Workshop "Mathematics and Mechanics of Biological Tissues" Book of abstracts

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Closing

Wrinkling of 3d (auxetic) bi-layers in tension

Valentina Balbi

University of Galway

Bilayers, such as those found in skin tissue, vesicles, and organ membranes, often exhibit instabilities under compression due to contrasts in material properties. While most studies have focused on compression, we investigate wrinkling instabilities in auxetic bilayer systems subjected to uniaxial tension. Our findings reveal that, with sufficient contrast in Poisson ratios between the film and substrate, compressive stresses can develop, leading to wrinkles aligned with the tensile direction. We modelled the onset of wrinkling analytically and validated our predictions using advanced Finite Element simulations in ABAQUS. These simulations included user-defined subroutines for a custom strain energy function and periodic boundary conditions (PBCs).

Wrinkling occurs when the substrate's Poisson ratio exceeds that of the film, with wrinkles disappearing as the Poisson ratios converge. Depending on the material contrast, we observed either short- or long-wavelength wrinkles, providing insight into how these instabilities can be controlled. Long-wavelength wrinkles form when there is a small contrast in Poisson ratios, while short-wavelength wrinkles emerge when the contrast is more pronounced. These variations offer potential for tailoring surface patterns in flexible electronics.

Through inverse analysis, we designed microstructural geometries with desired effective Poisson ratios. We conducted Finite Element simulations for both homogenized bilayers and bilayers with microstructural film layers, achieving strong agreement

in critical stretch values between the two. These findings offer valuable insights for controlling surface patterns in applications such as auxetic skin grafts and hydrogel organ patches.

Development and personalisation of multiphysics, multiscale models of cardiovascular function

Federica Caforio

University of Graz

Computational models of the cardiovascular system represent a powerful tool for studying cardiovascular physiology and various pathological conditions. This area of research holds significant promise in exploring the complex and interrelated biophysical components that govern cardiac function. A critical factor in the cardiac mechanical performance is the heart's bidirectional interaction with the vascular system. While current three-dimensional models of cardiac electro-mechanics (EM) tend to simplify the blood vessels with zero-dimensional systems, these fail to capture the essential details of pulse wave transmission. To address these shortcomings, one-dimensional (1D) vascular models are needed; however, linking 3D cardiac models with 1D vascular models remains a challenge. During this talk, I will present a new, stable method for integrating a 3D cardiac EM model with a 1D arterial blood flow model. This represents the first development of a coupled 3D-1D model of the left ventricle and arterial system, demonstrated with numerical benchmarks highlighting its robustness and accuracy for different temporal resolutions, and its ability to simulate the physiological effects that arterial changes have on pulse wave movement.
As part of clinical integration efforts, I will discuss recent progress made in personalising this model, despite the challenges posed by data availability and the computational demands of solving the inverse problem. Specifically, I will present a novel method

that integrates physics-informed neural networks with detailed 3D non-linear cardiac biomechanical models for reconstructing tissue displacement and estimating patient-specific properties such as passive stiffness and active tension. A distinctive feature of the proposed method is its exclusive dependence on limited clinical datasets, which may include displacement and occasionally strain data. Tests benchmarking this method have shown it to be precise, reliable, and potentially efficient in estimating patient-specific biophysical parameters within non-linear, time-dependent biomechanical models. This approach paves the way for detecting and characterising tissue heterogeneities, like fibrotic areas, thus potentially greatly enhancing diagnostics and treatment plans for cardiac diseases.

Growth and dynamics of multicellular aggregates: the role of mechanical stress and resource availability

Giovanni Cappello

Laboratoire Interdisciplinaire de Physique

The mechanism by which cells measure the size of the tissue in which they are embedded, and arrest their growth when the final size is reached, is a long-standing problem in developmental biology. The role of mechanics in this feedback is considered important. However, considering only mechanics is not sufficient to predict the finite asymptotic size ('size control'). Here we evaluate whether mechanics and resources availability interplay to allow the existence of a homeostatic size of multicellular tissues.

Coupled experimental and computational approach for the constitutive analysis of biological tissues

Emanuele Luigi Carniel

Centre for Mechanics of Biological Materials - University of Padova

This contribution presents notes about a coupled experimental and computational framework for the constitutive analysis of biological tissues, which exhibit anisotropic, nonlinear, and time-dependent mechanical behavior. The approach relies on anisotropic visco-hyperelastic models and inverse analysis techniques to identify constitutive parameters from mechanical tests. Experimental protocols are carefully designed to account for tissue preconditioning and strain rate effects. Generalized incremental stiffness moduli, including incremental Young's moduli and Poisson's ratios, are employed to assess parameter stability and to characterize strain-induced stiffening and anisotropy. The method provides a robust foundation for modeling the complex mechanical response of biological tissues under realistic loading conditions.

Self-organisation of migrating multicellular communities

Giulia Laura Celora

Mathematical Institute, University of Oxford

Collective cell migration is ubiquitous amongst multicellular communities and contributes to many phenomena, e.g., morphogenesis and cancer metastasis. Nonetheless, it is still poorly understood how cells coordinate to control the emergent collective motion of cell groups (or swarms). Recent experimental data suggests that physical interactions between cells within the swarms can result in emergent fluid-like properties. In this work, we propose a continuum, coarse-grained, active fluid model to study how physical interactions affect the complex spatiotemporal dynamics of collective migration of cell groups in response to self-generated chemical gradients. Our results reveal a new mode of pattern formation via self-organised shedding of migrating groups. A travelling wave analysis of the model elucidates the dynamics leading to the group shedding and how this arises from the interplay of physical interactions, cell proliferation and chemotaxis. Overall, our work offers a new perspective to the study of chemotaxis of multicellular communities revealing the role of physical interactions in mediating their collective dynamics.

Mechanics of microbubbles for biomedical applications

Nehal Dash

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Bubbles encapsulated with a shell composed of polymers, lipids, proteins, or a combination of these are called encapsulated bubbles (EBs). EBs are a promising prospect in various biomedical applications, especially serving as contrast agents for ultrasound imaging and as carriers for targeted drug delivery. In this talk, I will introduce an interface energy -based mathematical model within the framework of surface continuum mechanics to study the dynamics of an EB. This model naturally induces residual stress field into the bulk of the bubble, with possible expansion or shrinkage from a stress-free configuration to a natural equilibrium configuration. The significant influence of interface area strain and coupled effect of stretch and curvature is observed in the numerical simulations based on constrained optimization. This model provides a beter fit of the experimental data and resolves the spurious dependency of shell viscoelastic parameters on the initial size of the bubble which remained hitherto unexplained. A path towards a thorough modelling of these lipidic shells through both elastic and surface tension contributions may also have been opened by this model, through a curvature-dependent surface tension to describe the spherical oscillations of EBs, allowing for an interesting analysis of existing experimental data for radial oscillations of EBs. This model is extended to investigate the radial dynamics of an EB with a different nonlinear viscoelastic shell, analysing its behaviour

through time-series plots, phase space trajectories, and nonlinear frequency response. The interface energy model is also employed to study the nonspherical oscillations of an EB under the acoustic field. This has enabled a deeper understanding of the dynamics and stability of the EB to exhibit finite amplitude shape mode oscillations.

Modeling swelling-induced shape morphing in functionally grade polymeric gels

Sanghamitra Debta

Department of Chemical Sciences, University of Padova

Polymeric gels are soft, biocompatible materials made of three-dimensional networks of physically or chemically cross-linked polymer chains that can absorb large amount of water without disintegrating. Their ability to respond to external stimuli—such as temperature, pH, and solvent makes them useful for biomedical applications, including drug delivery systems, tissue scaffolds, and soft actuators. When fabricated into thin films (100–200 μm), hydrogels exhibit reversible shape changes in response to solvent due to diffusion-induced swelling that generates a strain gradient across the film thickness. Traditionally, bilayer structures composed of materials with distinct properties are employed to harness such feat and achieve programmable deformations. However, the sharp interface between layers often results in stress concentration and delamination, limiting long-term reliability and mechanical performance. To overcome these challenges, we propose a mono-component functionally graded hydrogel film with a smooth variation in material properties through the thickness, enabling more uniform stress distribution and fast actuation under different environmental conditions. In this presentation, a coupled swelling-induced deformation model is discussed based on the Flory-Huggins theory to capturing the free energy change from solvent-polymer mixing. By leveraging the analogy between heat conduction and solvent diffusion, the built-in coupled temperature-displacement elements in Finite Element tool ABAQUS are used to simulate the time-dependent

shape morphing of the films. Model predictions including curvature and folding pathways are validated against experimental results. This combined experimental and computational framework provides a robust platform for designing smart, stimuli-responsive functional material systems tailored for biomedical applications such as responsive implants, wound healing devices, and micro-scale soft robotic components.

Incompatibility-driven growth

Alexander Erlich

CNRS / Université Grenoble Alpes

This presentation investigates how organisms reach a specific size, focusing on residual stress, which remains in tissues even after external forces are removed. The relative role of mechanics and biochemical processes in determining organ size is an open question, and it is unknown how stress is built and maintained during growth.

The central hypothesis suggests growth incompatibility as a missing link between tissue growth, size, and residual stress. Growth incompatibility is the challenge of fitting parts of a grown tissue without voids or overlaps, acting as the geometric "seed" of residual stress. We use the Ricci curvature of the growth metric tensor to approximate incompatibility at both tissue and cell levels.

We propose a theoretical framework where growth incompatibility acts as a geometric regulator for size termination during tissue development. Inspired by vertex models of morphogenesis, we explore the hypothesis that the Ricci scalar curvature is prescribed in space and time. Under this assumption, our model successfully reproduces experimental observations, such as the opening patterns after tissue cuts in Drosophila wing discs and multicellular spheroids, including the curvature of cut edges and consistent opening patterns following repeated cuts.

Traditional biological growth models rely on a homeostatic (Eshelby-like) stress tensor to define an ideal target state. Any deviation from this state triggers growth and remodeling, aimed at restoring balance between mechanical forces and biological adaptation. Yet this homeostatic stress lacks clear biological

interpretation and is often arbitrarily prescribed. To address this limitation, we focus on growth incompatibility, removing the constraint of fixed Ricci curvature used earlier. Instead, we propose a formulation that penalizes deviations from a target incompatibility state, analogous to the Einstein-Hilbert action in General Relativity. This provides a biologically and physically grounded approach that hints at a link between cellular mechanics and tissue-scale regulation of stress and size.

Mechanics of entropic biopolymer networks from the thermodynamics of molecular motors

Jocelyn Etienne

CNRS - Université Grenoble Alpes

Contractile biopolymer networks, such as the actomyosin meshwork of animal cells, are ubiquitous in living organisms and contribute in a large part to their function such as muscle contraction or embryonic morphogenesis.
Their contractility relies on the active behaviour of molecular motors which crosslink the biopolymer of the network and can transduce at the molecular scale chemical energy into mechanical work (Jülicher et al, Rev Mod Phys 69, 1997).
The active gel theory (Kruse et al, Eur Phys J E 16, 2005), which provides a thermodynamic framework for these materials, has been mostly used in conjunction with the assumption that the microstructure of the biopolymer network is based on rigid rods (Liverpool and Marchetti, Phys Rev Lett 97, 2006). However, experimentally, crossed-linked actin networks exhibit entropic elasticity (Gardel et al, Science 304, 2004). Here we combine an entropic elasticity kinetic theory, in the spirit of the Green and Tobolsky model (J Chem Phys 14, 1946) of transiently crosslinked networks, with an active flux modelling motor activity (Jallon et al, J Elast 2025).
We determine this active flux using Onsager reciprocal relations applied at the microscopic scale of individual motors. We derive the macroscopic active stress that arises from the resulting dynamics and obtain a closed-form model of the macroscopic mechanical behaviour. Although similar to models commonly

chosen in the active gel theory, the choice of entropic elasticity provides it with specific features of quantitative importance (Etienne et al, Proc Natl Acad Sci USA 112, 2015). Additionally, the analytical clarity of the derivation allows us to give microscopic interpretation of macroscopic active behaviours of contractile networks.

Constitutive modelling of passive skeletal muscles

Sara Galasso

Università degli Studi di Padova

The mechanical response of skeletal muscles is influenced by their microstructural organisation, characterised by fibre arrangements that give rise to anisotropic mechanical properties. Capturing this complex behaviour is essential for biomechanical applications. However, the development of constitutive models for muscular tissue is often obstructed by the numerous material parameters involved, which in most cases lack a clear physical meaning and are hence challenging to determine from standard measurements.

In this talk, we will first discuss a general formalism designed to facilitate the experimental identification of material functions for their constitutive characterisation within the context of Cauchy elasticity. Specifically, we present a theoretical framework for anisotropic nonlinear elasticity based on the decomposition of strain and stress tensors on a tensorial basis adapted to the local microstructure of the material [1]. This decomposition aims at organising the involved degrees of freedom into a mathematically clear and mechanically motivated scheme, which may support theoretical comprehension and experimental investigation.

Then, we will propose a basic constitutive model for the passive elastic response of skeletal muscles. For its construction, we start from experimental data to identify nonlinear material functions for the stress–strain relation, within the aforementioned framework. In particular, two peculiarities in the material response evidenced by the data are a characteristic anisotropic

strain-hardening in tensile tests and an asymmetry under traction or compression. Our biomechanically-motivated model intends to capture these nonlinear phenomena.
This is a joint work with Giulio G. Giusteri.
Reference:
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Dynamical anomalous transport of molecules subject to inhomogeneous body forces

Alberto Girelli

Università Cattolica del Sacro Cuore

Classical advection-diffusion models often fall short when it comes to capturing the complexity of transport in systems with strong spatial and temporal variability. In this talk, I will present a multiscale modeling framework that addresses these challenges by incorporating time-dependent diffusion coefficients and spatially heterogeneous, multiscale body forces into the advection-diffusion equation.

Using asymptotic homogenization, we derive effective macroscopic equations that reflect the underlying microscopic dynamics across multiple scales. A key feature of this work is the formulation of novel cell problems that account for the dual time dependence of diffusion and the multiscale nature of the driving forces. These lead to the emergence of additional source terms that significantly impact the effective behavior.

Moreover, we consider the effects of a non-zero divergence in the advective velocity field, which introduces corrections to the macroscopic advection velocity, capturing microscale source and sink effects. To demonstrate the practical relevance of the model, I will present numerical results focused on water molecule diffusion in packed erythrocytes — a biologically relevant system exhibiting distinct temporal scales. This example illustrates how the proposed approach can effectively track the evolving transport dynamics in time-dependent environments.

How Cells Find Their Way: Modeling Cell Reorientation and Neuron Pathfinding on Cyclically Stretched Substrates

Chiara Giverso

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Mechanical cues are known to influence both the direction and rate of axonal growth. In particular, experiments have shown that neurons cultured on planar substrates subjected to cyclic stretching tend to reorient and align at stable equilibrium angles within the range $[60°, 90°]$ relative to the principal stretching direction. Understanding this behavior is crucial for deciphering how physical forces contribute to neural development and regeneration.

In this work, we introduce a mathematical model that couples axonal reorientation and elongation in response to cyclic mechanical stimulation. The model integrates a linear viscoelastic formulation of growth cone reorientation, enhanced with a stochastic term to account for intrinsic variability, with a moving-boundary framework for tubulin-driven axonal growth. This coupled system allows us to simulate the pathfinding behavior of neurons under different mechanical conditions.

We perform numerical simulations across a range of stretching frequencies and strain amplitudes, exploring how these parameters affect the trajectory and dynamics of axonal growth. The model reproduces key experimental observations, including the convergence of axonal orientation toward a preferred angular

range. Furthermore, it captures the dependence of reorientation speed on the stretching regime: both higher frequencies and greater amplitudes lead to faster alignment of the neuron. Overall, the proposed model provides an interpretable and flexible framework for investigating the mechanosensitive dynamics of axonal pathfinding. It offers insight into how external cyclic forces can direct neuronal architecture and may serve as a foundation for future extensions incorporating substrate adhesion, nonlinear cytoskeletal behavior, or heterogeneous mechanical environments.

Variational problems for nematic axisymmetric films

Chiara Lonati

Politecnico di Torino, Italy

Nematic films are thin fluid structures, ideally two-dimensional, made up of liquid crystals (that can usually be found in cell membranes or displays) in the nematic phase, and so endowed with an in-plane order: the molecules tend to align along a direction specified by a unit vector, called director, that tends to be uniform and is constrained to be tangent to the flexible surface.

Some variational models for nematic films have been introduced by Giomi in 2012 [3] and by Napoli and Vergori [5] in 2018; both exploit the Frank energy and adopt the one-constant approximation.

At equilibrium, the optimal shape of the nematic film results from the competition between the surface tension, which favors the minimization of the area, and the nematic energy, that promotes the uniform alignment of the director. The main difference between the two mentioned approaches is the expression of the energy of the nematic vector field, that is the covariant derivative in the first case and the complete surface gradient in the second one.

In [1], we consider a film that is a revolution surface and attaches to two parallel coaxial circles, with the energy functional introduced by Giomi. We exploit convexification, the results in [4] and the Direct Method of Calculus of Variations to minimize the energy functional, proving the existence of a minimizer and its fundamental properties.

In [2], the global energy in the same geometrical setting involves also the extrinsic curvature; we prove existence of a unique minimizer and we provide its explicit expression and its geometrical characterization.

References

[1] G. Bevilacqua, C. Lonati, L. Lussardi, A. Marzocchi, A variational analysis of axisymmetric nematic films: the covariant derivative case, arXiv:2405.20154, submitted (2024).

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[4] A. Greco, Minimization of non-coercive integrals by means of convex rearrangement, Advances in Calculus of Variations, 5:2 (2012).

[5] G. Napoli, L. Vergori, Influence of the extrinsic curvature on two-dimensional nematic films, Physical Review E 97:5 (2018).

Mathematical modelling of viscoelastic dynamics in cell-matrix interactions

Giulio Lucci

INdAM & Department of Industrial, Electronical, and Mechanical Engineering, Roma Tre University

Cellular mechanosensing, i.e., the way in which cells perceive and react to mechanical signals in their environment, underlies critical biological events from tissue development and repair to tumour invasion. Although the rigidity of the surrounding matrix has long been seen as a major determinant of cell behaviour, recent experiments highlight that the time-dependent, viscoelastic nature of the matrix plays an equally crucial role in controlling focal adhesion turnover and cytoskeletal remodelling. Accurately capturing these viscous effects is therefore essential for predicting how cells respond in both healthy and diseased tissues.

In the first part of this talk, we examine how cells realign in response to cyclic stretching of their substrate, a process whose kinetics are strongly dependent on the stretch frequency. To address this, we treat the system as an anisotropic continuum and combine a Maxwell-type viscoelastic constitutive law with an evolution equation for the cell orientation angle. When studying the response to periodic strains, the results reproduce the observed frequency-dependent realignment behaviour, which is rapid at high frequencies and slow at low frequencies.

Next, with the aim of relaxing the assumption of perfect adhesion between substrate and cells, we assign separate viscoelastic properties to the substrate and the adhesion layer. Working in a one-dimensional framework, we derive the mechanical equations

and solve them analytically in the Laplace domain, to investigate the interplay between substrate and adhesion-layer viscoelasticity. Our results show the existence of a characteristic length, which may vary in a non-monotonic way with the deformation frequency. By solving the model numerically, we also show that viscoelasticity gives rise to transient force amplification, phase lags in stress transmission, and frequency-tuned adhesion dynamics.

Elastic plateau–rayleigh instability in soft cylinders: surface elasticity and periodic beading

Francesco Magni

SISSA

The Plateau–Rayleigh instability shows that a cylindrical fluid flow can be destabilized by surface tension. Similarly, capillary forces can make an elastic cylinder unstable when the elasto-capillary length is comparable to the cylinder's radius. While existing models predict a single isolated bulge as the result of an instability, experiments reveal a periodic sequence of bulges spaced out by thinned regions. This phenomenon, known as beading instability, characterizes several neurological pathologies such as Alzheimer's and Parkinson's diseases, where axons exhibit the formation of a non-physiological bead-on-string morphology, as well as the deformation of inert soft matter like hydrogel filaments. Most existing models postulate that surface tension is independent of the deformation of the solid, neglecting variations due to surface stretch.

In this work, considering a general framework for soft cylinders, we assume that surface tension arises from the deformation of material particles near the free surface, treating it as a pre-stretched elastic surface surrounding the body. Exploiting the theory proposed by Gurtin and Murdoch, we show that a cylindrical solid can undergo a mechanical instability with a finite critical wavelength if the body is sufficiently soft or axially stretched. Post-buckling numerical simulations reveal a morphology in qualitative agreement with experimental observations. Period-halving secondary bifurcations are also observed.

The results of this research have broad implications for soft materials, biomechanics, and microfabrication applications where surface tension plays a crucial role.

Deformation localisation in viscoelastic liquid crystal elastomers

Angela Mihai

Cardiff University

Combining the self-organisation of liquid crystals (LCs) with the flexibility of elastomers results in a special class of stimuli-responsive solid materials called liquid crystal elastomers (LCEs). These materials deform in response to changes in the LC orientation driven by temperature variation, electric, magnetic, or optical fields, and their LC alignment changes when mechanical loads are applied. This makes LCEs a top choice for advanced bioinspired devices and engineering designs. Compelling experimental evidence further suggests that, under certain conditions, the stress-strain curves of nematic LCEs display strain-rate dependent hysteresis during mechanical loading and unloading. For LCEs, the shape of the nonlinear stress-strain curve is typically invariant with respect to strain rate. In this case, at fixed rate, the macroscopic deformation may be captured by nonlinear hyperelastic models. In addition, appropriate viscoelastic models must account for dissipation induced by viscous polymer deformation coupled with LC rotation, but capturing this coupling remains an ongoing enquiry. In this talk, I will present a mathematical model for viscoelastic LCEs where different contributions are clearly defined and represented computationally. Finite element simulations of deformation localisation uniquely characteristic to these materials illustrate the efficiency of our modelling approach.

Homogenised modelling of the electro-mechanical behaviour of a vascularised poroelastic composite representing the myocardium

Laura Miller

University of Strathclyde

We propose a novel model for a vascularized poroelastic composite representing the myocardium which incorporates both mechanical deformations and electrical conductivity. Our structure comprises a vascularized poroelastic extracellular matrix with an embedded elastic inclusions (representing the myocytes) and we consider the electrical conductance between these two solid compartments. There is a distinct length scale separation between the scale where we can visibly see the connected fluid compartment separated from the poroelastic matrix and the elastic myocyte and the overall size of the heart muscle. We therefore apply the asymptotic homogenisation technique to derive the new model. The effective governing equations that we obtain describe the behaviour of the myocardium in terms of the zero-th order stresses, current densities, relative fluid–solid velocities, pressures, electric potentials and elastic displacements. It effectively accounts for the fluid filling in the pores of the poroelastic matrix, flow in the vessels, the transport of fluid between the vessels and the matrix, and the elastic deformation and electrical conductance between the poroelastic matrix and the myocyte. This work paves the way towards a myocardium model that incorporates multiscale deformations and electrical conductivity whilst also considering the effects of the vascularisation and indeed the impact on mechanotransduction.

Modeling mechanical instabilities driven by differential swelling in soft tissues

Paola Nardinocchi

Sapienza Università di Roma

Swelling can be a potent driving force for mechanical instability in various biological materials, where it leads to shooting mechanisms which are used for a variety of purposes including reproduction, prey capture, and defense [1, 2]. This study explores how solvent uptake, leading to an increase in material volume, generates significant internal stresses which can initiate mechanical instabilities and shooting mechanism in a rod which adheres to a substrate by capillarity and detaches from that substrate, thus generating a catapult mechanism. The phenomenon is critical in diverse fields, from hydrogel mechanics and biological tissues to energy storage devices. Understanding the interplay between swelling kinetics, material properties, and geometric constraints is crucial for predicting and mitigating these instabilities. This knowledge is essential for designing dedicated artificial shooting mechanisms, that could be used, for example, for puncturing biological tissues with high accuracy and high-speed pick-and-place applications.

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[2] C. Llorens, M. Argentina, N. Rojas, J. Westbrook, J. Dumais and X. Noblin, *Journal of The Royal Society Interface* 13, 2016.

A coupled multiscale model of the human cornea accounting for the collagenous microstructure and the extracellular matrix

Anna Pandolfi

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The human cornea is a complex, highly specialized structure necessary for the vision function of the Eye. The cornea, due to its shape and transparency, refracts and transmits the light to the retina. Cornea's mechanical properties, critical for maintaining corneal shape and function under intraocular pressure, arise from the composition of a hydrated proteoglycan-rich extracellular matrix (ECM) reinforced by an intricate network of collagen fibrils organized into lamellae. Despite extensive research, existing biomechanical models often fall short of capturing the coupled interplay between the ECM and collagen reinforcements, especially under physiological and pathological conditions. This work seeks to address this gap by proposing a novel computational model that integrates a continuum representation of the ECM with a discrete collagen-crosslinking network. The continuum approach for the ECM is chosen to represent its viscoelastic behavior and interaction with fluid flow, critical for corneal hydration and load transmission. Conversely, the collagen network is modeled as a discrete, anisotropic reinforcement system, capturing the directional stiffness imparted by the collagen fibrils and their crosslinking. The model is developed to account for the influence of enzymatic degradation, age-related changes, and disease processes such as keratoconus, where alterations in the ECM-collagen coupling are known to drive structural instability.

The innovation of this approach lies in its multiscale integration, bridging the molecular mechanics of collagen crosslinking with macroscopic corneal behavior. By explicitly linking the continuum matrix with a collagen-reinforced network, the model offers some possibility to deepen our understanding of corneal mechanics.
The inclusion of experimentally derived parameters for collagen alignment, crosslink density, and ECM properties, we will hopefully make the model predictive in the simulation of physiological responses to intraocular pressure and external mechanical perturbations.
This is a joint work with Christopher Miller, Maria Laura De Bellis.

Shape instabilities driven by topological defects in nematic polymer networks

Silvia Paparini

University of Padova, Department of Mathematics "Tullio Levi-Civita"

Nematic polymer networks (NPNs) are anisotropic rubbers formed by cross-linked polymeric chains with rod-like mesogenic segments, which, in the nematic phase, align along a non-polar director n. In NPNs the coupling between nematic order and polymer network is strong enough to constrain the director field to follow elastic deformations. Consequently, variations in the degree of orientation of the mesogenic segments, s, can drive the system out of equilibrium, inducing shape changes. Many biological systems of cells and cytoskeletal elements similarly form a nematic phase where elongated constituents align parallel to each other, inducing partial orientational order. A key characteristic of
nematic systems is the existence of singularities in the director field, known as topological defects. These can be classified by their topological charge m, and play a major role in the self-assembly of biological matter, such as plasma membrane, wood, silk, and the insect cuticles. Developing organisms further grow persistent protrusions or deplete material to relieve mechanical stresses originating from the presence of topologically required defects.
This talk aims to provide a mathematical framework describing the out-of-plane shape changes of initially flat LCN sheets containing a central topological defect. Adopting a variational approach, we define an energy associated with the deformations

consisting of two contributions: an elastic energy term accounting for spatial director variations, and a strain-energy function describing the elastic response of the polymer network. The interplay between nematic elasticity, which seeks to minimize distortions in the director field, variations in the degree of order, with the consequent tendency of monomers in the polymer chains to distribute anisotropically in response to an external stimulus, and mechanical stiffness, which resists deformation, determines the resulting morphology. We analyze the transition to instability of the ground-state flat configuration and characterize the corresponding buckling modes.
This is a joint work with Giulio G. Giusteri and L. Angela Mihai.

Geometric control by active mechanics of epithelial gap closure

Giulia Pozzi

DISMA - Politecnico di Torino

Epithelial wound healing is one of the most important biological processes occurring during the lifetime of an organism. It is a self-repair mechanism closing wounds or gaps within tissues to restore their functional integrity. In this talk we derive a new diffuse interface approach for modelling the gap closure by means of a variational principle in the framework of non-equilibrium thermodynamics. We investigate the interplay between the crawling with lamellipodia protrusions and the supracellular tension exerted by the actomyosin cable on the closure dynamics. These active features are modeled as Korteweg forces into a generalised chemical potential. From an asymptotic analysis, we derive a pressure jump across the gap edge in the sharp interface limit. Moreover, the chemical potential diffuses as a Mullins–Sekerka system, and its interfacial value is given by a Gibbs–Thompson relation for its local potential driven by the curvature-dependent purse-string tension. The finite element simulations show an excellent quantitative agreement between the closure dynamics and the morphology of the edge with respect to existing biological experiments. The resulting force patterns are also in good qualitative agreement with existing traction force microscopy measurements. Our results shed light on the geometrical control of the gap closure dynamics resulting from the active forces that are chemically activated around the gap edge.

Modelling cell trans-migration to understand cancer invasion

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The talk will focus on modelling cell migration in confined environments and in particular on how to describe the presence of thin structures such as base membranes, cell lining and vessel walls. The method to identify the proper interface conditions is discussed for a cell population also in the case in which it is characterized by heterogeneous phenotypic characteristics regarding cell motility. In this latter case, the way in which the interface conditions depend on the phenotype is found, determining the ability to cross the thin structure. In this way the membrane can act as a selector of more invasive phenotypes with respect to more residential phenotypes.

Supercontraction-induced torsion in spider silks is just a dual Poynting effect

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Supercontraction represents an important counterintuitive shrinking behavior of silks wires under increasing humidity. While fibers shortening is due to the entropic recoiling of structural molecules in the wire direction induced by H-bonds disruption by water molecules, surprisingly fibers also exhibit a significant coupled torsion. Previous studies described this effect based on the unverified assumption of helical structural fibers in spider silks wires undergoing shrinking. Here, based on a recent theoretical discussion demonstrating the possible insurgence of torsion in compressed non linear fiber reinforced elastic cylinders, named dual Poynting effect, we show for the first time that the supercontraction induced shortening of the fiber may lead to a coupled torsion also in the more realistic case of structural molecules undergoing shortening oriented along the fiber direction. The effectiveness of the model is demonstrated also in quantitatively predicting the experimental torsion behavior of spider silks under increasing humidity. We argue that this result can be interesting also in the perspective of designing new simple humidity controlled torsional actuators.

Multiscale analytical method for the homogenised response of composite materials with evolving internal structure: multilayered and fibre-reinforced cases

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We present a multiscale analytical framework to derive explicit expressions for the homogenised coefficients characterising the mechanical response of composite materials undergoing structural transformations within their internal structure [1,2]. Among the various forms that such structural transformations—referred to as remodelling in this contribution—may take, we focus on the case where the process is purely mechanical and assumed to occur at lower scales, which are not explicitly resolved [3]. Although the study is fundamentally theoretical, it is motivated by biological scenarios in which tissues, such as bones, dynamically adapt their mechanical properties in response to internal and/or external stimuli [4]. A central objective is to address the computational challenges associated with determining the effective macroscopic behaviour of such evolving materials. To this end, we formulate the governing equations based on the balance of linear momentum and the evolution law for inelastic distortions, both derived from the Principle of Virtual Work. Employing the asymptotic homogenisation method [5], we systematically derive the local (cell-level) problems and the corresponding macroscopic equations. Notably, in the cases of fibre-reinforced and multilayered composites, we solve the local problems analytically and, consequently, obtain closed-form expressions for

the homogenised mechanical properties of the composite. These properties are parameterised by space and time, thus capturing the evolving behaviour of the media under consideration.
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Nonlinear waves and biological tissues

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Techniques such as elastography (including ultrasound elastography and magnetic resonance elastography) rely on the propagation of mechanical waves through tissue to infer mechanical properties. Nonlinear effects can provide additional contrast and sensitivity to features such as stiffness gradients, lesions, or fibrotic regions. Nonlinear wave phenomena—including harmonic generation and shock formation—can enhance imaging resolution or offer diagnostic signatures of pathology. For instance, cancerous tissues often exhibit different nonlinear responses compared to healthy ones.
This talk aims to investigate whether this is indeed the case and to identify the main obstacles to the technological implementation of nonlinear wave-based techniques.

Stress free morphing

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We study the morphing of 3D solids within the framework of non-linear elasticity with large distortions. In this work, we explore the possibility of deforming elastic 3D bodies through distortions with the aim of proposing a blueprint for the characterization of compatible metric tensors to which there correspond a sought shape transformation, that is a 3D morphing towards a target shape having zero stress. Shape-morphing has been used as modeling tools to the study of biological growth [1,2], and the morphing of 2D bodies has been extensively studied in the recent decade, both from the theoretical point of view [3, 4], and from the point of view of morphing design [5].
We support that morphing through compatible distortions is a key strategy exploited by nature, enabling living organisms to perform vital tasks such as change shape, move, adapt to the environment [6]. Design of morphing is now at the core of many applications, and our work investigates about the possibility of designing stress-free morphing for 3D bodies, following [7, 8].
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What is active stress?

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We discuss the meaning of the concept of active stress from two points of view. One, is the perspective of a stochastic microscale model. Another, is the approach of phenomenological macroscopic continuum thermodynamics.

From cell to tissue tension: revisiting a century-old biophysical concept

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Dating back to D'Arcy Thompson's early 20th-century legacy, surface tension has become a central concept in describing the mechanics of living matter—from biomolecular condensates to tissues—often modeled as simple liquids, though they may more accurately resemble gels. Over time, a wide range of modeling frameworks (e.g., Potts, vertex, phase-field, active-foam) and experimental techniques (e.g., micropipette aspiration, AFM, membrane tether pulling, tension inference) have relied on the assumption that biological shapes are governed by effective surface tensions. Yet, despite its broad utility, the notion of tension carries a diversity of interpretations and occasional inconsistencies across the field.

In this talk, I will revisit the concept of surface tension across biological scales—from single cells to multicellular tissues—through biological, theoretical, and experimental lenses. At the single-cell level, I will explore cortical tension as a dynamic, anisotropic, and spatially heterogeneous property, using finite element simulations to highlight its complexity beyond the often-assumed isotropic view. I will also discuss the limitations of traditional methods such as parallel plate compression for assessing cortical tension and introduce an alternative methodology developed in collaboration with G. Charras' group.

At the tissue level, I will present recent efforts to address the inverse mechanical problem of inferring individual cell tensions

from microscopy images. Finally, I will revisit Steinberg's classical notion of tissue surface tension using a 3D foam-like simulation framework to reinterpret both historical and recent compression experiments conducted with collaborators.

Swimming changing length

Marta Zoppello

Politecnico di Torino

Inertialess hydrodynamics is notorious for its time-reversibility constraints. Reciprocal motion is unable to produce net propulsion, as per the celebrated Scallop Theorem. One way to break the time-reversibility is to increase the degrees of freedom of the swimmer. Models for swimming are particularly useful for the design of Nature-inspired robots, which necessarily undergo simplifications and reductions in the available degrees of freedom. A relevant issue is therefore the search for minimal models, involving a small number of parameters, but still describing the essential features of the swimmer, including its ability to successfully move and reach a given final position. With this in mind, we study different kinds two-link (scallop like) microscale swimmers that can not only control the angle between their links but also to change their length using different mechanisms of actuation.

The first length-change mechanism, stretching links, consists of an active longitudinal strain along each link of the swimmer. This mechanism is inspired by soft active materials, such as hydrogels and magnetosensitive elastomers, which have been receiving an increasing attention in the design of microscale robots.

The sliding links model is inspired by isoperimetric robots, namely the sum of the lengths of the two links is constant and shape change is produced by the filament sliding through the hinge.

Another mechanism of actuation is the growth: inspired by vine robots and root robots, there is no active deformation along each link, neither in length nor in curvature, and elongation is produced by new material points appearing at the tips of the filament.

Finally, the growing links model serves also to introduce our last mechanism, the telescopic links, in which each link works as a telescopic pole with two sections one sliding inside the other one, with the outer section being the one closer to the hinge.

In all four models we prove that the micro-swimmers are able to achieve net motion in any direction using periodic actuation. Our theoretical results are in good agreement with numerical simulations.