during maturation

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Abstract

Trees can modify the orientation of their trunk and branches by asymmetrical production of reaction wood. Biomechanical models which simulate gravitropic movements exist, but recent studies show that they cannot fit the righting-up movement of young, fast growing poplar trees at the intra-annual scale. This discrepancy could be explained by the fact that cell maturation is not considered in these models. However the maturation phase is yet not well known in terms of kinetics. The aim of this study is to provide knowledge about the kinetic of maturation from a mechanical point of view.

A large-scale experimental campaign has been carried out to achieve this objective. Several *Populus cv I4551* undergoing the same gravitropic reaction have been felled regularly during the whole growing season. Samples cut from a same tree but at different radial positions provide spatial information. Comparisons between trees felled at different time along the season give temporal evolutions.

Infradensity measurements, longitudinal cyclic tensile tests and bending tests have been performed on these samples cut from both tension and normal wood sides. Tensile test samples are thin lamellas of 200 µm thick in radial direction. Cyclic tests reveal a complex mechanical behaviour, in particular tension wood lamellas exhibit a strain-hardening behaviour whereas normal wood lamellas exhibit a strain-softening behaviour. We found a linear relationship between stiffness and strain which enables us to characterize each sample despite its strain-dependent behaviour. Bending tests have been performed on larger specimens (1.5 mm thick). In comparison to tensile test on thin lamellas, these thick samples exhibit a linear behaviour so we can directly measure a modulus of elasticity. This difference in behaviour highlights important size effects in the mechanical behaviour of green wood.

The analysis of tensile and bending tests leads to similar conclusions in terms of kinetics of maturation. The longitudinal rigidity increases radially from the cambium to a peak located at a distance of 2.5 mm from the cambium, and then it decreases until growth ring limit. This peak is also observed temporally speaking 3 weeks after cell creation. That means that a single cell have a rigidity which first increases with time, and then decreases. At the same time, infradensity is steady after about only 1 week. These results show that cells undergo a complex maturation process which seems to be active even after cell wall deposition.

Keywords

mechanical properties, maturation, intra-ring, green wood, tension wood

General biomechanics and functional morphology of *Dracaena marginata*

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²Competence Networks Biomimetics and BIODON

Abstract

Although monocotyledons do not develop wood like softwood and hardwood trees, many monocots show arborescent growth forms (e.g. Pandanaceae, Dracaenaceae or Arecaceae). The aims of this study are to investigate the structural organisation and biomechanics of the arborescent monocot *Dracaena marginata* with focus on the organisation and integrity of their ramifications. Their shoots are hierarchically organized, consisting of isolated lignified vascular bundles (fibres) in a partly lignified parenchyma (ground tissue). These fibres run in a regular spiral manner within the main stem and the branches whereas they form a densely packed, irregular and intertwined network within the stem-branch-transition zone. Here, newly formed branch-tissue is connected to the stem by clasping around the main shoot. In transverse- and cross-sections stem and branch tissue can be easily distinguished. Biomechanical investigations of predefined sections of stem, ramification and branch have shown a gradual decrease of the tensile Young's moduli for individual fibres as well as for tissue samples comprising both fibres and ground tissue with increasing height and proximal position within the cross-section. The stress-strain state of the ramification upon quasi-static loading of a lateral branch was assessed by optical 3D-deformation analysis using a GOM Aramis system by longitudinally cutting the ramification in half. Thereby a clear view on the in-plane strain distribution and intensities within the ramification is obtained. Upon quasi-static loading of the ramification, different zones of strain-concentrations can be observed in the branch-stem transition region. These results suggest the existence of 'weak' mechanical zones and can thus be correlated well with findings of earlier studies on fracture mechanics of monocot ramifications that show three distinct failure modes.

Keywords

Biomechanics, ramification, monocotyledons,

Longitudinal growth stresses in trees: analytical models and functional implications

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Abstract

During growth, trees develop mechanical stresses of high magnitude having a particular distribution across the sections of stems and branches. These growth stresses result from the cumulated effect of the loading associated to the increasing weight and the generation of maturation stress at the tree periphery. Interest on this question is motivated by both its technological implications (deformation and cracks in sawn products) and the comprehension of its biomechanical function in the living tree.

In this presentation, new analytical developments and their functional implications will be presented. As an extension of the well-known Kübler's model, simple analytical models were developed to calculate the field on longitudinal growth stresses in stems. Different canonical cases are considered: (i) a straight axisymmetric trunk, (ii) a branch that bends without reacting, and (iii) a stationary tilted stem (i.e. a stem keeping its shape constant during growth). The stress field resulting from growth in these cases will be shown, using realistic parameters taken from various literature sources. These parameters define how the stem size, weight and maturation stress change during tree growth. In order to validate these models, simulated stress fields will be compared to measured patterns of residual strains. Finally, the results will be discussed with respect to their functional implications. Three functions of growth stresses can be distinguished: the “motor” function enabling stem to re-orient in response to disturbance, the “posture control” function enabling stems to keep a constant shape during growth by counteracting the effect of gravity, and the “skeletal” function related to the consequences of pre-stressing in terms of resistance to external bending loads.

The conclusion enhances the fact that growth stresses in stationary tilted stems (e.g. a branch or tree at a forest border) are asymmetric, and that this asymmetry is adapted to optimize the resistance against wind loading.

Keywords

Growth stress, Tree, Branches, Bending strength, Model

Factors affecting the fracture properties of branches

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Abstract

The fracture properties of wood are dependent on its unique anisotropic structure and mechanical properties. We have already shown that the ways in which branches break should depend on their wood density and anatomy. This affects how orangutans and other great apes build their nests. The properties of the wood also affect the ways in which it may be utilised by man. It is shown here that the ways in which wood may be split depend strongly on the distribution of growth rings, vessels and rays, while there is an optimal angle at which branches should be attacked with an axe to cut through it with minimum effort.

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Keywords

Branches, wood, fracture, splitting

Longitudinal and tangential maturation stresses in Eucalyptus plantation trees

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Abstract

The postural control of trees is ensured by the generation of asymmetric longitudinal stresses around the circumference in the newly formed wood layer during the maturation process. In normal and tension wood, these longitudinal (L) tensile stresses are associated with tangential (T) compressive stresses. This study aims at assessing the relationship between L and T maturation stresses, in order to discriminate between hypothetical micromechanical models of maturation stress generation at cell-wall level.

In this study, the strain during the release of maturation stress along L and T directions (RLMS and RTMS) were measured at breast height on 5 positions around the circumference of 30 *Eucalyptus nitens* trees. Experiments were performed in a 17 years-old plantation on trees having DBH within a range of 18-28 cm. Up-right trees as well as tilted trees were selected in order to include various biomechanical situations. These measurements also enable evaluation of the Poisson's ratio of wood.

Results show that all trees produce asymmetric RLMS around the periphery but with a high between-trees dispersion of the mean RLMS level: the maximal RLMS of some trees was in several cases found lower than the minimum of some other trees. Analysis of the relation with tree diameter indicates that the higher the growth rate, the lower the mean RLMS in the trees. Moreover, the difference between the maximum and the minimum RLMS within a tree decreased when growth rate increased. Measurements also indicate a clear relationship between the magnitude RLMS and RTMS, even after accounting for the Poisson effect: the higher the tensile longitudinal stress, the higher the tangential compressive stress. This relationship is strong at the between-tree level and could be detected at the within-tree level. These results will be analysed in relation with wood microstructure and the consequences for tree biomechanics will be discussed.

Tree

Keywords

longitudinal maturation stress, tangential maturation stress, growth rate

Why do all trees break at almost the same wind speed

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Abstract

Lodging is the loss of vertical position of an erected plant. There are two principal types of lodging: “root lodging” when the root anchorage rotates and “stem lodging” when the stem breaks. One of the main causes of lodging is the wind. It has been measured after the numerous recent storms in France that the wind speed necessary to cause tree lodging is weakly dependent of tree species, age and size: almost all trees fail for a wind speed exceeding 40 m/s. The aim of the present study is to understand this universal critical wind speed.

The root system of trees may be weakened by many factors (fungies, excess of water in soil, engine wheels in human planted forests, rocky soil) and those factors increase the sensibility for root lodging and then decrease the critical wind speed. As we are looking for a universal critical wind speed, we studied the case of trees with infinite rigidity of roots and only considered the case of stem lodging.

We conducted experiments on brittle rods (wood, graphite and glass): inducing mechanically a longitudinal curvature to those rods we were able to break them and measure the critical longitudinal curvature for a given material of a given geometry. The dependance of the critical longitudinal curvature is predictable for a rod of a given material and a given geometry.

In the case of trees, this longitudinal curvature is caused by wind pressure on the tree. Applying our experimental results to the case of real trees geometries, we are able to predict a critical wind speed for stem lodging. We find a low dependance with trees characteristics, which is consistent with experimental observations.

Keywords

stem lodging, elasticity, brittle material, critical wind speed

The bending strength of tree stems: towards a model that accounts for the pre-stress field and the post-plastic behaviour of wood

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Abstract

Trees stems are known to be pre-stressed structures. The field of pre-stress (usually referred to as growth stress) within a section results from the superposition of two kinds of stresses: support stress resulting from the increase in tree weight, and maturation stress set during the formation of new wood layers. Analytical and numerical models have been developed to simulate the stress field within a stem as depending on biomechanical parameters such as the height, mass and lean angle of the stem, its growth rate, the shape of cross-sections, and the heterogeneity of wood properties (including elasticity, visco-elasticity and maturation stress). These models, as well as direct observations, show that in most cases the core of the stem is subjected to high compressive stress, while the periphery is under tensile stress. They also show that a variety of stress patterns can result, depending on the particular growth history of a tree.

The tensile maturation stress at the periphery is known to improve the bending strength of the stem by compensating for the relatively low compressive strength of green wood. This is the reason why a tree stem has higher bending strength than a sawn beam of equivalent dimension, shape and mechanical properties. However, evaluating the extent of this strength improvement is not trivial, because the complex post-elastic behaviour of green wood has to be taken into account.

We developed and implemented a mathematical model that computes the bending strength of a stem from parameters defining the rheological behaviour and initial state of wood across a section of any shape. This first formulation makes a number of approximations. It is unidirectional and only considers compressive and tensile stresses (shear stress is neglected). The behaviour of wood is assumed damageable elasto-plastic in compression and elasto-fragile in tension. Based on simulations, the influence of various kinds of growth stress patterns on the bending strength of tree stems will be assessed, and the biomechanical significance of these relations will be discussed.

Keywords

tree stems, bending strength, growth stresses, plasticity, computational mechanics

Components testing of hazel forks

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Abstract

The ability to accurately predict the load-bearing capacity of tree forks would improve tree surveying, tree surgery techniques and the biomechanical modelling of a tree's structure.

In this study, a components testing method was used to investigate the strength of forks of hazel (*Corylus avellana* L.). Intact forks, and ones in which either central or peripheral xylem lying under the branch bark ridge at the apex of the forks had been removed, were subjected to tensile pulling tests. The strength of forks was compared with that of the arising branches by carrying out a three-point bending test on the smaller arising branches of the intact specimens.

All forks failed in tension, splitting between the arising branches. Removing the centrally-placed xylem, constituting approximately a fifth of the width of the fracture surface, reduced tensile strength by around 33%, while removing the outer four-fifths reduced strength by 50%. Intact forks had around 74% of the breaking strength of the smaller arising branch.

It is concluded that the tensile strength of the centrally-placed xylem at the apex of a tree fork is a critical strengthening component. This helps to explain the weakness of forks with included bark, which lack this component. However, co-dominant forks without included bark do not necessarily represent a significant flaw in the structure of trees.

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Keywords

bifurcation, components testing, *Corylus avellana*, hazel, included bark, tensile pulling tests, tree fork

Detecting wind acclimation in trees in the urban forest using dendrochronology

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Abstract

Consistent with the Thigmomorphogenetic Theory, altering the wind environment of a tree will potentially induce a change in growth patterns in the trunk of the tree, translated into changes in annual tree ring growth increments. The change in growth increment will be a response of the tree to increase its cross sectional area in the direction of the new or increased mechanical load. This study was initiated to determine if mature trees growing in the urban forest of the Presidio of San Francisco, California, U.S.A. could respond to an altered wind flow pattern resulting from the removal of mature trees downwind of the stand. The U.S. military planted radiata pine (*Pinus radiata* D. Don.), and Monterey Cypress (*Hesperocyparis macrocarpa* (Hartw.) Bartel) over 100 years earlier to serve as a wind break against strong prevailing winds off the Pacific Ocean. . Trees of both species previously exposed to increased wind stress due to downwind removals were cored along cardinal coordinates (north, south, east, and west) using an increment bore. The cores were mounted in wood core mounts, sanded to clearly expose annual growth rings and the ring pattern cross dated. The dated growth rings were measured and analyzed for statistical cross dating using the program COFECHA. The tree ring width series were detrended using the program ARSTAN using a 50-year cubic smoothing spline. A dendroclimatic analysis was performed using the program DendroClim to compare the standardized tree ring chronologies against climatic variables of temperature and precipitation. The period from 1950 to 2000 was used as a calibration period to reconstruct tree response to the climatic variables and then the period 200 to 2011 was reconstructed and analyzed for departures from the expected climatic growth response. The *Pinus radiata* provided the best cross-dated chronology. *Hesperocyparis macrocarpa* was more problematic to cross-date. The trees did show an altered pattern of growth ring width after tree removals indicating that these trees were responding to the new, altered wind exposure pattern.

Tree

Keywords

thigmomorphogenesis, urban forestry, acclimation growth, dendrochronology, tree-rings

Functional branching morphology of arborescent columnar cacti

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Abstract

In contrast to trees, the ramifications of arborescent columnar cacti possess pronounced constrictions at the junction between branch and stem. Beneath the succulent cortex, the cactus wood, normally forming a broad cylinder of wood lamellae [2,3,4], is reduced to a compact socket with distinct indentations on the adaxial and abaxial side. Notwithstanding the common theory that neckings in regions of the high bending stress represent structural weak points, the ramifications of columnar cacti provide sufficient stability to the side shoots, even under superposition of static and dynamic loading.

To explain this counterintuitive structure-function relationship, detailed knowledge of anatomy and material properties on all hierarchical levels is required. Branched specimens collected in the botanical gardens of the TU Dresden and the University of Freiburg were examined concerning the functional morphology and the arrangement of the constituent tissues. Trunk and ramification segments were prepared by enzymatic maceration to conceive the axial course of the vascular bundles. In addition, the fiber orientation inside the ramification was analyzed by modern optical and radiographic means (e.g. 3D-laserscanning, micro-focus computer tomography).

Based on these studies, representative geometric models of the selected species were created with Computer Aided Design (CAD) software and evaluated in Finite Element Analysis (FEA). The required elastic constants for these models were determined in uniaxial material tests on the four main tissues. The parenchymatous pith and cortex were tested in compression tests, whereas the wood and the cuticle were tested in tension tests.

Under self-weight conditions, the results showed that the load adaptation does not follow the simple rule of stress homogenisation and minimization by material accumulation in highly stressed areas [1,5]. The succulent cortex limits the secondary growth of the vascular tissue, hence it seems more advantageous to tune the tension stress by geometric changes to already predominant fiber directions. Another surprising detail is that the compression stress on the abaxial side is partly dissipated by the parenchymatous cortex. Under lateral wind drag, the tension stress maximum in the vascular tissue occurs in the same region as under dead load and again the cortex partly dissipates the compression stress on the backside.

These results indicate that load-adaptation in cactus ramifications is realized by a combination of shape optimization and fiber arrangement. The biomimetic transfer of the design principles might help to develop alternative concepts for branched light-weight fiber-reinforced composites especially for structures with limited design space.

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Keywords

Arborescent columnar cacti, wood structure, ramification, load adaptation

The role of elastic deformation in the statics of inclination angle of leaves

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Abstract

The distribution of leaf inclination angles within a tree canopy is of primary interest for botanists. Indeed it plays an important role for light interception by trees and thus rules gas and energy exchanges between trees and environment. Few measurements have been done and only empirical models exist for describing this quantity. Here we suggest a simple mechanical model representing the dependence of the distribution of inclination angles with the flexibility and the mass of leaves. This model is based on an a priori construction of the rigid tree structure, trunk and limbs, and a model of the non-linear elastic deformation of the leaf.

First, we construct an idealized geometrical structure of a tree by an iterative law. This geometrical structure stands for the structure of sympodial trees. We use only two parameters for describing this structure: the branching angle θ and the number of branching N , also named the iteration number. The branching angle is the typical value of the angle between two emerging branches. Such a geometrical construction gives a classical normal distribution of inclination angles of branches on a tree. We analysed experimental distributions of inclination angles of branches on several sympodial and monopodial trees: all these distributions are well fitted by our normal distribution when adjusting branching number and branching angle.

Second, we develop a simple model of flexion of leaves under gravity: a plane, rigid and weighty lamina and a flexible petiole with no mass, as an *Elastica* beam. This approximation allows us taking into account the effect of gravity on the leaf. Solving numerically the differential equations shows that the gravity number $G = MgL^2/(EI)$ rules the petiole deflection due to lamina weight. Thus we find a relationship between the petiole base inclination angle and the leaf plane inclination angle.

Finally, we combine the statistical results obtained on a rigid tree structure and the mechanical modelling of leaves to find the probability distribution of leaf inclination angles on a tree subjected to gravity. These findings are compared to leaf inclination measurements of real trees.

We conclude that knowing the exact geometry of a tree is not essential for describing correctly the leaf inclination angles distribution and the effect of flexibility on these angles.

Keywords

Leaf, Inclination angle, Model tree, Flexibility

Gravitropic response of Beech trees growing in different competitive environments

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Abstract

This work aims at assessing the gravitropic response (i.e., tension wood production and growth stress formation) of beech trees (*Fagus sylvatica* L.) growing in different competitive environment. Four Beech tree plots corresponding to four initial plantation densities (2500, 5000, 10000 and 40000 stems/ha) grew without any intervention during 26 years. Regular inventories of the stem circumference at 1.30 m height were performed over time, in each plot. Twenty six years after plantation, ten mean trees (based on the 1.30 m height circumference) were selected in each plot. Their morphology was assessed (1.30 m height circumference, total tree height, stem leaning, height of the crown base, crown projection area, crown asymmetry, distance of the crown center to the stem). The variation of the peripheral growth stresses was assessed on the standing trees using the single hole method. Next, the selected trees were cut and the discs at 1.30 m height were taken. An image processing method was used to segment the discs into seven radial growth zones (based on the successive circumference measurements over time) and, therefore, to assess the radial production of tension wood over time.

At the end of the experiment, the morphology of the trees was strongly different between the plots (decreasing stem circumference and crown projection area with increasing plot density). The stem leaning was significantly higher in the 40000 stems/ha plot. The analysis of the last growth zone showed a strong correlation between tension wood production (i.e., angular extension and rate) and growth stresses. Finally, statistical models were established to identify the morphological variables involved growth stress formation. These models revealed the strong involvement of the stem leaning, but also the height of the crown base and crown asymmetry. As an overall conclusion, this work reveals that assessing the detailed tree morphology and the spatial distribution of the aerial tree biomass should be necessary for further investigation of gravitropism in mature forest stands.

Tree

Keywords

Tension wood, growth stresses, tree morphology, stand density

Sclereids to structurally optimise resistance to bending stress in *Malus* peduncles

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Abstract

The apple fruit is well known from our everyday diet. But who ever thinks about the fruits peduncle? The peduncle not only attaches the apple fruit to the branch, but it must also resist increasing fruit weight as well as high multiaxial statical and dynamical stresses. This fact has led us to the question how *Malus* peduncles are able to adapt to the rising stress levels during fruit development?

We investigated peduncles of five *Malus* species and one cultivar during fruit development from the flower to the ripe fruit. To characterize the structure-function relationship of the specific peduncles tissues, we combined biomechanical static/dynamic tension and three-point-bending tests with anatomically analysis using microscopy.

Two constructural different anatomical principles were found within the investigated *Malus* species: Type 1, whose peduncles possess centrally located fibres and type 2, which formed in addition to fibers a sclereid ring. The results indicate that peduncles of both types absorb tensile stress mainly through centrally arranged fibers. Bending stresses are absorbed by fibers in type 1, whereas in type 2 the flexural modulus increases mainly by subsequent differentiation of isodiametric sclereids in the direction of the acting maximal tension. Hence, sclereids act as an active structurally optimisation to increase the rigidity to bending stress.

Keywords

biomechanics, *Malus*, sclereids, functional anatomy

Is bending strain better than tilt angle to understand the level of growth stresses in mature trees?

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Abstract

Tree biomechanics studies were firstly justified by questionings brought by forest managers and wood technologists alerted by the consequences of the release of growth stresses during harvesting and sawing process, or still, the excessive distortion of wood products occurring during drying and linked to reaction wood presence. Physiologists demonstrated that reaction wood formation could be controlled by both local lean (graviperception) and bending strains (thigmomorphogenesis). As many physiological processes in trees, the way trees use one perception process or the other could be drive by age and disturbance level. However, the gigantism of trees and the difficulty of catching relevant variables at this scale probably explains why so many researches were focused on small trees or strongly bent trees. Nowadays, thanks to new technologies such as terrestrial LiDAR, (Light Detection And Ranging) a renewal of focus towards biomechanics of mature trees is possible with an unparalleled level of description for the time spent in measurements. The saved time can be utilized to include a large number of trees in such study.

Here, we intend to present results concerning a study in progress where forty trees of different species and sizes were described by means of a terrestrial laser scanner in the framework of a project called EMERGE funded by the French National Research Agency and dedicated to a better assessment of the biomass of forest trees. The clouds of 3D points delivered by the scanner were used to reconstruct a geometrical model for each tree until a minimal diameter of 7 cm, thanks to the 3D metrology software platform Polyworks. By adding green wood density information, we can assess the mass distribution and then bending moments along the stems.

In this study, Growth Stress Indices, that measure globally but quantitatively reaction wood biomechanical quality, were measured by the single drilled hole method developed by CTFT. Locations of the holes along the periphery were governed by the maximal local tilt angle. Then longitudinal stresses and strains caused by the bending moment resulting from the upper part of the trees above a given height of the trunk were computed (assuming an homogeneous modulus of elasticity).

With these previous methods we are able to compare the variations along the periphery of the tilt angle with respect to the horizontal plane, bending strains and GSI values at the same height, and in the same coordinate system. Results about relationships between local lean, strains and GSI, are discussed at the cross section and at the tree population levels.

A demonstration of the terrestrial laser scanner can be organised during a poster session or during a field trip of the social program.

Keywords

Terrestrial Lidar, Bending strain, Posture control, Mature Trees

Tree safety evaluation by pulling test and wind load analysis

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Abstract

Tree safety in urban area became more and more important during last decades, due to accidents by uprooting and trunk fracture. As a matter of fact, strong winds appear to be by far the main cause of tree rupture.

Urban tree managers therefore need to achieve periodic inventories and hazard tree diagnosis. Several methods can be used, based on empiric or engineering approaches.

The engineering models SIM (Static integrated measurement)[1] and more recently Arbostat[2] are based on wind load analysis and measurements under static load. This paper focuses on the presentation of this so called “pulling test” method.

- Wind load

The wind load is achieved following the Eurocode 1 procedure. A reference Wind speed is selected beyond several geographical zones. Several factors are then integrated for wind pressure calculation: landscape roughness, tree species, crown dimensions and area, shape, drag factor. Other parameters like tree natural frequency and damping coefficient are used to calculate a “gust reaction factor”, which expresses the dynamic response of trees to gusts.

The wind load is quantified *in fine* by a moment of flexion ranging from less than 50 to over 1000 KNm.

- Measurements

The measurements are achieved with several sensors, dynamometer, inclinometers and elastometers. Inclinometers measure the inclination of the root plate under load in 10^{-3} degrees and elastometers measure trunk longitudinal deformation in microns (strain).

The tree is pulled from a point in the crown by a manual winch to a maximum of 16 KN.

- Safety calculation

The safety factors for the root system and the trunk are calculated by extrapolation of measured values to high winds. Reference values for green wood properties and the general tipping curve allow calculate fracture and uprooting loads (Wessolly and Erb, 1998).

Field cases will be presented before discussion.

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References

Wessolly L and Erb M (1998). Baumstatik und baumkontrolle (Patzer Verlag Berlin Hannover)

Keywords

Urban tree safety evaluation - wind load analysis - static pull test

Structural sensitivity analysis and model comparisons of Zea Mays stalk flexibility

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Abstract

Resistance of Zea Mays (L.) to stalk lodging has been an elusive goal for plant geneticists. This study uses structural models of the corn stalk to better understand the geometric and material factors that control stalk flexibility as a preliminary step to more advanced studies on the factors that control stalk lodging. A variety of structural models were applied to study stalk flexibility, and each model was subjected to stochastic sensitivity analysis to rank the model parameters in order of influence. Models used include Euler-Bernoulli, Timoshenko, and finite element approaches. Results indicate that Poisson's ratio consistently has very little effect on stalk flexibility while the length of internode regions is consistently the most influential parameter. Comparisons between model predictions are discussed relative the advantages and disadvantages of each modeling approach.

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Keywords

Zea Mays, sensitivity analysis

Effect of Growth Stresses on Anatomical and Physical Properties of *Fagus orientalis* L.

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Abstract

Growth stresses develop in trees' trunks during formation and maturation of their growth rings. The asymmetric of growth stress field causes formation of abnormal wood called reaction wood. This study has been conducted to characterize the effect of growth stresses on anatomical and physical properties of *Fagus orientalis*. Longitudinal growth stress was measured at 8 equidistant points on circumference, at breast height of 19 standing Beech trees in parcels 117 and 223/220 at Kheyroudkenar Research Forest. Using displacement gauge, longitudinal Point with greatest stress history on each sample tree was marked, and then trees were cut down to collect test materials for anatomical and physical properties. On cross-section of each sample bolt segment of harvested trees, area with greatest stress and its opposite were identified to cut out specimens. Results of investigations have shown that in the area with greatest values of longitudinal stress, tension wood has formed. In this area comparing with opposite wood of cross-section, number of vessels, diameter of vessels' lumen and typical fiber diameter were lower, but length and wall thickness of fibers and average percent of fiber content, shrinkage and swelling rates were higher. There were no significance statistical differences between moisture content and basic specific gravity in wood of both areas.

Keywords

Growth Stress, Beech Trees, Number of Vessels, Diameter of Vessels

Session BIOMAT

Biomechanics of Biomaterials Performances

The hierarchical structure and mechanics of plants

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Abstract

The cell walls in plant tissues are made up of just four basic building blocks: cellulose, the main structural fiber of the plant kingdom, hemicellulose, lignin and pectin. Although the microstructure of plant cell walls varies in different types of plants, broadly speaking, cellulose fibers reinforce a matrix of hemicellulose and either pectin or lignin. The cellular structure of plants varies from the honeycomb-like cells of wood to the closed-cell, liquid-filled foam-like parenchyma cells of apples and potatoes. The arrangement of the four basic building blocks plant cell walls and the variations in cellular structure give rise to a remarkably wide range of mechanical properties: the Young's moduli span 4 orders of magnitude while the compressive strengths span nearly 3 orders of magnitude. Here, we review the microstructure of both the cell wall and the cellular structure in four plant materials (wood, arborescent palm stems, bamboo and parenchyma) to explain the wide range in mechanical properties in plants.

Keywords

Hemicellulose, Biomechanics of Biomaterials Performances

Preparation of Poplar wood plastic reinforced composites: influence of Tension and Normal wood fibers on defibrization and mechanical properties

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Abstract

The potential of poplar tension wood fibers as reinforcing agent for Thermoplastics Wood Composites was explored. Natural fibre composites (NFC) are mixtures of a polymer matrix with a renewable material such as wood sawdust for Wood Polymer Composites (WPC). When compared to glass or carbon fibres, lignocellulosic fibres have the advantages of being more ecological. They are also lighter. And when their relative low densities are considered, they show mechanical properties competitive with regular synthetic fibres. However, in WPC, the reinforcement of the matrix is almost zero or very low. Basically, the wood floor material is mainly used as filler agent for reducing the amount of plastic used and for lightening of the end used products (i.e. in automotive, in decking industries).

Considering the high biomechanical function of tension wood for trees with high cellulose content and organization of microfibrils along the fibre axis, we hypothesize that tension wood could be an opportunity as biomass material for WPC of enhanced mechanical properties. Moreover, tension wood is particularly detrimental in term of wood processability and stability (shrinkage...) for structural wood products. Therefore, it would be a good market for this low value product.

In this context, composites of Polycaprolactone (PCL) filled with 20% poplar tension wood (TW) fibers or with normal wood (NW) were set. Poplar wood materials were debarked before being grinded as floor. Compounding was done with a laboratory scale single screw extruder. Composites mechanical properties were evaluated from the strands obtained. They were grinded and standard dumbbell specimens were injected for PCL or PCL/poplar composites. Tensile properties in uniaxial extension were measured. Young's modulus, strain and stress at break measurements were determined.

All composites filled with 20% poplar wood were stiffer but less ductile, as generally observed for fiber-reinforced composites. TW fiber composites exhibited significantly enhanced properties compared to PCL, and interestingly + 20-25% reinforced mechanical performances compared to NW composites.

This result point out that TW fiber can be exploited as prospective materials for making stiffer thermoplastic composites. Therefore, in this current study we have sought to address major questions about the origin of this difference:

i) Is the extra reinforcement observed with TW due to fibers morphology? Indeed, during grinding the fracture propagation pathways or locations can have lead to marked differences in the aspect ratio of TW or NW elements.

ii) And/or is the surface properties are different (roughness, surface energy...) and responsible of the better interface adhesion between TW and PCL? In fact, new surfaces created during the grinding may have lead accessible distinct chemical functions (topochemistry) more or less in favor of efficient bonding with the PCL matrix.

iii) Or finally is the TW extra reinforcement due to higher intrinsic cell wall properties?

Keywords

WPC, tension wood

The effect of Ca²⁺ and cellular structure on apple firmness and acoustic emission

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Abstract

Consumers demand fruits which are firm, crispy and juicy. These attributes are the mechanical properties contributing to the quality assessment of this fresh food products. This study presents the influence of calcium lactate treatment (0-6%) and cellular composition on two mechanical attributes of apple tissue: firmness and total acoustic emission (AE) events registered in the puncture test. The experiment was performed on five apple cultivars stored for nine months in a normal or controlled atmosphere. The microstructure was characterized quantitatively on control samples by confocal scanning laser microscope followed by image analysis. The mean area and perimeter of detected objects, which were either cells or spaces, and estimated cell wall fraction were used for characterization of the tissue microstructure.

Treatment with increased Ca²⁺ concentration caused a significant increase of firmness and total AE events. The effect was particularly positive in the case of very soft apples (stored in a normal atmosphere) due to greater extent of de-esterification of homogalacturonan. Analysis of the results, together with a review of the literature, suggests that calcium importantly changes the cracking mode of tissue, from intercellular debonding to cell wall rupturing. Firmness and the total AE events significantly relate negatively with the object's size and positively with estimated cell wall fraction. A rough accordance of the number of split cells open across cell walls by puncture probe and the total AE events registered in the test, which was saturated in high Ca²⁺ concentrations, was noticed..

Keywords

Fruit, firmness, calcium, cell wall, acoustic emission

Respective effects of lignins and of extractives on the dynamic mechanical behaviour of wood

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Important parts of the presented works were performed in the following institutions:

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-LMGC – CNRS/Université Montpellier II, France

-Graduate School of Life and Environmental Sciences, Kyoto Prefectural University, Japan

Abstract

This contribution takes place in the context of understanding some of the sources in the diversity of mechanical behaviour of wood and related plant bio-materials. Lignin is known to play a predominant role in wood viscoelasticity. Nevertheless, during the last two decades, it has been shown that secondary metabolites or “extractives”, that are compounds of low molecular weight and huge diversity in chemical nature, could also play a prominent role in modifying the internal friction (or damping coefficient, $\tan\delta$) of wood, by as much as by a factor 2. However, the role of lignin has mainly been assessed, experimentally, in the physical domains of creep and of thermal softening, that is, over relatively long time scales or at low frequencies. Conversely, the effects of extractives have mostly been demonstrated through experiments at audio-frequencies. This contribution aims at synthesising what we apparently know (and what we do not know) about the respective influences of this highly variable polymer (lignin), and of those highly variable mono- or oligo-mers (extractives), on the dynamic mechanical behaviour of wood in different physical conditions (frequency ranges and moisture contents). It will include a combination of literature review, and of several personal experimental works.

In the domain of audio-frequencies, on air-dry wood, our experiments include: (i) assessment of vibrational properties of many wood species and wood types and statistical correlations with known (quantitative) extractives' content; (ii) effects of artificial variation in extractives' content (extractions with solvents of different polarities); (iii) comparison of vibrational properties between wood types with different lignin content and nature (compression and normal wood of gymnosperms). In the domain of low-frequencies, on water-saturated wood, our experiments by thermo-activated DMA (dynamic mechanical analysis) include: (i) effects of quantitative and qualitative variations in lignin (comparison between normal and tension wood, chemical or enzymatic delignification); (ii) effects of extractives' removal from 5 wood types, in link with physical effects of various hygro-thermal re-conditioning treatments for studying water re-saturated wood that was previously air-dried.

Results suggest that, in the audio-frequency domain for air-dry wood, some extractives can have much bigger amplitude of effect on internal friction, than natural variations in lignin amount and structure do. Whereas, for thermal-softening in the low-frequency domain on water saturated wood, the effect of lignin variations is indeed (as expected) predominant both on the amplitude and on the temperature of the main $\tan\delta$ peak. However, smaller but clearly significant effects of extractives are also observed on thermal softening, and further research on this effect will be proposed.

Keywords

Wood diversity / Dynamic mechanical properties / Viscoelasticity / Internal friction / Damping coefficient / Lignin / Extractives

Sorting the timber by a musician VS acoustical indexes

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Abstract

Methods based on acoustical parameters (Wegst, 2006) to sort timbers for use in musical instrument industry and acoustical anisotropy in two perpendicular flexural vibrations of a beam (Roohnia et al. 2011) to sort timbers for their perfectness have been previously introduced in the literature. Here, a summation method considered the modulus of elasticity, damping coefficient and acoustical conversion efficiency evaluated from two flexural vibrations in LR and LT planes. This scientific sorting system has come to count the errors of traditional timber sorting method by a musical instrument maker based on qualities of sounds from their flexural excitation. Considering the statistical correlations and analyses between two sorting methods, the dexterous instrument maker was approximately successful to locate the worst timbers where this traditional ear-base selection was coincided here by the scientific sorting method. But there were lots of errors for the rest of qualities by the traditional method while some of the traditionally superior ear-base graded timbers showed worse acoustical qualities based on their acoustical scientific indexes.

Keywords

acoustic/ music/ scientific/ sort/ timber/ traditional/ vibration

Vibrational based nondestructive testing of wood; an acoustical approach from lumber to small beams

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Abstract

Possibility of assessing the vibrational properties of actual lumbers versus small rectangular beams using free flexural and longitudinal vibration technique has been investigated. 10 pieces of lumbers from pine wood were randomly selected and free-free flexural and longitudinal vibration test performed on them. Samples then were cut to smaller and smaller rectangular beams in two steps while the mentioned tests performed on stepwise converted beams. Examined factors were included modulus of elasticity, specific modulus, acoustic coefficient (sound radiation index), damping coefficient (internal friction index), and acoustical conversion efficiency. Good correlation obtained from the results of rectangular timbers with different sizes. So based on results, the cited technique can be considered as a suitable method for acoustical analyzing the timber regardless its dimensions.

Keywords

acoustic/ assessment/ flexural/ longitudinal/ lumber/ timber/ vibration

Session MICROMECH

Cell wall, cell and tissue micromechanics

Plant micromechanics

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Abstract

Plants manifest a wide variety of adaptable parameters at the micro- and nanostructural level. Material properties are adjusted by varying cell types and their shapes, the thickness of cell wall layers, the orientation of cellulose microfibrils within the wall layers as well as the chemical composition of the cell wall. The talk presents methodical approaches to unravel structure-property relationships at the cell and cell wall level and reviews current knowledge on the mechanical design of plant cell walls.

A further focal point is on the influence of plant cell wall modifications on material properties. Micromechanical and (nano) structural characterization can reveal the impact of genetic treatments of plants as well as of chemical modifications of plant cell walls on the material performance. The gained insight can deepen our understanding of plant cell wall assembly and may be utilized to develop innovative plant biomaterials.

Biochemical and biomechanical properties of fungal spore walls

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Abstract

Many plant species live in symbiosis with mycorrhizal fungi and this interaction significantly augments plant growth. Fungal spores are therefore increasingly used as biological fertilizer. Although fungal spores are known to be resistant structures, they are subjected to stress-inducing or mechanically damaging treatment during the manufacturing process of the spore formulations produced for agricultural use. It is poorly understood, however, how mechanical stress affects spore functioning, and the biomechanical properties of the spores are largely unknown. In order to investigate the biochemical composition and mechanical behavior of the cell wall protecting fungal spores, we studied *Glomus intraradices*, a commercially available mycorrhizal fungus, using micro-mechanical testing and immunohistochemistry. The spores of *G. intraradices* are formed both inside and outside the root, representing two very different environments. Using micro-indentation we examined spore stiffness and visco-elasticity and we determined whether these parameters were correlated to spore size, wall thickness or origin of the spores. Finite element modeling enabled us to determine the material properties of the spore wall material through reverse engineering. We also assessed how the spores respond to osmotic stress and used this behavior to determine the pore size in the cell wall. To further relate the mechanical behavior to the biochemical composition of the spore wall we determined the subcellular localization of the structural cell wall components chitin, $\beta(1,3)$ glucan and glomalin using confocal laser scanning microscopy. The different layers of the wall showed distinct labeling profiles that varied depending on the age of the spores and on the extra- or intraradical origin.

Keywords

micro-indentation, fungal spores, cell wall

Searching for polysaccharides specific to tension wood fibers

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Abstract

In hardwood trees, tension wood formation is a remarkable adaptive mechanism that makes possible for the tree to reorient its axis. Tension wood differs from normal wood by anatomical, chemical and physical characteristics: it is less lignified, and contains more cellulose of higher crystallinity, with longitudinally oriented microfibrils. In poplar, tension wood fibers harbor an extra cell wall layer, named G-layer, responsible for the peculiar mechanical properties of tension wood (1). We propose that differences between tension and normal wood mechanical properties are linked to the polysaccharide composition of the G-layer. In order to investigate the nature of these links, we realized immunolocalisation studies with light microscope observation. 158 monoclonal antibodies (from CCRC, LM, JIM and MAC series) raised against various epitopes specific to different families of plant cell wall polysaccharides were tested. For each antibody tested, we analyzed where labeling was present, not only between tension and opposite wood (that is completely devoid of G-fibres), but also according to cell type, cell wall layer, and this along the gradient of xylem cell differentiation. Most antibodies directed against xyloglucans, fucosylated or not, specifically labeled the primary wall / middle lamella in both tension and opposite wood fibers. This was also the case for several antibodies specific to rhamnogalacturonans I. Some other antibodies labeled only the S2 layer, such as most antibodies directed against xylans, whereas, unexpectedly, a few other xylan-specific antibodies exhibited a wider range of labeling. None of the antibody tested was able to specifically label opposite wood cell walls. On the contrary, among all the antibodies directed against rhamnogalacturonan I or arabinogalactan epitopes that were tested, eighteen of them specifically labeled the G-layer in tension wood fibers and, for some of them, the labeling was restricted to newly formed G-layers. Overall, from the signals obtained with each of the antibody tested, differences between tension and opposite wood fibers when observed were only detected at the level of the G-layer whose composition appears to evolve throughout its maturation. Furthermore, our study strongly suggests the involvement of specific arabinogalactan-proteins and pectins during G-layer construction. Finally, we optimized a procedure for G-layer isolation in order to analyze the polysaccharide composition of purified G-layers by mass spectrometry.

In the presentation, we will discuss more in details all the results obtained using these two complementary approaches.

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Keywords

Tension wood, G-layer, poplar, polysaccharides, immunolocalization, MS analyzes

A micromechanical analysis of interaction between cellulose microfibrils and matrix substances in wood cell wall by using the X-ray diffraction method

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Abstract

- Background and scope

The wood cell wall consists of “two-phase structure”, that is, the rigid cellulose microfibril (CMF) and lignin-hemicellulose matrix (MT). For better understanding of the origin of mechanical and physical properties of wood, it is inevitable to make clear the mechanical and physical interaction between the CMF and the MT substances in the cell wall.¹⁾ Based on such a background, we have tried to apply the X-ray diffraction technique to analyzing the micromechanical behaviors of cell wall components and their interaction.^{2,3)} In this presentation, we discuss the effects of repeated wetting-and-drying or boiling treatments on the lattice spacing of the cellulose crystal, d_{200} and d_{004} , in green softwood specimen by using the X-ray diffraction method. We thus try to demonstrate the microscopic mechanism of drying shrinkage and growth stress (maturation stress) generation from the viewpoint of “two-phase structure” in the wood cell wall.^{4,5)}

- Material

In the present study, we tested three Japanese softwood trees, that is, sugi cedar, hinoki cypress, and karamatsu larch. All the tested trees had straight trunks, forming normal matured wood. Wood blocks were sampled from living sapwood regions, and they were trimmed into crosscut and quarter-sawn specimen with dimensions of $5 \times 15 \sim 18 \times 15$ mm (thickness \times length \times width). X-ray diffraction method was applied to determining the changes of d_{200} and d_{004} lattice spacing in the cell wall before and after treatments.

- Results and discussions

(1) Mechanical interaction between the CMF and the MT substance during the repeated wet-and-dry treatments – Microscopic mechanism of drying shrinkage of wood⁴⁾

Macroscopic dimensions of softwood specimen, measured using a micrometer, showed well known behaviors, that is, shrinkage by drying and swelling by rewetting in both longitudinal and tangential directions. On the other hand, lattice spacing showed different results. In particular, d_{200} lattice spacing expanded considerably with drying in the early stages of repeated wet-and-dry treatments (1.01~1.51 %), whereas no such dynamic change was observed in d_{004} lattice spacing. Expansion of d_{200} lattice spacing due to drying tended to become smaller after giving repeated wet-and-dry treatments. Those suggest that the CMF could be pulled laterally by the shrinking MT substances during drying, and such a tensile stress would give some microscopic damage in the wood cell wall, specifically an interfacial separation between the CMF and the MT substances after repeated wet-and-dry treatments.

(2) Behaviors of the CMF and the MT substance during boiling treatment – Microscopic mechanism of growth stress (maturation stress) generation in wood cell wall⁵⁾

X-ray diffraction technique revealed that the d_{200} lattice spacing in green wood specimen significantly expanded (0.18~0.21 %), while d_{004} lattice spacing slightly contracted (-0.07~ -0.11 %) after boiling treatment in hot water. This suggests that a trace of growth stress still remained in the CMF and the MT region in the green cell wall even after releasing the wood specimen from the living stem, and those remaining growth stresses were reduced by the thermal-softening in boiling water, which caused an increase of d_{200} and a decrease of d_{004} . A simplified elastic analysis was applied to the stress field around the CMF crystal, and origins of increasing d_{200} and decreasing d_{004} were analyzed. The result leads to a conclusion that the CMF is transversely compressed by the swollen MT, at the same time, the CMF generates a longitudinal tension inside the living cell wall, and a combined effect of those microscopic stresses causes the observable fiber deformation, i.e., the maturation strain.

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- 5) In preparation for submission.

Keywords

micromechanics, two-phase structure, X-ray diffraction, maturation stress, drying shrinkage

Probing the stiffness of plant tissues - nanoindentation of germinating seeds

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Abstract

Whereas the genetics of seed germination is well understood, it is still uncertain how the cell walls are changing their physical properties through the process. In the process of germination, in order to protrude, the radicle must overcome two barriers: endosperm and testa. Whilst testa is dead tissue, endosperm is a thin multicell layer living tissue, with a known role in protection and nutrition of the embryo but uncertain mechanical properties. The dry seed imbibes moisture and all the tissues (dead and living) expand before the testa ruptures. Then both radicle and endosperm expand until finally, the endosperm ruptures. During this process there is no cell division, so all increase in size occurs through extension of cell walls. This change in size is governed by the driving force (from turgor pressure) and any changes in stiffness of the cell walls (from cell wall composition and microstructure). The difference in stiffness between tissues is significant. For example our nanoindentation results (12.5 μm radius diamond spherical indenter) show that the testa stiffness of *Lepidum sativum* is ~ 2.7 GPa, whilst hydrated endosperm has a stiffness of ~ 0.1 GPa. This paper examines whether there is a varying stiffness response for different tissues at different points in the germination cycle. Spherical indenters of varying radii allow us to compare the response between shallow indentations where the response is mainly from a single cell in the tissue, to the response when the indentation covers a number of cells.

In addition to the challenges of small sample size which plant cells represent, it is difficult to measure the mechanical properties of living hydrated tissue, therefore tissue is often fixed before mechanical testing and these values taken to represent those of the living tissue. We will also examine whether this is a reasonable approximation by nanoindentation of living and fixed samples.

Keywords

mechanical testing, nanoindentation, plant tissue

Wood axial mechanical properties at the tissue level in connection to sub-cell wall organization

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Abstract

The purpose of this work is to highlight the longitudinal mechanical properties at the tissue level, taking into account the entire cell wall structure. In order to describe experimentally the relation between the cell wall structure and the longitudinal mechanical properties, monotonic micro-tensile test have been performed until rupture at the tissue level. After detailing and discussing the general behavior of the stress-strain curve, we will focus on the small strain region that can be more easily linked to biomechanical aspects.

Fine structural characterizations have been performed using three experimental devices: (i) Environmental scanning electronic microscope (ESEM) to describe the sample section and determine the solid fraction required to estimate the “true” stress level, (ii) X-Ray diffraction to measure the mean value of the microfibrils angle, and (iii) confocal Raman micro-spectroscopy to highlight the “chemical” distribution of cell wall components and take into account the sub-cell wall organization.

Considering the huge variation of mechanical properties among and within trees, our study is focused on one growth ring of fir (*Abies alba* Mill.). Thus 27 successive microtome slices in the longitudinal-tangential (LT) plane were prepared. From each slice, two samples were made with an approximate size of [0.08 ´ 0.4 ´ 4] mm³ in directions [R, T, L] respectively. Each sample was mechanically tested by imposing a quasi-static displacement. The Young's Modulus was estimated by considering the linear portion of the stress-strain curve until 0.2% of strain. One slice out of two was tested in water saturated conditions; the other was tested at 10% of EMC (Equilibrium Moisture Content). Swelling was taking into account for the stress calculation by using experimental observations with a thermoelectric cooling device (Peltier effect) inside our environmental scanning electronic microscope.

Our results point out the exponential variation of Young's Modulus across the growth ring in air-dry conditions between early wood and late wood, from approximately 3 GPa to 20 GPa. These values will be compared to saturated samples where the variation is lower, from 2 GPa to 9 GPa once taking the swelling into account. The whole data set will be discussed and analysed in connection with the structural and chemical features at the sub-cell wall level.

Keywords

micro-tensile; tissue level ; sub-cell wall ; Environmental scanning electronic microscope ; X-ray diffraction; confocal Raman micro-spectroscopy

The origin of maturation stress in tension wood: using a wide range of observations and mechanical considerations to discriminate between hypothetic mechanisms

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Abstract

The active generation of stress in maturing wood plays an essential role for the biomechanics of trees. Their main function is to act as a motor system, enabling the postural control of the tree and adaptive reorientations. At the macroscopic level, the mechanism underlying this function is well-known: the asymmetry of stress magnitude around the tree periphery generates a bending moment that may counteract the bending moment induced by the increasing self load or induce changes in stem curvature. In angiosperm trees, the asymmetry of maturation stress is generally achieved through the differentiation of tension wood (TW) on one side of the tree.

However, the underlying mechanism at the microscopic level (why and how TW develops a tensile stress during its maturation) is not yet fully understood. Actually, the relation between the structure and function of tension wood is puzzling: its function consists in shrinking longitudinally, but one its characteristic structural feature is to have a gelatinous layer (G-layer) constituted of a large amount of stiff crystalline cellulose oriented almost parallel to the cell axis. This design seems consistent with its function only if tensile stress results from the shrinkage of cellulose. The paradox lies in the fact that cellulose in wood has a defined crystalline configuration and a great chemical inertia, so that it is difficult to imagine a mechanism by which it would spontaneously shrink after its incorporation into the cell-wall. A revival of interest on this issue during the last ten years yielded a number of experimental results on the fine structure, biochemistry, topochemistry, mechanical behavior and *in vivo* mechanical state of TW, as well as a number of hypothetic mechanisms that would generate the tension.

Our aim is to identify which mechanism best describes the real process. This presentation will briefly review existing results and hypotheses, and use micro-mechanical models to discriminate between them. Evidences that the *in vivo* tensile stress is supported by the microfibrils of the G-layer will be presented, and mechanisms consistent with this fact will be analyzed with respect to their consistency with other observations and mechanical considerations.

Keywords

maturation stress, micromechanics, tension wood, biomechanics

Measuring mechanical properties of growing cells by combining Cellular Force Microscopy, osmotic treatments and Finite Element modeling

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Abstract

Primary growth in plants is thought to be driven by turgor pressure and controlled by cell wall loosening and the integration of new wall material. The experimental testing of this hypothesis, however, offers some serious challenges. There exist only few methods which can measure mechanical properties at a cellular level, and the interpretation of such data is difficult. In our work we use a combination of osmotic treatments, Cellular Force Microscopy (CFM) and Finite Element modeling to measure mechanical properties at the cellular level. CFM is a recently developed micro-indentation method. It consists of a three-axis robotic arm which moves a microelectromechanical system (MEMS) force sensor. The machine is able to indent a sample with a probe and to measure the force applied. The resulting force-indentation curve can then be used to calculate the stiffness of the sample. We have applied the method to tobacco BY2 cells, lily pollen tubes and onion epidermal tissue. Our measurements demonstrate that CFM is a flexible technology that can measure stiffness at both single cells or over large areas of a tissue.

One problem that is intrinsic to all micro-indentation methods is that the forces measured reflect mechanical, geometrical, and experimental parameters. Measuring a large apparent stiffness, for example, might indicate a stiff cell wall or high turgor pressure. These ambiguities make it difficult to compare stiffness values from different samples or from different positions in the same sample. To overcome this problem we have developed computational models that simulate our mechanical experiments. These models are formulated within the framework of finite elasticity and solved using the Finite Element Method (FEM). Fitting the parameters of our models to CFM and osmotic treatment data allowed us to quantify turgor pressure and elasticity in BY2 cells and lily pollen tubes. We further used the models to investigate how individual parameters affect the virtual CFM experiments. This approach can be seen as an *in silico* sensitivity analysis that has been validated by mechanical testing on BY2 cells. It has helped us to optimize our experimental design and to improve the specificity of CFM.

Keywords

Cellular Force Microscopy, Mechanical modeling, cell wall elasticity, turgor pressure

Functional micro-mechanics of plant tissues: assessing the contribution of cellulose to the mechanical behaviour of wood

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Abstract

All plant cell walls are composite materials made of cellulose embedded in a matrix of amorphous polymers. A large part of cellulose is present in a crystalline state. Its mechanical behaviour has been extensively studied, and appears to exhibit very high strength and stiffness and to be mostly insensitive to water. The behaviour of plant cell-walls strongly depends on cellulose properties, but also on its organisation in the wall and its interaction with amorphous polymers. The purpose of our micro-mechanical approach is to understand the relation between the macroscopic behaviour, the micro-structure, the rheological properties of the constituents and their interactions.

The stiffness of wood mainly originates in its high content of crystalline cellulose. The mechanical state of crystalline cellulose can be probed by X-Ray diffraction (XRD) and lattice analysis. This study aims to assess the real contribution of cellulose to wood stiffness at different levels of strain and moisture content. Four-point bending tests were performed on longitudinal spruce specimens in air-dry and wet conditions. The macroscopic strain was measured by strain gages, while the cellulose crystal strains were scanned along the height of the specimen using wide-angle X-ray scattering.

Results show that the crystal strain is proportional to macroscopic strain below a threshold that depends on moisture content. In the proportional domain, the ratio between crystal and macroscopic strains is lower than 1, and this value cannot be explained just by the projection effect of microfibril orientation. This evidences that some amorphous components contribute to the wood strain in an additive way. This additive contribution is significantly larger in wet wood than in dry wood. In the compressed side of the specimens, deviation from linearity of the relation between wood strain and crystal strain is observed at a threshold of 0.38% for dry wood, and 0.1% for wet wood. Above this value, the crystalline cellulose does not deform anymore during wood deformation. This demonstrates that the behaviour of amorphous wood constituents and their interaction with cellulose have a major impact on the rheological properties of green wood.

Keywords

wood, cellulose, micro-mechanics, X-Ray diffraction

Medicago truncatula seed germination and radicle growth: A microstructural NMR clarification

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Abstract

Medicago truncatula seed germination is a model to study radicle emergence and development in leguminous plants. During the first hours of imbibition, the radicle develops by cell expansion. After about 21 h of germination, with radicle emergence, cell divisions begin. This model allows addressing necessary processes for growth: tensile stress in the cell wall and turgor pressure. In this work the combined contributions of water and cell walls synthesis and modifications during cell expansion, cell division and cell differentiation were assessed.

NMR relaxometry (T1, T2) was used to follow the different steps of germination up to 48h of seed imbibition through the characterization of water interactions with metabolites and macromolecular components. These measures were realized at -20°C, revealing only non-freezing water, and at +20°C after thawing to characterize water redistribution after partial cell destruction. Auxin, oryzalin and fusicoccin were used to, respectively, increase or stop cell division and favor cell expansion.

At the two temperature of measure, the curves representing T1 and T2 evolution during imbibition show inflexion points (2.5, 5, 15, 21 and 24h). The chronology of these events was compared to the kinetics of water uptake and to modifications in osmolytes (sugars, organic acids) concentration as well as in cell wall polysaccharides composition and structure. Two remarkable inflection points at 5 and 21h were associated with typical events during seed water uptake and corresponded also to modifications in osmolytes concentration and cell walls composition.

NMR relaxometry proved to be a powerful analytical method, revealing T1 and T2 evolutions related with different steps in seed germination and radicle growth. The results at the different temperatures will be discussed on one hand, with regard to the role of water and osmolytes concentration in the turgor pressure regulation of cell expansion, and on the other hand, to seed and radicle microstructure evolution (cell volume and number, cell wall organization) modulated by auxin, oryzalin and fusicoccin.

Keywords

cell expansion, water status, cell wall polysaccharides, NMR relaxometry, seed development

Fungal degradation of Scots Pine (*Pinus sylvestris* L.) wood: micromechanical and microstructural characterization at the cell wall level

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Abstract

The activity of fungi plays a major role among the degradation processes of all biological materials in nature and, thus also on wood. As a consequence of fungal decay, the inherent heterogeneous microstructure and the composition of wood are modified in different ways, depending on the fungal species: white rot fungi degrade all major wood polymers, namely cellulose, hemicelluloses, and lignin, whereas brown rot fungi only degrade wood polysaccharides selectively. The mechanical properties of wood are controlled by its inherent microstructure and composition. Consequently, a change of the microstructure results in altered mechanical properties. Herein, we investigate corresponding changes of microstructural and mechanical properties of Scots pine (*Pinus sylvestris* L.) tracheids, as well as changes in their composition. For that purpose sapwood samples, degraded by one fungus causing brown rot (*Gloeophyllum trabeum*) and one fungus causing white rot (*Trametes versicolor*), as well as in reference condition were investigated. Only early stages of degradation of both decay types, characterized by mass losses of approximately 1 %, 5 % and 10 %, respectively, were considered. Mechanical properties of the wood cell walls were determined by means of nanoindentation (NI), yielding the indentation modulus and hardness. The local microfibril angle (MFA) was determined by wide angle X-ray scattering (WAXS). Compositional data were acquired by means of wet chemical analyses and Fourier transform-infrared spectroscopy (FT-IR). Indentation hardness and indentation modulus of the middle lamella increased during both brown rot and white rot degradation. Increased compressive stiffness of main components of the middle lamella, i.e. lignin and hemicelluloses, indicates modifications of these components. An increase of hardness of the S2 cell wall layer with increasing degradation could also be observed, due to the increase in polymer matrix stiffness and the insensitivity of hardness to the MFA. The chemical composition varied within the samples and also within the annual ring, thus resulting in substantial variability of the indentation modulus. When relating the indentation modulus to the local MFA, still no decisive trends were found and although the chemical composition of wood was altered during degradation, a strong correlation between micromechanical properties, i.e. indentation modulus and hardness, and wood chemistry was not observed, presumably due to the highly variable degradation processes.

Keywords

fungal degradation, micromechanics, nanoindentation, cell wall stiffness, FT-IR, WAXS

Mechanical properties of epidermal cells of whole living roots of *Arabidopsis thaliana*: An atomic force microscopy study

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Abstract

The knowledge of mechanical properties of root cell walls is vital to understand how these properties interact with relevant genetic and physiological processes to bring about growth. Expansion of cell walls is an essential component of growth, and the regulation of cell wall expansion is one of the ways in which the mechanics of growth is controlled, managed and directed. In this study, the inherent surface mechanical properties of living *Arabidopsis thaliana* whole-root epidermal cells were studied at the nanoscale using the technique of atomic force microscopy (AFM). A novel methodology was successfully developed to adapt AFM to live plant roots. Force-Indentation (F-I) experiments were conducted to investigate the mechanical properties along the length of the root. F-I curves for epidermal cells of roots were also generated by varying turgor pressure. The F-I curves displayed a variety of features due to the heterogeneity of the surface. Hysteresis is observed. Application of conventional models to living biological systems such as cell walls in nanometer regimes tends to increase error margins to a large extent. Hence information from the F-I curves were used in a preliminary semiquantitative analysis to infer material properties and calculate two parameters. The work done in the loading and unloading phases (hysteresis) of the force measurements were determined separately and were expressed in terms of “Index of Plasticity” (η), which characterized the elasticity properties of roots as a viscoelastic response. Scaling approaches were used to find the ratio of hardness to reduced modulus (H/E^*).

Keywords

AFM, *Arabidopsis*, root

Enzymatic investigation of plant cell wall mechanical properties

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Abstract

Plant cell wall can be described as an assembly of interacting networks of polysaccharides (cellulose, hemicellulose, pectins) with some structural proteins. The interactions between and within each of these networks greatly contribute to the wall mechanical properties. Various enzymes remodel polysaccharide structures with consequences on their interactions and wall rheology during cell growth and development. This restructuring enables wall extension under turgor pressure and incorporation of newly synthesized polysaccharides (1). Thus, according to plant physiology and cell development state, the cell wall composite structure can exhibit extensible or rigid properties.

In the wall, polysaccharides are linked and interact through various linkages and interactions. Several organization patterns of polysaccharides have been postulated. But, the contribution of specific polysaccharide chemical structures to plant cell wall mechanical properties is unclear. This study attempts to establish relationships between cell wall polysaccharide structure and mechanical properties in apple fruit parenchyma. This tissue is taken as a model of cells with primary-like cell wall which deconstruction mechanisms during ripening are well documented.

The role of major polysaccharide structures on mechanical properties of apple tissue will be assessed after vacuum impregnation of specific enzymes. The function of pectins on cell-cell adhesion will be evaluated by modifying ionization of homogalacturonan structural domains with pectin methylesterase and by changing its abundance with a polygalacturonase and pectin lyase. The contribution of pectins to cell wall rigidity will be assessed by arabinanase and galactanase hydrolyses of rhamnogalacturonan structural domains. Hemicellulose fine structure contribution will also be investigated. The role of xyloglucan side chains on cellulose interaction will be assessed by successive degradation by a β -galactosidase and a α -fucosidase. Changes in the visco-elastic properties of the parenchyma will be measured as a function of time concomitant with enzymatic modifications. Wall polysaccharide chemical and organization modifications will be followed by several methods, such as CPG, HPAEC, MALDI-TOF MS and NMR spectroscopy.

The expected results intend to establish qualitative and quantitative links between biochemical composition and structure of polysaccharides with mechanical properties of a primary-like plant cell wall. These results will participate to the development of biomechanical models linking spatial organisation of cell, cell wall rearrangement and mechanical properties (Barbacci & *al.*, proposed in session 11). As a long-term perspective, the approach will be extended to take into account other enzymes and proteins involved in cell wall reorganization and disassembly during fruit ripening.

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Keywords

Enzyme; destructuring; mechanical properties, cell wall, polysaccharide

Deposition and Organisation of Cell Wall Polymers during Tension Wood

Cell Wall Maturation as studied by FTIR Microspectroscopy

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Abstract

The up-righting system of angiosperm trees allowing them to keep and control their verticality is operated thanks to a modified type of wood, called “tension wood”. The mechanism underlying the generation of maturation stress in tension wood fibres is not yet fully understood, but the fact that the tensile stress is supported by its characteristic additional cell-wall layer (the gelatinous layer, or G-layer) has been recently demonstrated. Fibre mechanical properties are mainly determined by the arrangement of polymers within the cell wall: cellulose, hemicelluloses (xylan and glucomannan) and lignin, and the interactions between them. To progress on the understanding of the generation of tensile maturation stress, the ultra-structural arrangement of cell-wall polymers, as well as their orientation, were investigated by Fourier Transform Infra-red microspectroscopy (FTIR) along a sequence of cell differentiation from the cambium to the mature wood in tension and normal wood of poplar.

The FTIR data indicate that the maturation process can be divided to three phases where the second corresponds to the G-layer formation. The polarised FTIR measurements allow to follow the orientation of cell-wall component and interesting differences were found between normal and tension wood. Results will be discussed with respect to the mechanism of stress generation.

Keywords

Fourier transform infrared (FTIR) microscopy; tension wood; polymers; orientation; polarisation

Biomechanical aspects of seed germination: endosperm weakening of *Lepidium sativum* (garden cress) and *Nicotiana tabacum* (tobacco)

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Abstract

In many mature seeds of Brassicaceae, e.g. *Lepidium sativum* (garden cress), and Solanaceae, e.g. *Nicotiana tabacum* (tobacco) species, the embryo is surrounded by two covering layers: the testa (seed coat) and the endosperm. These tissues are a mechanical barrier for radicle protrusion and the growth potential of the embryo has to overcome the tissue resistance of the endosperm during germination. Germination of endospermic seeds is a two step process in many species including *L.sativum* and *N.tabacum*. During germination rupture of the testa is followed by rupture of the micropylar endosperm by the emerging radicle, which marks the completion of the germination process. The puncture-force method allows a direct measurement of the resistance of the seed 'coats'. The radicle is removed and a rounded metal pin replaces the radicle while force and displacement are recorded. Live-streaming with a high-resolution camera allows the monitoring of the deformation during the puncturing and therefore the detection of breaking behaviour. These analyses are related to molecular events (e.g. transcriptome changes) and combined with mathematical modelling of biomechanical processes.

Testa rupture is an important event during seed germination. Drastic changes which can be shown on the molecular level can also be shown on the biomechanical level. Stiffness and puncture resistance of the endosperm change during the germination process. In addition to time-dependent changes also effects of hormonal treatments are reflected in puncture-force measurements. In mature seeds of the model organism tobacco (*N.tabacum*), the embryo is surrounded by three to five layers of rather thick-walled endosperm cells. Puncture-forces of the tissue decrease to only 25% of the original value during germination. The stiffness of the micropylar endosperm tissue which surrounds the radicle tip decreases about 80%. Seeds of garden cress (*L.sativum*) have one to two cell layers of endosperm surrounding the embryo. *Lepidium* seeds provide an excellent model system for the experimental investigation of endosperm weakening. Prior to testa rupture the mechanical properties of the 'coats' are not changing during water uptake whereas a drastic endosperm weakening occurs during the further germination process after testa rupture. The seeds of both species allow to study spatial aspects of the seed germination biomechanics as different regions of the endosperm can be analysed separately and in a comparative manner.

This study contributes to the ERA-NET Plant Genomics systems biology project vSeed (<http://vseed.info>) which aims to develop a dynamic mathematical description of germination on multiple levels with an interdisciplinary cross-species approach.

Keywords

Seed germination, endosperm weakening, *Lepidium sativum*, *Nicotiana tabacum*

Nanoindentation-based methods for quantifying the mechanical response of living plant cells *in vivo*

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Abstract

Plant cell walls are complex and dynamic structures mainly composed of a network of extended polysaccharides providing structural support and protection to the cell. Thickness, rigidity, and extensibility of the cell wall determine the size, shape, morphology, and growth behavior of a plant. In addition, the turgor pressure within each cell changes throughout the life cycle of the plant in response to genetic and environmental changes. The connection between the plant biology and the mechanical response of the cell (e.g., turgor pressure and cell wall viscoelasticity) provides insight into mechanisms responsible for cell adaptation. In this presentation, nanoindentation-based methods are used in conjunction with finite element analysis to study the mechanics of living plant cells *in vivo*. First, nanoDMA (dynamic mechanical analysis) and relaxation measurements are used to quantify the viscoelastic behavior of plant cell walls using shallow indentation depths. Subsequently, a new *in vivo* method is presented to determine turgor pressure within plant cells based upon quasi-static nanoindentation using cyclic tests with variable depths. The experimental results are matched iteratively using the computational model to determine the turgor pressure. These methods are verified by testing samples (*Arabidopsis thaliana*) in different environmental states including, normal, turgid, and plasmolyzed. The response of the plant cell wall depends upon parameters including the geometry of the cell wall, turgor pressure, radius of the indenter, the viscoelastic properties of the cell wall, and the turgor pressure. These properties are also quantified at various stages of plant development. Finally, using a similar combination of experiments and simulations, the failure stress of a plant cell wall is determined. For this purpose nanoindentation experiments are conducted using spherical tips varying in diameter from 70 nm to 3 μm . The computational model is used along with the known parameters to study the effect of the tip size on load displacement behavior and stresses. The effect of failure stress is investigated in plasmolyzed, normal and turgid conditions. These methods are anticipated to be useful for research studies on single plant cells associated with a wide variety of biological and environmental responses. [Research supported by the US National Science Foundation and the Nebraska Center for Energy Sciences Research].

Keywords

nanoindentation, cell wall, viscoelastic, turgor pressure

Session Motion

Plant motions and plant tribology

Moving fast without muscle: the physics of rapid plant movement

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Abstract

Although they lack muscle, plants have evolved a remarkable range of mechanisms to create motion, from the slow growth of shoots to the rapid snapping of carnivorous plants and the explosive rupture of seed pods. In this talk, I will discuss some of the key physical mechanisms used by plants to achieve movements, summarizing current knowledge and recent discoveries. I will first discuss movements that rely only on the transport of water, and emphasize that the poroelastic timescale of water diffusion through soft plant tissue imposes constraints on the possible mechanisms for motion. I will then show how plants use mechanical instabilities to speed up their movements beyond the limits imposed by simple hydraulic mechanisms, using our work on the closure mechanism of the carnivorous plant Venus Flytrap as an illustration. Finally, I will briefly discuss alternative schemes, involving capillarity or complex fluids.

Keywords

muscle

Helical Buckling of Plant Roots: Mechanics and Morphology

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Abstract

How do plant roots respond to heterogeneities in their environment as they grow? Using a simple model system consisting of a layered hydrogel, we present a controlled mechanical barrier to the roots allowing us to perturb their growth. Interestingly, we find a localized helical root morphology which forms prior to the root passing through the gel layer interface. We interpret this geometry as a combination of a purely mechanical buckling caused by continued root elongation modified by the growth medium and a simultaneous twisting near the root tip. We study the morphology of the helical deformation as the modulus of the gel is varied using 3D time-lapse imaging and demonstrate that its shape scales with gel stiffness as expected by a simple model based on the theory of buckled rods. Our results demonstrate that mechanics is sufficient to account for the shape and its variations. In addition, we hypothesize that the twisted growth near the root tip arises from a touch-activated response.

Keywords

root morphology, buckling, 3D time-lapse imaging, active response

To buckle or not to buckle

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Abstract

Buckling is characterized by a sudden failure of an object submitted to a stress smaller than the ultimate stress that the material is capable of withstanding. Buckling of their tissues is one of the mechanisms that plants have evolved to achieve velocities larger than those that may be reached by the sole regulation of the volume of antagonistic motor cells through the variation of their osmotic pressure. It is, however, not always possible to determine unambiguously what mechanism is at play in a particular plant from the examination of high-speed videos alone. For example, there still exists a controversy regarding the origin of the closing of the leaves of *Dionaea* in about 400 ms, although this plant has been intensively studied since Darwin's work. Moreover, the movement of other plants, like the aperture of the door of aquatic *Utricularia*'s traps in about 1 ms, is just a little too fast for most of today's cameras. Modeling of these movements therefore represents an appealing complementary tool to unveil their complex dynamics.

In this talk, I will report on the models we have recently developed to investigate the fast movements of *Dionaea*, *Aldrovanda* and *Utricularia*. The two key features of these models are the following: (i) they are based on realistic trap geometries obtained from triangulated surfaces; (ii) plant tissues are modeled as thin and homogeneous elastic solid membranes with a Young's modulus E close to 10 MPa, in agreement with experimental observations. These membranes are subjected to the adequate stress and the evolution equations for each vertex are solved numerically. I will show that these models reproduce accurately the movements of the investigated plants. More interestingly, a closer examination of the properties of the computed movements provides those details, which are not easily extracted from videos. For example, the models confirm that the closure of *Dionaea*'s traps and the opening of the door of *Utricularia*'s ones indeed involve the buckling of their tissues, while the snapping of the leaves of *Aldrovanda* in about 100 ms is more likely based on the kinematic amplification of the bending motion of their midrib.

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Different mechanics of snap-trapping in the two closely related carnivorous plants *Dionaea muscipula* and *Aldrovanda vesiculosa*

-S. Poppinga and M. Joyeux, *Physical Review E*, 84 (2011) 041928 (1-7)

Ultra-fast underwater suction traps

-O. Vincent, C. Weisskopf, S. Poppinga, T. Masselter, T. Speck, M. Joyeux, C. Quilliet and P. Marmottant, *Proceedings of the Royal Society B : Biological Sciences*, 278 (2011) 2909-2914

Mechanical model of the ultra-fast underwater trap of *Utricularia*

-M. Joyeux, O. Vincent and P. Marmottant, *Physical Review E*, 83 (2011) 021911 (1-12)

Keywords

fast movements, buckling instability, modeling

A Universal Dynamic modelling Of aerial Gravitropism

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Abstract

Postural control is one of the main features of plants adaptation to aerial life. But if the primary molecular and cellular transduction pathway has been studied into details, the postural control dynamics has been poorly studied currently. Here the focus is given on plants gravitropism and the regulation of the movement by perception.

Kinematics experiments on different angiosperms plants showed that the gravitropic movement could exhibit different transitory shape (C-shape, S-shape). Nevertheless the curvature dynamics and the final shape seem quite universal. This universality suggests that a core dynamics could be specified independantly of mechanism, species or length and time scale.

A mathematical modelling of plants gravitropism has been developed in order to understand the regulation of the movement. This modelling demonstrates that perception of the inclination vs gravity alone is unable to account for the diversity of observed movements. Another perception is then assumed, called proprioception, where the plants is able to sense its own deformation and respond in order to remain straight. This simple addition is then sufficient to account at the same time for the experimental displayed movements and the different final shape over a sample of 10 species .

This results show the existence of an adimensional number, ratio of lengths measured on the initial and the steady state of the plants. This open avenue to a better characterisation and understanding of plant gravitropism.

Keywords

Gravitropism, minimal modelling, movement, phenotyping

Hygroscopic coiling movement of the seed dispersal unit of stork's bill

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Abstract

Seed dispersal enables plants to scatter their progeny into new growing locations. Many times hygroscopic tissues are involved in dispersal by contracting in specific directions as they mature and dry. The hygroscopic structure may react to the diurnal humidity cycle and facilitate the release of seeds from the mother plant and their propulsion along the ground. One example for such mechanism exists in the awns of the stork's bill (*Erodium gruinum*). However, while studied hygroscopic movement mechanisms are characterized by differential contraction of two tissues, here only a single layer creates the movement. We showed that single cells that build the active layer coil as they dry (1). In these cells we detected cellulose microfibrils arranged in an unusual tilted-helix, which forces the cells to adopt a coiled configuration when they dry. Using X-ray diffraction and polarized light microscopy we follow the cellulose tilt along the awn. We find that the tilt angle is gradually reduced towards the awn top, together with a more open structure of the coil. The top part shows faster water movement, as estimated by rates of weight gain at high ambient humidity, and seen in videos. This may be explained by a gradual increase in the concentration of the aromatic ferulic acid in the cell walls, as detected by Raman microspectroscopy and fluorescence microscopy. We hypothesize that this compound renders the top coil more hydrophobic, and thus more sensitive to humidity changes. The ferulic acid glues the cells harder together, contributing to the high mechanical stability of the open-coil top. This region, which acts as a hinge between the active coiling part and the straight tail allows pushing the dispersal unit along the ground, and enables higher force transmission for seed burial.

References

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Keywords

hygroscopic movement, coiling, cellulose, microfibril angle (MFA), helix, small-angle X ray scattering (SAXS), Erodium, Raman microscopy

Mechanical analysis of bursting fruit of *Vicia angustifolia* (*Vicia sativa* subsp. *nigra*) with spiral motion

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Abstract

The bursting of a plant fruit is a very interesting phenomenon in a biomechanical viewpoint because it is a mechanical phenomenon directly related to reproduction of the plant. If a plant has a fruit that can burst powerfully and thus spread its seeds widely, it has a reproductive advantage. Many types of plant fruit probably have been adapted structurally in an evolutionary process. Strain energy is stored in pericarp of fruit due to growth, swelling or drying just before bursting. Thereafter, the storing strain energy is rapidly released when the pericarp bursts. The quick and wide motion of the pericarps in a specific direction is an advantage to disperse seeds far away. The motion of pericarp during burst depends on their tissue structure and mechanical stress condition just before burst. We clarified that pre-burst stress distribution of the pericarp is advantageous to make it large and fast motion to spread seeds, for the fruit of *Impatiens* which performs roll up motion by swelling stress, in previous study. In this study, we focused on bursting fruit of the *Vicia angustifolia*, the pericarps of which accumulate stress by drying and then scatter seeds by spiral motion. Finite-element analysis to simulate bursting of the fruit was carried out to consider the bursting mechanism.

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Keywords

Vicia angustifolia, Bursting fruit, Spiral motion, Finite-element analysis

Branch Motion of Mature Decurrent Crowns: Experimental and Theoretical Analysis

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Abstract

It is thought that trees develop structural properties and architectures that help withstand loading conditions by dissipating wind energy through damping mechanisms. The role of branch motion in reducing potential dangerous wind loads has been the focus of relatively few studies. Even fewer studies have measured mature tree branch motion in wind loaded conditions. In this investigation a 3-Dimensional motion capture system tracked the movement for six branches on each of three mature *Fraxinus americana*. Branch frequencies were calculated from for both wind loading and hand loading conditions. Individual branch frequencies and phase angle values were calculated after pruning removed portions of the tree crown mass. Wind loaded branch sway frequencies ranged between 0.2 and 1.1 Hz while the pull and release test induced mean frequencies of 0.2 Hz. No significant difference between phase angle shifts or frequencies was found after the removal of tree crown mass.

To provide a rigorous process for quantifying the mechanical response in an unambiguous way, a new physics-based model is developed to describe the vibrations of a tree. Specifically, this is a two dimensional model that describes the motion of the center of mass of the trunk and each of its N branches. The trunk and branches interact through torsional springs that serve as equivalent bending stiffnesses for each constituent parts. A Newtonian analysis yields a set of $(N + 1)$ highly nonlinear, coupled, second order ordinary differential equations that, when solved, describe the response of the trunk and each branch. Several low dimensional examples ($N = 2$ and $N = 3$) are used to highlight the solution process and to discuss the predicted physical behaviors uncovered by this model.

Keywords

3-D motion capture, phase, frequency, link model, physics

The ultrafast fern sporangium catapult

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Abstract

We study the mechanism of spore discharge in ferns. It consists in the fast release of a spring-like structure, the sporangium, which contains the spores, after its opening due to dehydration. Thirteen cells constituting the annulus surround the capsule containing the spores. Through a thin membrane, the water inside these cells evaporates. The resulting decrease in volume, along with cohesive forces induced, lead to a change in curvature of the annulus. When the negative pressure is too high in the annulus cells, cavitation bubbles are nucleated. This releases the tension in the cells and leads to a very fast motion of the sporangium that springs back at 10 m/s.

We present our observations, measurements and modeling of the whole mechanism for natural, isolated, sporangia. The three phases: opening, cavitation and fast closing are studied in detail. We focus here on the fast closing phase. We show in particular that the poroelastic nature of the annulus leads to a two times scale recoil: an uncommon behavior among fast plant motion which enables a very efficient discharge: a wonderful example of an autonomous catapult (1).

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Keywords

Fern sporangium, spores dispersal, fast motion, poroelastic, cavitation

Growth Dynamics of an avocado tree leaf

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Abstract

Simple observation of plants with appropriate time constants is enough to be fascinated by the beauty of plants motions. Their diversity is also remarkable, but most of them seem to be the straightforward consequence of their growth : a spatially in-homogenous differential growth in the biological tissue implying different mechanical deformations.

One could insist on the biological gain that get the plant thanks to its motions (temporal regulation of its shape, size and position). We focus on the coupling between motion and growth.

Our approach is phenomenological : We start from macroscopic observation. Actually, We take the same approach as previous studies where 2D motions were observed, modeled and understood (by one of the author [1])

Nevertheless, to study the 3D motion of a leaf though, we had to develop a 3D stereoscopic tool. We can for example record temporal evolution of local growth rate of curvature. These data will serve then as basic ingredients for a macroscopic modeling of the system.

References

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Keywords

leaf motion differential growth

Exploring the attachment mechanisms of *Peperomia* fruits (Piperaceae)

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Abstract

The aim of this project is to examine the functional and evolutionary importance of fruit attachment mechanisms in the plant genus *Peperomia*. Epiphytic *Peperomia* fruits bear sticky substances on their surface which are most likely adaptations to dispersal by animals as vectors. We are exploring the functionality and composition of this sticky secretion with regard to dispersal ecology and biomimetic potential of the adhesive. Pull-off measurements and qualitative cryo-SEM analyses have been performed to characterize the behaviour of the *Peperomia* adhesive. According to our observations, the adhesive shows viscoelastic properties resembling those of pressure sensitive adhesives (PSA). The fruits remain sticky under water, and even ethanol and acetone treatment do not affect their stickiness but likely assist potential rehydration. Furthermore, the adhesive seems to be highly drought-resistant with the capability of subsequent rehydration leading to initial pull-off forces. We intend further biomechanical and biochemical investigations to complete the profile of the *Peperomia* adhesive according to its prospective biomimetic value

Keywords

adhesive attachment, plant glue, fruit dispersa

Mechanism of active closure of the Venus flytrap : pressure probe measurements at the cellular level

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Abstract

From a biomechanical perspective, plants offer a fascinating example of living systems capable of producing non-muscular movements. While most of these movements are slow, some compete in speed with those observed in the animal kingdom and are involved in essential functions such as seed/pollen dispersal, defense and nutrition. Of these spectacular examples that have long fascinated scientists, the Venus flytrap, whose leaves snap together in a fraction of second to capture insects, has long been a paradigm for study. Recently, we have shown that this motion involves a snap-buckling instability due to the shell-like geometry of the leaves of the trap. However, the origin of the movement that allows the plant to cross the instability threshold and actively bend remains largely unknown. Two main mechanisms have been proposed in the literature: (i) a rapid flow between cells due to changes of osmotic pressure, (ii) a rapid cell expansion due to mechanical modifications (softening) of the cell wall. In this study, we investigate these mechanisms using a cell pressure probe that gives direct mechanical and hydraulic measurements at the cellular level (cell wall elasticity, cell membrane permeability, turgor pressure). In parallel, we develop a non-invasive indentation method using a small bead attached to a rheometer to probe mechanical properties at the intermediate tissue level. Our results provide new clues to understand Venus flytrap's cryptic non-muscular engine.

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Keywords

plant biomechanics, poroelasticity, cell mechanics, microfluidic, osmotic pressure

Regulation of shape and position of the stem during two consecutive years after tilting in maritime pine

(*Pinus pinaster* Ait.)

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Abstract

Maritime pine (*Pinus pinaster* Ait.) is an important conifer in terms of volume of wood obtained, but its wood quality is usually reduced by the lack of stem straightness. The biomechanical processes underlying stem straightening reactions after tilting provide an alternative approach to the assessment of stem form in breeding programs. In this species, importance of geotropic and autotropic secondary reactions in the straightening process after tilting has already been demonstrated. In this study we analyzed the extent to which two year old plants tilted 45 degrees are able to fully recover the orthotropic position and how regulation of shape and position of the stem happens in two consecutive years after tilting. The results indicate that the main part of the straightening occurs in the first growing season after tilting, is stopped during the winter and resumed in the next growing season. Once the growing apical part reach 90 °, the remnant curvatures in the basal part are modified by a continuous balance between gravitropic and autotropic reactions. Studied plants were 2 years old when tilting. The monitoring was performed by periodic photographs of each plant from the same point. Subsequently, we studied the reaction wood formed in the two growing periods.

Keywords

Pinus pinaster; straightening, tilting, autotropism, geotropism, reaction wood

Fast plant movements

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Abstract

Here we report on our recent research regarding biomechanics and functional morphology in different examples of fast plant movements. The first example is the suction trap of aquatic carnivorous bladderworts (*Utricularia* spp.). Suction functions with a release of stored elastic energy in the trap body and the very fast opening and closing of a trapdoor, which performs a buckling/unbuckling process with a complete curvature inversion. This deformation is morphologically predetermined owing to radially arranged cell patterns on the inner side of the two cell layers thick trapdoor. The same trapping behavior is also present in non-aquatic species of *Utricularia*. In the second example we show that the two closely related carnivorous snap-trap plants *Dionaea muscipula* (Venus Flytrap) and *Aldrovanda vesiculosa* (Waterwheel Plant), both from the Sundew family (Droseraceae), feature completely different trap closure mechanics. *Dionaea* trap lobes shut by abruptly flipping their curvature from concave to convex, whereas the lobes of *Aldrovanda* do not change curvature during closing. Here, shutting relies on kinematic translation due to the deformation of the trap leaf midrib that connects the two lobes. The third plant investigated is the carnivorous sundew *Drosera glanduligera*. Generally, sundews are well-known for possessing sticky traps with glue tentacles which show slow nastic and tropistic bending motions to secure caught prey. *D. glanduligera* significantly differs from all other species: additionally to the glue-tentacles it features marginal, glue-free snap-tentacles that rapidly bend inwards after mechanical stimulation. The motion possesses enough force to lift up prey animals approaching the trap and to catapult them into the sticky trap leaf lamina. This novel combined trapping/retention mechanism is discussed with a focus on functional tentacle morphology. In the fourth section we present our results on ballistic spore discharge in the polypod fern *Adiantum peruvianum*. The discharge is owing to a cohesion-force induced tensioning and subsequent elastic relaxation of the leptosporangium annulus ring. We tracked the motion of the sporangia in action and the spore trajectories and found that the ejection process comprises a combined catapulting/shaking behavior of the sporangium, leading to the formation of two distinct spore clouds. We hypothesize that this mechanism promotes wind dispersal and is likely to be a general principle for spore ejection in leptosporangiate ferns.

Keywords

fast plant movement, elastic relaxation, *Adiantum*, *Aldrovanda*, *Dionaea*, *Drosera*, *Utricularia*

Foliar disease transmission: Insights from fluid dynamics

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Abstract

Rainfalls are suspected to trigger the spread of a multitude of foliar diseases, which could be devastating for agriculture and forestry. Previous studies were mostly carried at the ecological scale. This study focuses on the dynamics of ejection of pathogens from contaminated leaves when impacted by a single raindrop. Visualizations using high-speed imaging reveal a wealth of key fluid dynamical phenomena critical to the ejection of pathogen-loaded droplets from infected plants. We discuss the dramatic influence of leaf compliance on the size and range of the ejected droplets and the different modes of precipitation-induced foliar disease transmission identified.

Keywords

Rain, epidemiology, leaf compliance

Hygroscopic Movement in Geraniaceae- Diversity, Structure and Evolution

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Abstract

Geraniaceae is a family of flowering plants characterized by *hygroscopic seed dispersal mechanisms, in which long narrow appendages (awns) are attached to the seed capsules*. These awns are essentially dead tissue that responds to humidity changes, contracting and deforming to facilitate the dispersal of the seeds. *The awns within the Geraniaceae family display several types of deformations, mainly bending and coiling, when coiling is the most common*. Some species have a relatively thin and soft coiling awn that enables seed dispersion by wind, while species that have a more robust awn rely on dispersal by animals and catapulsion. On the other hand, species utilizing a bending awn rely only on catapulsion for their seed dispersal. In this work we elucidate the structural variation leading to the different functionality of the awns. We chose five representative members of the three main genera in the Geraniaceae family; *Erodium*, *Pelargonium* and *Geranium*. The awns of the chosen species display different deformation. We characterized the cell wall nanostructure by small angle X-ray scattering as well as polarized light microscopy, using the LC-PolScope system. This system, that has been widely implemented in cytoskeleton studies, has been rarely used in the investigation of plant cell wall organization. Here we show this system to elucidate spatial aspect in the information obtained from the X-ray analysis. We found that while the bending awn relies on a bi-layered structure similar to bilayer thermometers, coiling awns rely on an unusually tilted cellulose microfibrils organization within the cell walls (1). We show that specific variation in the layering of the awn, along with the change in the cell wall nanostructure, controls the dry awns topology and adjusts the dispersal mechanism functionality to the changing environmental conditions.

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Keywords

hygroscopic movement; coiling; cellulose; microfibril angle; small-angle X-ray scattering; polarized light; LC-PolScope; Geraniaceae

Session Growth

Biophysics of growth

Anisotropic expansion of higher plants

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Abstract

How does a plant build an organ with a specific and heritable shape? The shapes of plant organs arise by expansion. Cell walls deform under turgor and the shape of the organ represents the sum of all deformations over all cell walls. Turgor is hydrostatic pressure and is isotropic; nevertheless plant cell walls almost always deform anisotropically. Growth anisotropy derives from the distribution of stresses within the wall as well as from anisotropic material properties of the cell wall. Anisotropy varies in both direction and degree. The direction of anisotropy is accepted to be specified the orientation of cellulose microtubules but what specifies the degree of anisotropy has been little studied. In green algal cells, pioneering work of Paul B. Green showed that the degree of expansion anisotropy tends to be constant. I will present data for the roots of vascular plants indicating that expansion anisotropy varies appreciably. To explain this variation, the degree of anisotropy has been hypothesized to be controlled by the degree of alignment among cellulose microfibrils. I will support this hypothesis with evidence from polarized light microscopy and high-resolution scanning electron microscopy, with the proviso that relevant scale for the variation in cellulose alignment is not local (i.e., among neighboring microfibrils) but rather global (i.e., among cells). Nevertheless, properties in addition to microfibril alignment almost certainly help specify the degree of anisotropy, properties whose identity remains indecipherably masked.

Keywords

plants

New methods for probing cell mechanics in growing plant tissues

Routier-Kierzkowska A.-L., Weber A., Kierzkowski D., Nakayama N., Barbier de Reuille P., Kuhlemeier C., Smith R.S.

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Abstract

Plant organs are complex structures that must maintain their mechanical integrity while growing. At the cell level, this requires the coordination of cell wall modification and/or turgor pressure between neighbors. How do organ shape and global mechanical properties emerge from regulation at the cellular level? Is growth driven by changes in turgor pressure? or by changes cell wall elasticity? and which cells or layers of cells are responsible for determining organ shape?

To answer these questions it is important to be able to quantify the mechanical properties of cells. However, these kind of measurements in living cells is a technical challenge. To address this gap, we have developed Cellular Force Microscopy (CFM), a micro-indentation technique for in-vivo stiffness measurements of individual cells (*Plant Physiology*, 2012). With CFM, a large range of forces and displacements are possible, making it suitable for measurements on both plasmolyzed and turgid tissues. Repetitive measurements can be performed over time, showing that the technique can be non-invasive. CFM can be also used to ablate cells and measure forces as the cell wall is deformed until it ruptures. Depending on experimental conditions, the stiffness measured by CFM can give an insight into cell turgor, local wall elasticity as well as cell wall strength. We use physical based simulations to untangle these different contributions to the measured stiffness (see A. Weber abstract).

Another approach to quantify cell wall elasticity is to track deformation in response to changes in turgor pressure. Using osmotic treatments to modify turgor, we showed that shoot meristem, which produces new leaves, is divided into zones of distinct elastic properties (*Science*, 2012 335:1096). To precisely quantify cell expansion, we have developed software called MorphoGraphX to extract cell geometry from 3D confocal stacks. Using our software we could also track growth at the cellular level. Our results show that the slow growing central zone, containing the stem cell niche, is substantially strained-stiffened compared with the fast growing surrounding peripheral zone. Thus, wall mechanical properties do not only result from gene action and cell history, but feed back on morphogenesis.

Keywords

primary cell wall, turgor, elasticity, growth, biomechanics, micro-indentation, 3D reconstruction, imaging

Embryo growth, endosperm weakening and testa permeability are major targets for the inhibition of *Lepidium sativum* seed germination by myrigalone A

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Abstract

The soil water status, ambient light and temperature are key environmental factors that determine seasonal germination patterns and modulate persistence and dormancy of soil seed banks. Allelochemicals are produced by one species and often inhibit seed germination of competitor species. Little is known about their mode of action on molecular and biomechanical levels. Mature seeds of the Brassicaceae species *Lepidium sativum* possess a thin endosperm layer surrounding the embryo, which, together with the testa (seed coat), regulates germination by acting as a constraint to radicle protrusion. Prior to endosperm rupture and radicle protrusion, the embryo radicle/hypocotyl axis (RAD) elongates due to cell expansion growth, the testa ruptures, and the micropylar endosperm (CAP) weakens. Endosperm weakening is promoted by gibberellins (GA) and inhibited by abscisic acid (ABA). Molecular mechanisms of CAP weakening as an important biomechanical process depend on hormonally and environmentally regulated expression of cell wall remodeling proteins and apoplastic reactive oxygen species (ROS) that can alter the biomechanical properties of the RAD and CAP cell walls. The size of *L. sativum* seeds allows biomechanical and molecular tissue-specific analyses, such as puncture-force measurements of CAP tissue resistance, detailed quantification of embryo organ sizes and growth, and tissue-specific quantification of GA and ABA contents and mRNA transcript abundances. Myrigalone A is a flavonoid in fruit leachates of *Myrica gale*, a deciduous shrub adapted to flood prone habitats. MyA is a putative allelochemical and inhibits *L. sativum* seed germination. We show that MyA delays endosperm rupture and affects the biomechanical properties of the CAP tissue, the testa and embryo growth. MyA acts by inhibiting CAP weakening and this effect is much stronger in darkness compared to the light. The permeability of *L. sativum* seed envelopes is increased by MyA, causing an increased water uptake rate during imbibition. MyA also targets RAD growth, as MyA-treated seeds require a 1.4-fold larger embryo than the control for achieving 50% of endosperm rupture. Apoplastic ROS production in specific zones of the *L. sativum* RAD important for cell expansion growth is inhibited by MyA which acts as a radical scavenger. MyA also interferes with gibberellin metabolism by inhibiting GA3 oxidase, as well as with the GID1-type GA-signaling pathway. The phytotoxic effects of MyA are achieved by targeting several key molecular and biomechanical steps of seed germination and seedling establishment, securing the persistence of *M. gale* in a flood prone environment by degrading the surrounding soil seed bank.

Keywords

allelochemical, apoplastic superoxide, embryo growth, endosperm cap weakening, gibberellins (GA), imbibition, *Lepidium sativum*, myrigalone A (MyA), seed germination, testa permeability

The Mechanics of Hypocotyl Elongation in the Dark: A Study of Anisotropic Cell Expansion

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Abstract

When a seed germinates in the earth, it must rapidly grow up through the soil to reach light- enabling it to begin photosynthesizing. In Arabidopsis, this growth occurs through expansion of the hypocotyl- the organ separating the shoot and root apical meristems of the seedling. The Arabidopsis hypocotyl has a relatively fixed cell number and organization making it a simple system for study. During growth in the dark the hypocotyl extends purely by anisotropic cell expansion, where by cell length can increase by at least an order of magnitude. Cell expansion along the hypocotyl proceeds initially as a uniform slow growth phase, followed by an arcopetal exponential growth wave. We have examined the mechanics associated with anisotropic cell expansion and the exponential growth wave in the hypocotyl by monitoring the following parameters: 1) growth kinematics on the organ and cellular level, 2) cell wall elasticity dynamics using Atomic Force Microscopy, 3) pressure estimation via plasmolytic tests, and 4) central vacuole development. Using these parameters we have developed a simple and elegant model to describe the mechanics of anisotropic cell expansion.

After careful characterization of hypocotyl growth kinematics, we were able to match changes in growth to changes in mechanical properties as follows: Exponential anisotropic cell expansion was preceded and accompanied by changes in cell wall elasticity. Exponentially expanding cells and slowly expanding cells within the same hypocotyl at any stage did not show differences in pressure; however, the global pressure of the hypocotyl did begin high and decrease during hypocotyl extension. Finally, the exponential growth wave was always associated with changes in vacuole morphology.

In order to further understand the role of the cell wall in anisotropic cell expansion, both growth kinematics and wall elasticity were examined after microtubule disruption and cellulose inhibition- treatments which cause isotropic cell expansion in the hypocotyl. These treatments abolished the changes in cell wall elasticity normally seen in exponentially expanding cells. Interestingly, these treatments did not affect the acropetal procession of the exponential growth wave. Similar measurements were made after alteration of cell wall pectin modification by ectopic expression of a pectin methylesterase. Further investigations include deciphering a possible role of polar auxin transport in controlling the mechanics of dark grown hypocotyl cell expansion.

Keywords

growth, anisotropy, kinematics, hypocotyl, AFM

Investigation of the interaction between wall hydration and mechanical behaviour using composites of cell wall polysaccharides with bacterial cellulose

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Abstract

- Rationale:

Previous work by this group has used manipulation of cell wall water content using high molecular weight *osmotica* to demonstrate that cell wall mechanical behaviour is affected by the water content of the cell wall in sunflower hypocotyls. Furthermore, osmotic pressures of as little as 0.21 MPa, which would correspond to water potentials that would commonly be experienced by plants under field conditions, were found to reduce long-term extensibility to a degree that would appear likely to affect growth *in vivo*. This work investigates the effects of individual wall polysaccharides on wall extensibility and hydration.

Composites of bacterial cellulose (produced by *Gluconacetobacter xylinum*) incorporating apple pectin, polygalacturonic acid (PGA), rhamnogalacturonan II (RGII), xyloglucan, oat beta glucan and lichenan were prepared (including some composites with multiple components). Their mechanical properties were analysed using a constant-load extensometer under conditions of full hydration and after reduction of the water content using high molecular weight polyethylene glycol (PEG 6000). Additionally, dehydration and rehydration of the composites were investigated.

- Findings:

Composites with hemicelluloses (xyloglucan, oat beta glucan and laminarin) were similar to one another and were substantially more extensible than either bacterial cellulose alone or cellulose with only pectins. Although composites with apple pectin were more extensible than cellulose alone, these two materials were comparable in texture, whereas those incorporating hemicelluloses were much more prone to thinning under stress or even manipulation. Additionally, composites with xyloglucan lost a much greater proportion of their weight (72%) than cellulose (45%) or cellulose with apple pectin (44%) in PEG 6000 solutions with an osmotic pressure of 0.62 MPa. None completely rehydrated in control buffer alone after this treatment, but did when treated with cucumber expansin. Composites of cellulose with xyloglucan and apple pectin were substantially less extensible after treatment with PEG 6000.

- Conclusions:

These observations confirm the effect of water content on cell wall extensibility, suggesting that water “plasticises” plant cell walls. Additionally, the effect of expansins on rehydration of the composites suggests that they affect wall hydration and that this may contribute to their effect on extensibility and growth. Finally, we suspect that the effect of hemicelluloses on the texture of the composites may be related to their role in the wall and that the narrowing of these composites under stress and their loss of water when treated with PEG 6000 are related, reflecting a structure in which realignment of cellulose fibrils occurs much more easily.

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Keywords

Rheology, Growth, Water Stress

Control of cell wall integrity during plant growth

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Abstract

Plant cell walls are at the same time stiff and extensible. How this extensibility is controlled during turgor driven cell expansion while avoiding rupturing of the cell wall is still poorly understood. An elegant homeostasis mechanism has been described in the green freshwater alga *Chara corallina*. In this species, Ca/pectate cross-links are load bearing in the cell wall. Cells go through a growth cycle initiated by the deposition of pectate, which chelates Ca, thus removing existing cross links causing wall relaxation and cell expansion. Next, new Ca/pectate cross links become load-bearing causing the stiffening of the wall etc. In higher plants a similar mechanism may participate in growth control with the further complication that pectin is secreted in a highly esterified form, and thus unable to form Ca/pectate cross links, and that a battery of pectin methyl esterases fine tune the amount of pectate available for Ca/pectate crosslink formation. An additional sophistication in higher plants as compared to *Chara* is that at least one other load-bearing network exists in the growing cell wall consisting of cellulose/xyloglucan crosslinks.

In this presentation we will show that the control of pectin methylesterification plays a key role in the mechanical properties of the cell wall. We will also show that plant cells are endowed with mechanisms that sense the degree of pectin methyl esterification in the cell wall and which control the mechanical homeostasis of the cell wall.

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Keywords

Cell wall, pectin, pectin methylesterase, Arabidopsis, wall integrity

Invasive cellular growth in pollen tubes

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Abstract

The pollen tube is a cellular tunnel transport system that is generated to connect the male gametophyte with its female counterpart. Through this cellular protuberance the sperm cells are delivered from the pollen grain to the ovule. To be competitive, the pollen tube elongates extremely rapidly. At least two opposing mechanical constraints determine the size of this tubular protuberance: Fracture mechanics dictates that a smaller cell can invade the pistillar tissues with greater ease. However, a sufficiently large diameter is required to allow the sperm cells to pass through the tube. Although the tube diameter varies significantly between species, it is extremely well controlled within a single species. In a mechanical model based on finite element techniques we demonstrate how the pollen tube has to control the mechanical properties of its apical cell wall in order to produce a cylinder with the desired size. To understand how the pollen tube navigates the mechanical impedance presented by the pistillar tissues we grew pollen tubes in micro-channel devices and tested their ability to penetrate narrow spaces. These Lab-on-a-Chip based devices were also used to measure the invasive force of the pollen tube.

Keywords

invasive growth, cell growth, pollen tube

A model of crosslink kinetics in the expanding plant cell wall: yield stress and enzyme action

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Abstract

The plant primary cell wall is a composite material containing stiff cellulose microfibrils that are embedded within a pectin matrix and crosslinked through a network of hemicellulose polymers. This microstructure endows the wall with nonlinear anisotropic mechanical properties and allows enzymatic regulation of expansive cell growth. We present a mathematical model of hemicellulose crosslink dynamics in an expanding cell wall incorporating strain-enhanced breakage and enzyme mediated crosslink kinetics. The model predicts the characteristic yielding behaviour in the relationship between stress and strain-rate seen experimentally, and suggests how the effective yield and extensibility of the wall depend on microstructural parameters and on the action of enzymes of the XTH and expansin families. The model suggests that the yielding behaviour encapsulated in the classical Lockhart equation can be explained by the strongly nonlinear dependence of crosslink breakage rate on crosslink elongation. The model also demonstrates how enzymes that target crosslink binding can be effective in softening the wall in its pre-yield state, whereas its post-yield extensibility is determined primarily by the pectin matrix.

Keywords

cellulose microfibril; hemicellulose; yield stress; enzyme action

Kinematic analysis and regulation of TIP1 aquaporins expression in the growing root apex of poplar under osmotic stress

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Abstract

Regulation of gene expression is determined from instantaneous measurements made on discontinuous samples. However, in developing multi-cellular structures, cells are displaced and expand. Access to an unbiased view of the spatiotemporal regulation of gene expression occurring during development requires to properly quantifying the rate of change of transcript density in a moving and expanding element, such as a cell or an organ segment. A conceptual framework, combining transcript density at a high spatial resolution and a fluid mechanics formalism, was established to describe the regulation of gene expression in time and space along the root apex (Merret et al, 2010).

Aquaporins form a superfamily of intrinsic channel proteins that facilitate the bidirectional transfer of water and other small neutral molecules across biological membrane. The past two decades revealed that these proteins play an important role in plant water balance, notably in the response to water deficit. At the cell scale, some aquaporins were shown to be involved in the control of the water flow required for cell expansion (Hukin et al, 2002, Volkov et al, 2007). This study focused on the expression of the *TIP1* aquaporin subfamily, in the growing root apex of poplar cuttings grown in hydroponics and submitted to two levels of osmotic stress.

The 8 *TIP1s* showed specific expression patterns. Growth reduction was associated with a shift of maximal transcript densities towards the tip, where cell expansion was maintained. The analysis of the spatiotemporal patterns of regulation of gene expression highlighted that high density does not mean high induction but can also be due to moderate but prolonged induction. *PtTIP1;4* density profile overlapped the REGR profile, whatever the conditions. Moreover, the regulation of its expression had a similar temporal pattern in all treatments, even if the size of the growth zone varied, supporting the hypothesis of a functional link between *TIP1;4* and cell expansion. We show that the conclusions derived from the analyses of these dynamic processes, cell expansion and gene expression, are influenced by the way time and space are considered.

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Keywords

Kinematics, cell expansion, regulation of gene expression, aquaporin, root apex, water deficit

Growth of plants under dynamical stimulation

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Abstract

Plants are constantly submitted to dynamical loads due to wind and strain-dependant growth has been reported. Indeed, it is known that plants sense the strains induced by a static bending and adapt through a reduction of elongation and activation of radial growth [1].

However, the motion induced by the wind implies oscillations of the plant [2]. These oscillations can be described as a function of the plant vibration modes, that are here characterized by a modal shape and a frequency.

We are interested in the influence of the dynamics on thigmomorphogenesis, and in particular on the modification of radial growth. In a first experiment, we investigated the dynamic of a young poplar at a given state, then the radial growth of such a poplar submitted to different treatments was monitored during two months.

The motion of the plant submitted to controlled vibrations at a given amplitude, and with a varying frequency were recorded using a camera. The movies were then analysed in order to obtain the modes. We showed that the vibration modes are localized in three different parts of the plant : the whole stem, the apex and the leaves. We thus identified three typical modal shapes. These modes are also organized according to their frequency. At low frequencies, < 5Hz, we observed stem modes, between 5 and 15 Hz, apex modes. For higher frequencies, we saw vibrations of isolated leaves : leaf modes.

To study the influence of the dynamics on the growth, experiments on the same type of young poplars undergoing secondary growth were conducted. Three times a week, during eight weeks, three treatments were applied : (1) static bending, (2) static bending and maintained oscillations on the first stem mode, (3) static bending and maintained oscillations on an apex mode. In addition, we had a control group made of plants that were not stimulated.

In the basal part of the stem, the growth rates of the stimulated plants were significantly higher than those of the control group. The three treatments presented very similar growth pattern. Therefore, our results suggest a dominant perception of the static component of the stimulation.

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Keywords

Growth, Dynamic, Perception

Epidermal cell growth is quantised into cell periphery portions at contacts with different neighbours - a case study of arabidopsis puzzle-shaped cells.

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Abstract

Epidermis of an expanding arabidopsis leaf, similar to other dicots, is a mosaic of cells differing in identity, size, ploidy, and differentiation stage. Epidermal pavement cells exhibit a puzzle shape (wavy anticlinal cell walls) that becomes more pronounced and complex with cell differentiation. In our recent empirical study we have shown that growth of such a cell mosaic is heterogeneous and changes in time [1]. In particular, relative growth rates in area of individual epidermal cells or small groups of cells differ several fold from adjacent cells, and this pattern changes in time. Such spatial and temporal variation is related neither to cell nor to nucleus size.

In the present investigation we quantify shape, size, and growth of individual epidermal cells in expanding leaves of wild type *Arabidopsis thaliana* and mutant plants with cell cycle defects, paying special attention to heterogeneity of growth at subcellular level and local changes of cell shape. Using the sequential replica method we obtain stereopairs of scanning electron micrographs from leaf surface at consecutive time points. These stereopairs are further used to reconstruct the surface in 3D and compute various cellular parameters with the aid of codes written in Matlab.

Our results confirm the postulate that growth of plant cells is quantised into pairs of anticlinal walls belonging to adjacent cells, further called the cell wall segments. The fact that portions of a given cell periphery that are at contacts with different neighbours, grow with different rates is related to growth variation within an individual cell. Growth rate in length of wavy anticlinal wall of the cell is different at contacts with different neighbours. The growth variation of periphery of the individual cell is apparent also if only vertices (contact points of anticlinal walls of three neighbouring cells) are used for growth computation. We show that changes in anticlinal wall shape of the cell are also quantised into cell wall segments: anticlinal wall waviness appears at different time in wall portions at contacts with different neighbours, and this is dependant both on the cell wall age and length. We also search for relationships between parameters of cells contacting at the given anticlinal wall segment (e.g. cell surface area, circularity etc.) and the segment growth and waviness.

This work is financially supported by the advanced researchers grant from the National Science Centre (decision number DEC-2011/02/A/NZ3/00079).

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Keywords

epidermis, growth heterogeneity, anticlinal wall waviness, arabidopsis

Biophysical modelling of cambial activity and wood formation in conifers

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Abstract

Understanding wood density variations in conifers is of primary interest to industrial applications as well as dendrochronological studies. Softwood mechanical properties are indeed strongly related to wood density and its ring variations. Moreover, there is empirical evidence that wood density and ring width are influenced by climatic conditions (temperature, drought...).

At the cellular level, wood density is directly linked to the anatomical characteristics of xylem cells, especially lumen diameter and cell wall thickness. These characteristics result from cambial activity and xylem development, which involve complex environmental interactions and internal regulation mechanisms. The biophysical approach to modelling dynamics of xylem formation seems to be one of the most promising attempts to explain cause–effect relationships and, ultimately, predict wood properties from environmental conditions.

Hölttä et al. (2010) followed this approach and were able to predict the hourly stem diameter variations of a Scots pine. In their model, cambial dynamics is described at the individual cell level. Irreversible cell expansion and secondary cell wall synthesis are induced by turgor pressure and local sugar concentration. The cambium model is connected with a long-distance xylem and phloem transport model. Inputs are soil water potential and transpiration and photosynthesis rates.

Hölttä's model focuses on short-term cambial dynamics, and is not intended to simulate intra-annual density profiles along stem radius. However, it paved the way for integrative models that could simulate one (or better, several) whole growing seasons. Such integrative approaches will have probably to reduce the number of fitted parameters and thresholds.

Our research aims at amending and extending existing models to explore the complex processes which shape xylem cells. We put emphasis on the geometrical and mechanical constraints that control and limit cell growth. Biophysical mechanisms are used wherever it is possible.

In this talk, I will discuss what biophysical modelling can bring to our understanding of tree ring formation. I will show how this approach can be used to validate or reject empirical hypotheses on processes or couplings between processes.

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Keywords

biophysical modelling, cambial activity, wood formation

In vivo analysis of local wall stiffness at the shoot apical meristem in Arabidopsis using atomic force microscopy

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Abstract

Whereas the morphogenesis of developing organisms is relatively well understood at the molecular level, the contribution of the mechanical properties of the cells to shape changes remains largely unknown, mainly because of the lack of quantified biophysical parameters at cellular or subcellular resolution. Here we designed an atomic force microscopy approach to investigate the elastic modulus of the outer cell wall in living shoot apical meristems (SAMs). SAMs are highly organized structures that contain the plant stem cells, and generate all of the aerial organs of the plant. Building on modeling and experimental data, we designed a protocol that is able to measure very local properties, i.e. within 40-100 nm deep into the wall of living meristematic cells. We identified three levels of complexity at the meristem surface, with significant heterogeneity in stiffness at regional, cellular and even subcellular levels. Strikingly, we found that the outer cell wall was much stiffer at the tip of the meristem, covering the stem cell pool, than on the flanks of the meristem. Altogether, these results demonstrate the existence of a multiscale spatialization of the mechanical properties of the meristem surface, in addition to the previously established molecular and cytological zonation of the SAM, correlating with regional growth rate distribution.

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Milani P et al. *Plant J.* 2011 Sep; 67(6): 1116-23.

Keywords

Shoot Apical Meristem, Cell Wall, Mechanical properties, Atomic Force Microscopy.

Understanding the dynamic changes that occur at the cell periphery during morphogenesis in the shoot apical meristem

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Abstract

At its apex, the shoot apical meristem (SAM) contains a population of pluripotent stem cells that ultimately give rise to the plant aerial tissues. As cells become displaced from this central zone to the peripheral region, they undergo changes in growth and shape and carefully integrate various positional and mechanical signals to generate organ primordia. These changes arise principally by alterations in the organisation and deposition of cell wall components which appear to respond to the positional cues principally defined by auxin maxima. Both cell wall deposition and the distribution of auxin are influenced by the underlying microtubules which organise themselves according to the patterns of stress in the meristem [1,2].

We are examining, in detail, the changes in the cell wall, plasma membrane and microtubules that permit the proper form and function of the SAM. By manipulating expression levels of a group of genes involved in cell wall remodelling, we aim to alter the ability of cells in different regions of the meristem to resist or respond to patterns of mechanical stress. In the plasma membrane, we have generated tools that allow us to visualise microdomains in living cells of the meristem and are investigating links with phytohormone distribution. At the cortex, we are characterising an Arabidopsis mutant that perturbs microtubule function resulting in aberrant division and subsequent growth defects in early primordia formation at the peripheral zone. Together, the data will be used to update and test new models on morphogenesis and mechanical properties in the SAM.

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Keywords

shoot apical meristem, cell wall, primordia, cytoskeleton

A midline model for gravitropic root bending

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Abstract

Gravitropism in the root of *Arabidopsis* is driven by differential growth in the root's elongation zone. Growth is regulated primarily by the distribution of the hormone auxin, which in turn is regulated by gravity-sensing cells in the root tip. Here we present a simple mathematical model incorporating these ingredients that we use as a tool to explore the connection between root shape, hormone transport and the root's environment. We parametrise the root by its arc-length and angle to the vertical, and use local force and moment balances to describe the evolution of the axial strain and curvature, modelling growth using a Lockhart-type law at the level of individual cell walls. This formulation can incorporate mechanical interactions between the root and its environment. If bending is restricted to the start of the elongation zone, transverse motions that might be subject to large frictional resistance from the environment are minimized, enabling the root to elongate along its own path, while giving qualitative agreement with experimental data for roots grown in agar. This approach contributes a component of a larger multiscale model of root elongation and bending.

Keywords

root model, gravitropism, *Arabidopsis*, auxin, Lockhart

Cell wall mechanical properties of Arabidopsis hypocotyls in connection with growth and gravitropism: effects of xyloglucan endotransglucosylase_hydrolases, expansin-like proteins and brassinosteroids

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Abstract

To check whether cell wall proteins and brassinosteroids affect growth and gravitropism via the wall mechanics, we studied creep of frozen/thawed hypocotyls from 4-day-old etiolated Arabidopsis plants. We used transgenic lines overexpressing xyloglucan endotransglucosylase/hydrolase AtXTH18, expansin-like protein AtEXLA2 or wild type plants treated with 100 nM epibrassinolide (EBL). AtXTH18 overexpression stimulated growth of hypocotyls but decreased their creep rates vs. wt under all loads (500-750 mg) and pH values (5.0 or 6.0) tested. The reduced creep is explained by a 65% increase in the wall cross-sectional area of AtXTH18-OE hypocotyls vs. wt leading to a lower wall stress generated under any given load. Plotting creep rates for AtXTH18-OE and wt hypocotyls under different loads against the respective wall stress values gave straight lines. Their slopes (ϕ , *in vitro* cell wall extensibility) and intercepts with the abscissa (y , *in vitro* cell wall yield threshold) characterize cell wall material properties. AtXTH18-OE had more extensible wall material than wt because of lower y values. Additionally, AtXTH18-OE hypocotyls demonstrated a more linear creep vs. wt at pH 5.0. Thus the higher growth of AtXTH18-OE hypocotyls correlated with a lower yield threshold and a higher linearity of creep of their cell walls at pH 5.0. AtEXLA2 overexpression had no effect on growth of hypocotyls but increased their creep rate vs. wt at pH 5.0 and 6.0, although only under the maximal load (700 mg) tested. Heat-inactivated AtEXLA2-OE hypocotyls broke under a 700 mg load in 56% of cases versus 27% in wt. The linearity of creep at pH 5.0 was similar in AtEXLA2-OE and wt. Thus AtEXLA2 may control the ultimate strength of hypocotyls without changing their growth rate. EBL-treated Arabidopsis plants grown on horizontal Petri plates had shortened agravitropic hypocotyls lying flat on the surface of agar. Their creep rates at pH 6.0 were higher than those of untreated hypocotyls. Adding sucrose to the growth medium restored the upright growth of EBL-treated hypocotyls decreasing their creep at pH 6.0 to the control level. The shortened hypocotyls of EBL-treated plants demonstrated a less linear creep at pH 5.0 compared to untreated controls. Thus EBL may simultaneously decrease the wall strength (observed at pH 6.0) and the wall capacity for long-term extension (observed at pH 5.0). Overall, the linearity of creep at pH 5.0 demonstrated the best correlation with growth in Arabidopsis hypocotyls.

Keywords

Arabidopsis, hypocotyl, biomechanics, creep, XTH, expansin-like proteins, brassinosteroids, growth, gravitropism

A qualitative model of symplastic and intrusive growth of the vascular cambium of broadleaved trees - a biomechanical perspective

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Abstract

It is assumed that growth of cells is a mechano-osmotically driven process. The mechanical forces responsible for the plastic deformation of cell walls are generated internally by hydrostatic pressure of living cells, or externally by surrounding tissues. In vascular cambium there are two distinct types of growth. The first type is symplastic growth when neighbouring cells grow in a coordinated way. The second is intrusive growth in which cell ends or edges grow in between the cell walls of neighbouring cells. In this process the contacts between cells changes and thus the cambial cells are readjusted. A qualitative model is proposed in which consecutive processes involved both in symplastic and intrusive growth of the vascular cambium are described. It is hypothesized that these growth processes in the vascular cambium are driven by diurnal strains caused by transpiration. During the day water is lost and osmotic adaptation helps the plant to survive a short period of water stress. During the night water is replenished in a greater quantity than the amount lost during the day and this generates mechanical stress. The side effect of these two consecutive stresses is diurnal generation of mechanical stresses between tissues of different mechanical properties. The vascular cambium lying between the phloem and xylem is under tensile stress during the night and under compressive stress during the day. One of the most important factors enabling radial growth of the vascular cambium is radial tension which increases during the night due to the swelling of the phloem. It can be assumed that symplastic growth of the vascular cambium in a radial direction is an externally driven process of relaxation of cyclically generated tensile stress. The vascular cambium adapts to this tensile stress by (1) elastic deformation (lasting two hours starting from sunset) and by (2) elasto-plastic deformation of meristematic tissue (up to midnight). But when the value of the tensile stress overcomes the adaptive plasticity of the cambial cell walls, then the middle lamellae of tangential walls of meristematic cells can be forced apart locally. This paves the way for intrusive growth into the resulting micro-space formed (from midnight till sunrise). Intrusive growth is a process internally driven by turgor pressure. The formation of micro-cracks helps to relax critical tensional stresses that emerge locally. Micro-cracks are located mainly on boundaries between cambium-phloem and cambium-xylem, due to the large differences in the mechanical properties of the tissues which surround the vascular cambium. In the first location micro-cracks are dispersed along the whole initial layer of the cambium and are formed between tangential walls of initial cells and their immediate derivatives (causing the cells to readjust). In the second location on the boundary of the cambium and xylem the micro-cracks are formed in the place of future fibres and vessel elements. After sunrise the phloem shrinks and the vascular cambium is under compressive stress between the shrinking phloem and xylem. This compression is responsible for the partial withdrawal from the micro-spaces of cell ends or cell edges and their reintegration of the meristematic tissue. This model reinterprets the mechanism of radial growth of trees and integrates different cell events observed during this process such as intrusive growth of initial cells and fibres as well as vessel element formation.

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Keywords

vascular cambium, symplastic growth, intrusive growth, radial tensile stress, diurnal strains

Session Biomim

Plant biomechanics for biomimetics

Plant cells as inspiration for adaptive composites and actuators

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Abstract

The secondary plant cell wall is a composite of cellulose nano-fibrils and a water-swelling matrix containing hemicelluloses and lignin. The cellulose microfibril distribution in the plant cell wall not only controls the mechanical properties of the tissue but – in conjunction with the swelling capacity of the matrix – helps generating growth stresses; e.g., in conifer branches. A similar mechanism also provides motility to various seeds. Simple mechanical models are able to describe these experimental observations and predict that – depending on the detailed architecture of the cellulose fibrils – swelling may lead either to significant compressive or tensile stresses or to large movements at low stresses. The general actuation principle is based on the architecture of oriented fibrils which transform a simple pressure into complex movements. Such composite fibre architectures in plant systems are providing guidelines for the design of adaptive composite materials and actuators.

Keywords

cellulose

A tree-inspired damping mechanism in flexible structures: damping-by-branching

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Abstract

Strong dynamic loads in man-made slender structures are likely to produce large amplitude vibrations of due to their flexibility, which often cause functionality losses or inflict irreversible damages. The amplitude of motion results, on one hand, from the characteristics of the loading, and on the other hand, from the characteristics of the structure in terms of inertia, stiffness and damping. A high rate of damping, i.e. mechanical energy dissipation whatever the physical mechanism, is a standard way to limit vibrations of large amplitude and their undesirable consequences. However, adding damping in slender structures remains a challenging problem in engineering. As slender and flexible structures, trees repeatedly endure strong climatic events, yet with minor or no damages in most cases. Therefore, trees regularly submitted to natural flow excitations by wind are likely to possess efficient and specific strategies of damping. In fact, several damping mechanism have been identified in trees: viscoelastic behaviour of wood, aeroelasticity from the interactions with air, and the linear tuned-mass-damper effect between the trunk and the branches. However, the latter, as a linear mechanism, is not amplitude-dependent and therefore does not damp specifically large amplitude motions.

A new amplitude-dependent damping mechanism, inspired from trees, is identified and characterised here in the simplest tree-like structure, a Y-shape branched structure. Through analytical and numerical analyses of a simple two-degree-of-freedom model, branching is shown to be the key ingredient in this protective mechanism. This damping-by-branching originates in the geometrical nonlinearities and is therefore specifically efficient to damp out large amplitudes of motion. A more realistic model of the Y-shape structure, using beam finite-element approximation, exhibits the same effect, which seems to be robust. Similarly, two arbitrary multi-branched slender architectures show significant levels of damping of the trunk motion while only the relative branch motion is damped. Finally, the same numerical analysis is performed on a digitalised walnut tree geometry showing the significant damping contribution of this mechanism during large amplitude motions.

Keywords

Damping, branching, tree-inspired, flexible structures

Biomechanics of permanent attachment in self-clinging climbing plants

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Abstract

In the struggle for light climbing plants evolved various strategies to permanently attach themselves to vertical supporting structures like trees or rocks. The most common climbing mechanisms are twining stems, coiling tendrils and adhesive organs. In plants with adhesive organs two attachment strategies are found: tendrils with adhesive pads or adventitious roots. In both systems efficient attachment is due to a combination of structural form-closure on the micrometre scale and/or usage of organic glue allowing the plants to climb flat and smooth supporting structures. The two types of adhesive organs evolved several times independently in various plant families and thus might be evolutionary advantageous.

Based on our previous work on the attachment mode of *Parthenocissus tricuspidata* [1,2] and *Hedera helix* [3,4] we currently study the anatomy, morphology and biomechanics of attachment structures in other species of self-clinging climbers. By comparing the structural, chemical and mechanical properties of the adhesive organs we aim to identify the underlying functional principles. Attachment systems currently under investigation include the climbing roots of *Ficus pumila* and *Vanilla* spp. and the adhesive pads of *Amphilophium crucigerum* and *Passiflora discophora*. Latest results are presented.

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Keywords

adhesive pad, adventitious root, vine, self-clinging plants

How to understand root plates of trees

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Abstract

The Method of Force Cones is a new thinking tool which can be used for designing of material efficient structures as well as for an improved understanding of these by identifying main tension and compression paths. The method will be introduced and the highly loaded zone below a tree is assessed in this way. The Force Cone results are compared with Finite Element calculations in order to understand the mechanical interaction of neighbored trees. The question is answered whether the tree nearby is friend or enemy to a tree beside him by calculating soil stresses with the Finite Element Method. Furthermore this new root model is applied to trees at slopes and cliffs as well as to trees in containers. It is shown that this thinking tool is well appropriate for a first understanding of the tree root system.

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Keywords

Method of Force Cones, structural optimization, tree roots

Self-healing Processes in Plants as Concept Generators for Biomimetic Self-repairing Materials

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Abstract

In the course of 3.8 billion years plants have evolved the ability for rapid wound-sealing and wound-healing. As one can assume a high evolutionary pressure on the development of self-repairing abilities in nature, independent evolution of these properties including various mechanisms and structures in different plant groups and plant species is probable.

Studies revealed self-sealing of the sclerenchymatous outer ring of the twining liana *Aristolochia macrophylla* mediated by turgescient parenchymatous cortex cells. Due to their internal pressure these cells expand into (micro-)fissures and seal them. This functional principle has already been successfully transferred into the development of a biomimetic patent-registered PU-foam coating for pneumatic structures.

Within a current project model plants from different systematic groups were screened and selected according to different criteria, which make probable a high selective pressure on efficient self-repair. For example in succulent plants which evolved independently in various systematic groups strong effects were found. Growing in arid environments external wounds lead to an exceptional drought stress. Rapid self-repair protects the plant from dehydration and is therefore of eminent selective advantage. We selected *Delosperma cooperi* and *Delosperma ecklonis*, both species are members of the Aizoaceae family with succulent leaves.

After an artificial injury simulating physical damage from i.e. trampling, feeding or weather events wound sealing in leaves of *Delosperma cooperi* takes place by deformation and movement. Two principles are involved: (1) rolling in of the fringes of the lesion within a few minutes, and (2) curvature of the entire leaf within a time span of approximately 15 minutes. Subsequent wound healing leads to a permanent curvature of the leaf and callus formation in the wound region. In contrast, *Delosperma ecklonis* does not show any deformation or movement in order to seal artificial injuries.

In cross sections the almost cylindrical leaves reveal a centripetal arrangement of five tissue types consisting of an outer layer of epidermis with window cells, a peripheral ring of chlorenchyma, a thin net made of vascular bundles, an inner ring of parenchyma and a strand of vascular bundles in the leaf centre. Mechanical properties of the entire leaf and of single tissue layers were studied in tensile tests. In addition tissue pressure and cell turgor were measured. An analytical model describing the self-sealing process in *D. cooperi* is currently developed. By comparing data from *D. cooperi* and *D. ecklonis* conclusions can be drawn on necessary boundary conditions allowing self-sealing by movement.

Keywords

Self-healing, Plants, Biomimetics, Modelling

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Self-healing elastomers - learning from Nature's solutions

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Abstract

Self-sealing and self-healing are characteristic properties of living organisms. There exists a high selective pressure on the development of abilities for self-repair in nature, causing independent evolution of these properties in different evolutionary lineages including the development of various mechanisms and structures for effective self-sealing and self-healing. Over the last decade plants and especially plant species from extreme habitats proved to be a promising source of inspiration for the development of biomimetic materials and structures with a variety of different self-repairing properties.

In latex bearing plants fissures are sealed very efficiently by the coagulation of latex that is released into the lesion from micro-tubes (laticifers) where it is stored under high overpressure (> 10 bar). The chemical processes involved in the coagulation of rubber particles in latices of the weeping fig (*Ficus benjamina*) and other latex bearing plants were analyzed as to the self-sealing capacity and to their ability to restore mechanical integrity of damaged plant organ^[1,2]. Our results prove different coagulation processes in different studied plant groups varying as well in the mode of coagulation as in the time necessary for coagulation.

On the basis of the quantitative analyses of the coagulation processes in latex bearing plants, which were used as concept generators, new approaches for the production of self-healing elastomers were developed. The basic idea is to keep micro-cracks occurring in elastomers that are exposed to high cyclic mechanical loading (e.g. dampers, sealings) at a subcritical length by using of bio-inspired self-repair processes. Different ways of transferring the biological concepts into technical self-healing materials were tested, including micro-encapsulated healing agents^[3], ionomeric structures^[3] and micro-phase separation of self-healing agents in technical rubbers^[4]. The results of the most promising developments of bio-inspired self-healing elastomers are presented and discussed as to the level of bio-inspiration.

Our results prove that in addition to micro- and nano-structural properties assuring a fast wound sealing especially chemical properties of the biological concept generators are of high interest for the development of innovative self-repairing materials.

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Keywords

self-healing elastomers, bio-inspired, *Ficus benjamina*

Functional anatomy and biomechanics of papaya stems

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Abstract

The lack of wood according to the botanical definition as lignified secondary xylem is characteristic for the stem of *Carica papaya*. Although the plants are able to grow up to ten meters the secondary xylem is almost completely parenchymatous. It has been proposed that *C. papaya* compensates the lack of regular wood either by the turgor pressure of the parenchyma or the lignified phloem fibres in the bark or by a combination of both. Interestingly, the lignified tissue comprises only three to eight percent of entire stem mass and the phloem fibres do not form a compact tube enclosing xylem but a lattice like meshed structure.

Young_'s moduli of papaya stems from plantations and naturally occurring individuals have been determined in quasi-static three-point-bending-tests. One year old plants revealed from ca. 400 to 950 MPa, two year old revealed from ca. 700 to 1270 MPa, whereas older plants achieved ca. 530 to 2400 MPa. Since these values are low compared to woody plants the flexural stiffness of that particular construction may mainly based on a greater second moment of inertia.

Further specimens cut out of the phloem have been tested in three-point-bending-tests revealed up to 3000 MPa and in compression tests xylem revealed 5.0 to 10.0 MPa. Gradients in material properties with respect to plant height were not observed in the xylem but in the phloem fibres. In the latter the values of Young_'s modulus of the phloem correspond to fibre mesh density. The turgor pressure ranges between 8.5 bar and 12.5 bar. The osmotic potential was determined by immersing specimens of phloem and xylem into sucrose solution of changing concentration. Subsequent analyses of stiffness in three-point-bending-tests resulted in a decrease of more than 50 %. These results indicate that turgor has a considerable (if not essential) influence on rigidity.

Keywords

biomechanics, Caricaceae, functional anatomy

Thinking Tools in Biomechanics and the 45° degree angle

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Abstract

The survival of biological structures depends also on the adaption to their individual load situation. To analyze and explore the state of mechanical conditions in structures three related Thinking Tools, Shear Squares, Tensile Triangles and Force Cones are introduced. This Thinking Tools make a geometrical based analysis of mechanical structures in nature and engineering, without use of computer, accessible. Based on the Thinking Tools a number of grown structures like leaf vein formation and stem root junction are described.

Using these tools, common geometrical features in their natural variety are exposed. A universal shape of nature is presented for solitary trees, wind shaved trees and forest edges. In addition the biological grown shapes are compared to the shape of pebbles in a brook caused by erosion. v

A new multi-purpose tool is presented which is able to transport this knowledge into tree diagnosis (VTA – Visual Tree Assessment) and arboriculture.

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ISSN: 0947-8620, Karlsruhe 2007

Keywords

Biomechanics, Thinking Tools, shape optimization

Walking and jumping spores

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Abstract

The Equisetum plants, more commonly called horsetail, emit 50-microns spores that are spherical in shape and present four elaters, that are ribbon-like hygroscopic appendages attached to the spore. Under high humidity, the elaters are retracted. In this talk we present our investigations on the role of these elaters.

We recorded the unfolding of elaters, by imposing the humidity level of the air surrounding the spore. Under less than 75% of relative humidity, the four elaters start to deploy beautifully. The maximum extension is reached at 50%, and they tend to curl up for lower humidity levels.

With time-lapse image recordings, we show that under repeated cycles of dry and high humidity, the spores behave as random walkers, since they move by about their size in a different direction at every cycle. The process is apparently stochastic because of the complex shape of the elaters and hysteretic friction of the elaters on the ground.

For some spores, a decrease in humidity level results in spectacular jumps, the spores taking off at a typical velocity of a meter per second, as recorded by a high-speed camera. With these jumps, they reach centimetric elevations, hundred times higher than their size. The physical mechanism at the root of these 'Levy-flight' jumps is still under investigation. Nonetheless, we hypothesize it is based on elastic energy stored in the bending of elaters when they are stuck by friction, and that jumps occur when the elaters slip, which suddenly releases the elastic energy.

The walking and jumping phenomena thus provide motility, which we believe is helpful for the understanding of the biological dispersion of the spores. It could also bring biomimetic inspiration to engineer new motile elastic structures.

Keywords

equisetum, spores, hygroscopic, motility

Cross sectional organization of supporting tissues and vascular bundles in perennial plants as concept generator for biomimetic construction principles

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Abstract

Annual and perennial plants have to grow very fast and energy and material effective during their reproduction cycle. The cross sections of those plants show a strict geometric order of supporting tissues and vascular bundles. This suggests that the allocation of supporting tissues is optimized for stability by using a minimum of material. Tests in bending and torsion were performed in order to determine the mechanical properties of these plants and lead to a better understanding of the relation between structure and geometry of the body of these plants.

In this study *Leonurus cardiaca*, a perennial herbal plant with a squared cross section and uniform internodal segments with very little taper, served as a model plant for the analysis of optimal material organization. The findings of the relation between amount and orientation of supporting materials and vascular bundles help to describe the effects of this relation on the biomechanical properties of the plant. The results of this study were also used to create a biomimetic prototype by laser-sintering or 3-D-printing and to test the effects of different geometric parameters on technical materials like polyamide and ABS (Acrylonitrile Butadiene Styrene)

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Keywords

Plant Biomechanics, Biomimetics

The flower of *Strelitzia reginae* as concept generator for the development of a technical deformation system for architectural purposes

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Abstract

Plant movements are increasingly becoming of interest in biomimetic approaches for a transfer into technical applications, especially in the fields of architecture and constructional engineering. In the present study, a non-autonomous plant movement with external actuation by application of mechanical force is shown: the kinematics of the perch in the flower of *Strelitzia reginae* (Strelitziaceae) were transferred into a patented technical façade shading system called Flectofin®. The flower of *Strelitzia reginae* (Bird-Of-Paradise) is pollinated by birds, which land on a perch and bend it downwards by their body weight. The perch simultaneously opens up, which is a very fail-safe mechanism that can be repeated over 3000 times with no visible wear. The main advantage of the biomimetic translation –the Flectofin®- is the avoidance of local hinges that are prone to wear and maintenance, and are costly when they have to be replaced. The use of fibre-reinforced polymers (FRP) such as glass-fibre reinforced polymers (GFRP) allowed for developing a technical component with a flapping system based on the opening of the perch of *Strelitzia reginae*. The Flectofin® has also proven to be very well scalable, which is of high importance for façade elements. By implementing further optimization steps, e.g. contour geometry optimisation, the hinge-less flapping system Flectofin® has reached an advanced demonstrator status and served as inspiration for the development of another shading system that has been implemented in the Thematic Pavilion on the World Expo 2012 in Korea.

Keywords

Strelitzia reginae, biomimetics, façade shading system, Flectofin®

An analytic model of the self-sealing mechanism of the succulent plant *Delosperma cooperi*

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Abstract

After an injury, wound-sealing in leaves of the succulent plant *Delosperma cooperi* takes place by deformation and movement of the entire leaf within a time span of approximately 15 minutes. In cross sections the almost cylindrical leaves reveal a centripetal arrangement of five different tissue types. Based on anatomical data and mechanical properties of the five hulls representing the different tissue layers, we present an analytical model describing the self-sealing process.

A few assumptions on the leaf structure (axial symmetry around the central xylem strand and an additional translational symmetry along this axis, tissue layers are homogeneous and isotropic) and on the stress contrasts between the tissue layers from which the intact leaf derives its mechanical stability reduce the mathematical complexity of the equations of elasticity considerably. Thus, closed solutions for the distribution of stresses and strains within the intact leaf can be obtained. In a second step, leaf reaction after various types of incision is investigated. Leaf bending after non axially-symmetric incisions is modelled employing the theory of a viscoelastic compound beam. Knowledge of the relaxation functions of the five hulls representing the different tissue layers allow to predict the temporal development of the self-sealing process.

The formulation of the model in terms of closed functions facilitates to investigate the properties of the solutions. Examples are (i) sensitivity studies against variations of the input data or (ii) the effect of the scaling of elastic moduli on the conditions of closure and the time-dependence of closure behaviour.

Regarding the latter case, it is found that important self-sealing properties of *D. cooperi*-like composite materials (such as temporal development and final state of a geometric distortion accompanying the self-sealing process) depend on the contrasts between the elastic moduli of the different components but not on their absolute values. Thus, it becomes feasible to realise composite materials with identical self-sealing behaviour from raw materials with very different elastic properties. This finding probably facilitates the transfer of the model to technical systems which are based on non biological composite materials.

Keywords

Self-sealing, self-healing, plants, biomimetics, viscoelasticity, elasticity

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