Workshop
Mathematics and Mechanics of Active and Dissipative Matter

Book of abstracts

Trieste - SISSA, 15–17 June 2026

Organizing committee:
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Closing remarks

Oncogenic transformation of tubular epithelial ducts: how mechanics affects morphology

Davide Ambrosi

Politecnico di Torino

Epithelial tissues at a pre-tumoral stage exhibit morphological changes: in particular epithelial ducts depart from the cylindrical shape, showing invaginations and evagination in the regions of the surface with malignant cells. Experiments report that at the inner and outer boundary of the epithelial sheets are concentrated molecular motors able to generate a surface active tension, that can vary between healthy and tumor cells.
The mechanical origin of such morphology can be mathematically tackled by a continuum mechanical model [1] able to relate, also quantitatively, the role of the impaired surface tensions. The mathematical model, derived from first principles, accounts for the competition between the bulk elasticity of the epithelium and the surface tension of the apical and basal boundaries. The variation of the energy functional yields the Euler-Lagrange equations to be numerically integrated. The numerical results reproduce a variety of morphological shapes, from invagination to evagination, depending on the ratio between bulk and surface energy at variance of the length of the section. In particular, using parameters independently measured, we are able to reproduce experimental data reported for a ring partially made of transformed cells.
The numerical results obtained with a mathematical model that accounts, in a suitable way, for the thickness of the epithelial wall, prompt us to a deeper mathematical characterization that we address exploiting the Euler Elastica. In this framework we study the variety of possible shapes that a planar inextensible closed rod can take because of a piecewise inhomogeneity in its natural curvature. On the basis of numerical simulations, perturbation analysis and geometrical arguments, we are able to devise three morphological regimes and we provide a first order approximation of the curves that separate the shape regimes in the (k, s_0) plane, k being the jump in natural curvature in the relative curvilinear coordinate s_0. Our perturbation analysis, supported by geometrical arguments, compares well with the numerical results based on the fully nonlinear theory.

[1] D. Ambrosi, A. Favata, R. Paroni, G. Tomassetti. *Oncogenic transformation of tubular epithelial ducts: How mechanics affects morphology*, European Journal of Mechanics - A/Solids, 117 (105984), 2026

Instability phenomena in homogenized models of solids and structures

Davide Bigoni

Università degli Studi di Trento

Nonlinear elastic materials derived through the homogenization of periodic lattices exhibit a rich spectrum of instability phenomena, including the formation, disappearance, and reappearance of shear bands, as well as mixed-mode and compaction localization. Remarkably, it is shown that a material can lose and subsequently recover ellipticity, leading to restabilization of the underlying lattice and even to the emergence of "islands" of stability. A related homogenized shearable-rod model, inspired by origami-like microstructures, reveals faulting and a striking folding mode in which curvature localizes and becomes discontinuous—behaviour absent from classical rod theories and providing clear mechanical signatures of the architected microstructure.

Nonreciprocal mechanics in active hydrogel metabeams: statics and dynamics

Ariel Surya Boiardi

Okinawa Institute of Science and Technology

Reciprocity is a general property of linear physical systems that manifests itself through relations of symmetry. While this remarkable and fruitful property underpins powerful theoretical and experimental techniques, the additional constraints it introduces can represent an obstacle to desired behaviors or functionalities, such as materials and structures that guide, damp, or control flows of energy and information. Current approaches to wave control in acoustic metamaterials rely on complex architectures, including sensors, actuators and control units. In this context, synthetic active materials offer a promising alternative route, by seamlessly integrating sensing, actuation and control at the material level.

We consider a periodic structure assembled from polyelectrolyte hydrogel beams; building upon morphoelasticity theory, the active response of such metabeam to electric stimuli is modelled through the notion of spontaneous curvature, while accounting for viscous drag from the fluid environment. The periodic system exhibits nonreciprocal transmission both in the static and in the dynamic regime: by embedding internal activity, the hydrogel metabeam breaks reciprocity at the constitutive level. Floquet-Bloch analysis reveals self-oscillating modes, nonreciprocal wave propagation and compensation of viscous losses, enabled by the material's ability to harvest energy from environmental stimuli. These properties are tunable by adjusting the magnitude of the applied electric potential. Experiments performed on millimeter-scale, finite-size realizations of the periodic structure corroborate the theoretical findings, demonstrating direction-dependent transmission both in the static and in the dynamic regime and near-lossless wave transmission.

A multiscale framework for chemo-mechanical degradation of cellulose fibrous networks

Emanuela Bosco

Eindhoven University of Technology

This work presents a multiscale modelling–experimental framework for predicting the chemo-mechanical degradation of cellulose fibre networks, with particular emphasis on historical paper. Paper is represented as a two-dimensional periodic network of cellulose fibres exhibiting moisture-dependent chemo-hygro-elastic behaviour. Degradation is driven by cellulose hydrolysis, which reduces the degree of polymerization and progressively degrades the effective mechanical properties, leading to embrittlement.
The framework captures the coupled effects of acidity, moisture, and environmental conditions by modelling the time evolution of the degree of polymerization and tensile strength, calibrated through dedicated micro-tensile experiments. Moisture-induced stresses within the fibrous network may locally exceed fibre strength and trigger brittle damage. The effective hygro-mechanical properties of the degrading network are obtained through asymptotic homogenization, providing insight into degradation mechanisms and informing environmental strategies for the preservation of historical paper artefacts.

Multiphysics modeling of electro-chemo-mechanical coupling in advanced batteries

Luigi Cabras

Università degli Studi di Trieste

This work presents a multiphysics continuum framework for the electro-chemo-mechanical modeling of lithium-ion batteries, with focus on solid and gel polymer electrolytes. The formulation captures the coupling between ionic transport and mechanical response, including swelling, large deformations, and inelastic effects associated with lithium plating and stripping.
A key feature of the model is the inclusion of a dual ionic conduction mechanism, accounting for distinct transport pathways within the electrolyte. The mechanical response is described through elastoplastic and viscoplastic constitutive behavior, enabling the analysis of stress evolution during charge–discharge cycles.
The framework is employed to investigate the evolution of key physical quantities governing battery operation, including species concentration, electric potential, and mechanical stress and deformation fields under different operating conditions.
Results highlight the strong interplay between transport and mechanics, showing how swelling, stress accumulation, and inelastic deformation influence the overall electrochemical response. These findings provide a basis for future developments aimed at incorporating degradation mechanisms such as fracture and interfacial damage.

Rate-independent fracture onset via damage-accelerated disentanglement in viscoelastic elastomers

Jacopo Ciambella

Università di Roma "La Sapienza"

Elastomer networks contain two populations of constraints: permanent covalent crosslinks and transient physical entanglements. We show that fracture—driven by crosslink scission—releases topological constraints on neighboring entangled chains, causing viscosity to collapse within the fracture process zone. This damage-accelerated disentanglement produces a local "fast relaxation zone" where the effective relaxation time scales with crosslink breakage and vanishes for a fully broken network. The mechanism fundamentally alters energy flow during crack propagation: non-equilibrium elastic energy converts to heat faster near the crack tip than in the bulk. We contrast this with conventional phase-field models where damage reduces stress amplitude but leaves relaxation kinetics unchanged. The two scenarios yield distinct predictions for the spatial distribution of dissipation and the rate-dependence of tearing energy, providing experimental signatures to distinguish them. Yet the latter approach can explain the rate-independence of fracture onset observed in experiments, while the former cannot.

A COUPLED MECHANOCHEMICAL MODEL FOR AVASCULAR TUMOUR SPHEROID GROWTH

Tommaso Davì

Università degli Studi di Trento

This thesis develops a coupled mechano-chemical model for avascular tumour spheroid growth and presents its numerical discretisation. The model quantifies how nutrient and growth-factor availability and consumption interact with the spheroid's internal stress state and external mechanical loading and how these variables translate into cellular growth. Building on an existing biological framework, the original system is reformulated for three-dimensional multicellular aggregates and coupled to a continuum-mechanics description of the spheroid as a compressible hyperelastic solid.
Mechanical regulation of growth is incorporated through a mechanosensing feedback function that modulates the local growth rate based on an objective stress measure. The resulting system consists of a reaction-diffusion subsystem for nutrient and signalling-factor concentrations, a local evolution law for volumetric growth, and a quasi-static mechanical equilibrium equation, complemented by constitutive relations required to close the model. Several boundary-condition strategies are discussed, including formulations designed to reflect realistic medium-renewal protocols in vitro. The coupled problem is discretised and solved numerically using a staggered time-stepping scheme.
Numerical simulations are performed to investigate distinct growth regimes, the dependence of asymptotic size on external chemical conditions, and the impact of growth-induced and externally applied stresses on spheroid development. The results reproduce key qualitative behaviours observed in multicellular spheroid experiments and provide insight into the interplay between mechanics, metabolism, and growth dynamics.

Spontaneous oscillations in biological and bio-inspired systems

Antonio De Simone

Scuola Internazionale Superiore di Studi Avanzati – Scuola Superiore Sant'Anna

Active matter is a broad field with many potential applications. A common thread underlying many of the current research lines is the study of systems powered by some internal energy source, as in the case of organisms moving thanks to food metabolism. In fact, self-propelling systems need to overcome the resistance of the surrounding medium, drawing the required energy from internal sources. The study of locomotion and self-propulsion in biological and bio-inspired artificial system appears, therefore, as an ideal testing ground to put the concepts and tools of active matter at work.
We will report on recent progress coming from case-studies on the motility and collective feeding of unicellular organisms (flagellates and ciliates) and bio-inspired micro-robots, studied from the point of view of the mechanics of active matter.

Deformation, adaptation, and rupture in vaginal tissues

Raffaella De Vita

Virginia Tech

Declining birth rates in many countries, including the United States and Italy, have increased attention on maternal health and childbirth-related complications. Vaginal delivery places reproductive tissues under substantial mechanical loading and can contribute to pelvic floor disorders and tissue injury. Improving childbirth safety requires a quantitative understanding of reproductive tissue behavior under physiological loading, time-dependent deformation during gestation, and injury during delivery. In this talk, I will present an integrated experimental and computational framework to investigate vaginal mechanics across pregnancy and childbirth. I will first introduce a novel in situ inflation-based platform developed to characterize vaginal mechanics under physiologically relevant conditions while preserving anatomical attachments and pelvic support structures. I will then discuss how vaginal mechanical behavior evolves throughout gestation using inflation-based biaxial loading combined with digital image correlation. The results reveal reduced compliance at mid-pregnancy, followed by increased viscoelastic deformation in late pregnancy that may facilitate delivery while reducing injury risk. Finally, I will present a combined finite element and machine learning framework to investigate vaginal tissue tearing during childbirth. Simulations were used to examine how tear geometry and collagen fiber architecture influence stress amplification near tears, while machine learning models enabled rapid prediction of tissue response across loading and injury scenarios. Collectively, these studies reflect our lab's effort to develop quantitative approaches for improving maternal health and reducing childbirth-related complications.

Electro-mechanical control of wrinkling in soft dielectric film–substrate systems

Michel Destrade

University of Galway

This talk presents a theoretical and computational study of electro-mechanical wrinkling in a soft dielectric film bonded to a hyperelastic substrate. Unlike classical film-substrate wrinkling, where surface patterns are triggered by mechanical compression alone, this system allows the onset of wrinkles to be actively tuned by an applied electric field. The model combines finite deformation, nonlinear electro-elasticity, and linearized stability theory for a dielectric film under voltage and plane-strain loading. Using the Stroh formulation and surface impedance method, we derive exact bifurcation conditions, together with accurate sixth-order approximations and explicit asymptotic formulas for the critical stretch, voltage, and wavelength. Finite element simulations validate the analytical predictions and follow the post-buckling evolution, including secondary patterns such as period doubling and tripling. Overall, the results provide design guidelines for electrically tunable surface patterns in soft robotics, flexible electronics, smart surfaces, and bioinspired materials.

Nucleation in rank-one gradient plasticity: exact solutions and geometry-dependent regimes

Antonino Favata

Università di Roma "La Sapienza"

We investigate plastic nucleation in solids within a strain-gradient plasticity framework featuring a rank-one defect energy, formulated as an incremental convex variational problem. The designation rank-one refers to the fact that the defect energy is positively one-homogeneous with respect to the curl of the plastic strain. The core feature of the framework is the variational selection of the plastic support, which regularizes the singular localization of classical plasticity into a distributed nucleus of finite width and introduces a genuine strengthening effect: the yield threshold is elevated by a discrete energetic barrier, while the post-yield response remains perfectly plastic. For an annular domain under torsion, we identify two qualitatively distinct nucleation regimes governed by the interplay between the internal length scale and the domain geometry. In the first regime, plasticity spreads over the entire domain in a curl-free compatible configuration. In the second, it localizes in an inner nucleus sealed by a concentrated GND wall at a locked front that does not advance upon further loading. Closed-form analytical solutions are derived for both regimes without any a priori assumption on the plastic support, providing exact benchmarks for the numerical simulations. In the localized regime, both the plastic zone size and the yield threshold follow a square-root scaling law in the internal length scale, in contrast to the linear scaling of previous rank-one models where the plastic support is prescribed by microstructural constraints. Numerical simulations on elliptical geometries show that the scaling exponents and the nucleation pattern depend sensitively on the domain shape, identifying geometry as a control variable of the nucleation process on a par with the internal length scale.

Hierarchical chirality, symmetry breaking and alternating stresses in tissue mechanobiology

Massimiliano Fraldi

Università degli Studi di Napoli "Federico II"

Mechanical stresses play a key role in growth, remodelling and morphogenesis of biological systems, governing how living matter organize and repair their architecture, balancing physical properties and functions over time and across scales, from single cells to tissues and organs.
Bone - an exceptionally stiff and tough, hierarchically structured and continuously evolving material - is one paradigmatic example in nature of how stresses orchestrate tissue mechanobiology at any scale. It is designed to bear loads, resist fracture, and efficiently self-repair when damage does occur. While it is known that micro-damage nucleation is necessary for bone healing and remodelling, and that cement lines, interfaces and sacrificial elements help dissipate energy and deviate developing cracks, how microdamage does not evolve into catastrophic failure in such a stiff material is not yet understood. Here, by taking into account chiral anisotropy, hierarchy and concealed asymmetries of osteons, we bring to light a previously disregarded stress-based counter-intuitive mechanism that can add a fundamental piece in the puzzle of a comprehensive biophysical picture of bone mechanobiology, suggesting analogous working principles in soft tissues and some organisms, which we discuss briefly to envision new ways for optimizing structures and designing self-healing materials.

Modelling skeletal muscles from data with adapted Voigt representations

Sara Galasso

Università degli Studi di Padova

We present a constitutive model for the passive and active response of skeletal muscles. At variance with more classical approaches, the model is developed exploiting adapted Voigt representations of strain and stress tensors within the context of nonlinear Cauchy elasticity.
This framework allows us to identify non-trivial stress-strain relations in a rather direct way from experimental data, enhancing the mechanical interpretability of the material functions that describe the tissue response and obtaining additional insight on the distinct role of the contractile fibres and of the surrounding extracellular matrix.
We propose a two-material model, with an additive splitting of the stress contributions, in which only one component depends on an activation parameter. The constitutive model for the passive behaviour satisfactorily predicts the nonlinear stress response to elongation at different relative orientations with respect to the fibre direction and highlights the dominant role of the extracellular matrix. The activation model, essentially determined by the mechanics of the contractile fibres, captures well the isometric stress response through the prescription of an elasto-plastic evolution of the along-fibre active strain.
This is a joint work with Giulio Giusteri.

On the role of the incompressibility constraint in soft dielectric composites with high phase contrast

Massimiliano Gei

Università degli Studi di Trieste

Towards the accurate modelling of soft dielectric composites, this investigation aims at demonstrating that the incompressibility constraint customarily adopted in the literature may lead to largely inaccurate predictions. This claim is grounded on the premise that, even though in these composites each phase may individually be assumed to be incompressible, the volumetric deformation of the softest phase can provide a significant contribution to the effective behaviour if the phase contrast is high enough. To reach our goal, we determine the actuation response of two-phase dielectric laminated composites (DLCs) where the softest phase admits volumetric deformation. Our results, discussed in the light of the limit case in which the softest phase consists of vacuum, on the one hand, challenge the hypotheses usually assumed in the modelling of soft dielectric composites and, on the other hand, are expected to provide useful information for the design of high-performance hierarchical DLCs.

Remodeling and fluid flow in fiber-reinforced, hydrated biological media

Alessandro Giammarini

Politecnico di Milano

We report on two recently published papers [1,2]. In [1], we study the reorientation of the fibers reinforcing biological composite materials, such as articular cartilage, which can be assumed to consist of a fluid and a solid phase [3]. Differently from previous works in the field [4,5], but similarly to what has been done in [6,7], in our model the solid phase of the medium under investigation is reinforced by a network of fibers oriented according to an unknown probability density distribution that solves a Fokker–Planck equation. Aside from the standard stochastic term, in our study such equation features two drift terms: one is due to the forces exchanged with the matrix, assumed to descend from a hyperelastic strain energy density, and one is due to "configurational forces" that drive the orientation of the fibers towards a prescribed pattern also in the absence of the deformation of the matrix. In addition to the reorientation of the fibers we also consider the remodeling of the matrix, intended as a dissipative and essentially stress-driven process associated with the transformation of the internal structure of this constituent. In [2], we expand on the remodeling of biphasic, fluid-solid biological media by formulating a grade-one constitutive framework in the tensorial variables describing the remodeling distortions and their rate [8]. This is done with the purpose of resolving boundary effects and the formation of patterns inside the tissue. Moreover, we also assume the fluid phase to obey the Darcy–Brinkman law of flow [9], thereby allowing for a viscous stress in the fluid in addition to the purely hydrostatic stress foreseen by Darcy's law.

[1] A. Giammarini, A. Pastore, A. Grillo. *A model of fiber reorientation in fiber-reinforced biological materials combining statistical and configurational mechanics*, Mathematics and Mechanics of Solids. 2025;30(11):2619-2656.

[2] A. Giammarini, A. Pastore, A. Ramírez-Torres, A. Grillo. *A first-gradient approach to the remodeling and fluid flow in saturated porous media*, Mathematics and Mechanics of Solids, 30:2185–2223, 2025.

[3] M.H. Holmes, V.C. Mow. *The nonlinear characteristics of soft gels and hydrated connective tissues in ultrafiltration*, J Biomech 1990; 23: 1145–1156.

[4] S. Federico, T.C. Gasser. *Non-linear elasticity of biological tissues with statistical fibre orientation*, J R Soc Interface, 2010. Vol. 7, pp. 955-966.

[5] A. Grillo, M. Carfagna, S. Federico. *An Allen-Cahn approach to the remodelling of fibre-reinforced anisotropic materials*, J Eng Math, 2018, Vol. 109, No. 1, pp. 139-172.

[6] A. Gizzi, C.J. Cyron, C. Falcinelli et al. *Evolution of fiber distributions in homogenized constrained mixture models of soft tissue growth and remodeling: Uniaxial loading*, Journal of the Mechanics and Physics of Solids 2024; 183: 105491.

[7] N. Loy, L. Preziosi. *A statistical mechanics approach to describe cell reorientation under stretch*, Bulletin of Mathematical Biology 2023; 85(7).

[8] M.E. Gurtin, L. Anand. *A theory of strain-gradient plasticity for isotropic, plastically irrotational materials. Part II: Finite deformations*, International Journal of Plasticity, 21:2297–2318, 2005.

[9] A.R.A. Khaled, K. Vafai. *The role of porous media in modeling flow and heat transfer in biological tissues*, International Journal of Heat and Mass Transfer, 2003, Vol. 46, Issue 26.

Nematic defects, elasticity, and morphogenesis

Giulio Giuseppe Giusteri

Università degli Studi di Padova

Biological systems of cells and cytoskeletal elements can form a nematic phase where elongated constituents align parallel to each other, inducing partial orientational order. This order is described by a macroscopic director field that reflects the local orientation of the system. Topological defects in the nematic order are singularities in the director field; they are quite common and classified by their topological charge. In morphogenesis, the process of biological shape formation, defects act as organising centres enabling organisms to grow persistent protrusions or deplete material to relieve stress.

The aim of this talk is twofold. First, we propose a mathematical model for the coupling between mesogens disclination and polymeric network and describe, through a stability analysis, the out-of-plane shape changes of initially flat nematic polymer network (NPN) sheets containing a central topological defect. Second, we introduce a continuum mechanical model aimed at describing the morphogenesis of cellular aggregates guided by the interplay of nematic interactions, elasticity and stress-driven growth. We show how the presence of specific defects in the nematic order can lead to the appearance of characteristic features in the body of regenerating hydras, that are very simple aquatic invertebrates.

This is a joint work with S. Paparini and L. A. Mihai.

Active contact electromechanics of intestinal motility

Alessio Gizzi

Università Campus Bio-Medico di Roma

Intestinal motility is a fundamental physiological process responsible for the transport and absorption of nutrients through complex motion patterns such as peristalsis and segmentation. The intestine is a multilayered active tissue whose contraction is triggered by electrical stimulation, involving a strong coupling between electrophysiology, mechanics, and tissue structure. Such mechanisms are inherently multiscale, making the mathematical modeling of intestinal motility particularly challenging. Several electromechanical models have been proposed to investigate intestinal motility, providing valuable insights into the role of electrical activity and tissue mechanics, but tissue and whole-organ movement have been poorly addressed. In fact, intestinal deformation is frequently accompanied by non-negligible contact and self-contact phenomena, which have long been neglected in computational models. Only recently have a few studies begun to incorporate contact into electromechanical models of the intestine. In this work, we propose a generalized active electromechanical framework for intestinal motility that explicitly accounts for contact phenomena. The model is based on the active strain approach to couple electrophysiological and mechanical processes, and on a contact formulation relying on the augmented Lagrangian method, enabling a unified treatment of both self-contact and contact with external bodies or surrounding organs. Finite elements implemented through a staggered solution strategy have been customized within the open-source software GetFEM. The proposed framework allows the simulation of complex and clinically relevant scenarios, including intestinal self-contact, balloon dilation tests, and combined configurations involving simultaneous self-contact and balloon inflation. Numerical results are compared with in vivo experimental data from porcine subjects, showing good agreement and demonstrating the model ability to realistically capture the mechanical response of the intestine under physiological conditions and during interventional procedures.

Natural tilings: soft cells and the tainted love of the Nautilus

Alain Goriely

University of Oxford

Mosaic patterns and tilings are ubiquitous in nature, appearing in systems ranging from cellular tissues and geological formations to biological shells and foams. Traditionally, these structures have been modeled using polyhedral tilings composed of flat faces, straight edges, and sharp corners. However, careful observation reveals that many natural tilings deviate significantly from this paradigm: their boundaries are curved with smooth interfaces. This realisation has motivated the introduction of a new class of shapes known as soft cells, which arise as smooth deformations of standard tilings. Such cells are found in the geometry of metal and liquid foam as well as in many micro-structures modelled by triply periodic minimal surfaces. In this talk, I will explain the mathematics and physics of tilings, hard and soft, describe their construction and classification, and illustrate how they provide a more accurate geometric description of patterns found in biology, architecture, engineering, in the deepest sea and even in space.

Bedform formation in a dissipative particle bed driven by vertical oscillations

Luigi La Ragione

Politecnico di Bari

We investigate pattern formation in a dissipative granular bed driven by vertical oscillations of a plate. Experiments reveal a mechanism by which forcing-induced particle rearrangements generate bedforms. The system offers a simple setting to study how dissipation, instability, and collective mechanical response combine to produce emergent structure in driven particulate matter.

Variational and homogenized modelling of elastic multiscale structures

Chiara Lonati

Politecnico di Torino

Multiscale systems are widely present in both biological structures and technological applications. The ability to account not only for the macroscopic behavior of an elastic medium, but also for its microscopic arrangement, allows for a more complete and realistic description. Recently, I studied two problems in which a non-trivial interaction arises between two contributions coming from different scales of a structure.

In the first problem [1, 2], we prove the existence and geometric properties of an equilibrium configuration for a nematic film with surface tension using the Calculus of Variations. The key aspect is the non-trivial competition between the Frank energy of the crystal and the area functional.

In the second case [3], we derive the equations of Biot's poroelasticity from the microstructure under the assumption of incompressibility of both an isotropic linear-elastic solid and a low Reynolds-number Newtonian fluid flowing through its pores. By using the asymptotic homogenization technique, we obtain a macroscale system of PDEs, with corresponding cell problems at the pore-scale; moreover, we recover the equivalence between the change in volume of the porous solid and the volume of fluid exchanged.

[1] G. Bevilacqua, C. Lonati, L. Lussardi, A. Marzocchi. *A variational analysis of axisymmetric nematic films: the covariant derivative case*, arXiv:2405.20154, Calculus of Variations and Partial Differential Equations, 2026.

[2] G. Bevilacqua, C. Lonati, L. Lussardi, A. Marzocchi. *Existence and uniqueness of minimizers for axisymmetric nematic films*, arXiv:2601.09348, submitted.

[3] R. Penta, C. Lonati, L. Miller, A. Marzocchi. *Poroelasticity derived from the microstructure for intrinsically incompressible constituents*, Zeitschrift fur angewandte Mathematik und Physik, 2026.

Elastic Plateau–Rayleigh instability: the role of surface elasticity

Francesco Magni

Scuola Internazionale Superiore di Studi Avanzati

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 elastocapillary 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, a phenomenon known as beading instability. Most models assume that surface tension is independent of the deformation of the solid, neglecting variations due to surface stretch.
In this talk, 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. Using the theoretical framework 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.

Energy dissipation in linear viscoelastic solids

Francesco Mainardi

INFN - Università di Bologna

Among the models in linear viscoelasticity that are compatible with the second principle of thermodynamics are those whose relaxation moduli are represented by completely monotone (CM) functions of time, see for example Hanyga (2005) [1], Mainardi (2010-2022) [2]. The required CM property was formerly required indirectly in the treatise by Gross (1953) [3] being equivalent from physical point of view to discrete or continuous, non-negative distributions of simple exponential relaxations. Here we consider the dissipation of elastic energy for several models based on this CM property. These models include those known as fractional Zener and Andrade models, generalized Jeffreys-Lomnitz and Becker models, and finally the Lambert model, see Mainardi (2010-2022 [2] and Santander & Mainardi (2024) [4]. For all of them we intend to compare the corresponding loss of energy so complementing the previous researches.

[1] A. Hanyga. *Viscous dissipation and completely monotonic relaxation moduli*, Rheologica Acta 44, 614–621, 2005.

[2] F. Mainardi. *Fractional Calculus and Waves in Linear Viscoelastciity*, World Scientific, Singapore, 2010-2022 [First Ed. 2010].

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[4] J.L. Gonzalez-Santander, F. Mainardi. *A comparative view of Becker, Lomnitz, and Lambert linear viscoelastic models*, Mathematics (MDPI) 12, 3426, 2024.

Simple stimuli drive complex responses in non-Euclidean active shells

Roberto Marchello

Scuola Internazionale Superiore di Studi Avanzati

Synthetic active materials are pushing the boundaries of soft robotics and biomimetics. To fully harness these materials, we need to understand how internal stresses translate into complex shape changes and motion. Recent experiments have shown that polyelectrolyte hydrogel filaments can spontaneously oscillate in a steady electric field due to flutter, mimicking biological cilia and flagella. This observation prompted us to investigate the complex dynamics that active shells can exhibit in response to electrical stimuli. To capture this phenomenon, we develop a morphoelastic framework that extends nonlinear Koiter shell theory to account for the material's active response, coupled with low-Reynolds-number hydrodynamics. Such active shells are non-Euclidean, as they lack a stress-free reference state due to geometric incompatibilities induced by internal activity. Focusing on elliptic plates and cylindrical shells, our linear stability analysis predicts the onset of flutter while varying the model parameters. We then validate these theoretical predictions through nonlinear numerical simulations and physical experiments on actual hydrogel elliptic plates. The results align with our predictions: a constant, uniform electric field successfully drives large-amplitude, nonreciprocal oscillations in these structures. By matching mathematical theory with experimental reality, this study provides practical, grounded insights into both biological locomotion and the design of next-generation soft actuators.

Hybrid machine learning for swelling free-boundary problems

Luca Meacci

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The hydration of glassy biopolymers and active biological tissues involves a complex chemomechanical coupling between fluid transport and matrix swelling. Mathematically, this process can be formalized as a one-phase Stefan problem with moving boundaries. However, distinguishing the exact rheological regime (whether solvent penetration is throttled by slow macromolecular relaxation or pure hydraulic resistance) remains mathematically ill-posed due to the fundamental reliance on a priori phenomenological closures for the matrix permeability and porosity evolution. In this talk, we present a novel mathematical paradigm that merges rigorous macroscopic continuum mechanics with Machine Learning to resolve this physical ambiguity. We first formulate an effective free-boundary framework for capillary-driven imbibition in swelling media, coupling Darcy's law with the kinematics of a deformable solid skeleton. To bypass traditional constitutive guessing, we embed a Neural Ordinary Differential Equation (Neural ODE) directly within the governing physical laws. This AI-enhanced architecture strictly enforces "hard" macroscopic constraints (such as solid mass conservation, interface kinematics, etc.) while allowing the network to discover the latent microscopic porosity dynamics directly from macroscopic experimental observables. Applied to the rapid swelling of myxospermous seeds (e.g., Brassica napus), this Machine Learning approach reveals a globally sub-diffusive kinetic scaling, statistically identifying a hydraulic-limited transport regime and effectively overturning classical viscoelastic assumptions. By closing the mathematical model without sacrificing physical interpretability or mechanical rigor, this framework offers a scale-bridging tool for understanding and predicting the dynamics of bio-inspired, active, and dissipative soft matter.

Mathematical modeling of active biological soft materials

Alessandro Musesti

Università Cattolica del Sacro Cuore

Motivated by the prominent example of skeletal muscle tissue, this talk presents some of the main mathematical and mechanical approaches used in the modeling of biological soft active materials. Within the framework of nonlinear hyperelasticity, the material is assumed to be incompressible and transversely isotropic, consistently with the anisotropic structure of muscle fibers. Particular attention will be devoted to the constitutive modeling of activation mechanisms and to the formulation of strain-energy functions that are mathematically well-posed, mechanically meaningful, and capable of reproducing the experimentally observed response.

Modeling the biomechanics of the human iris with an active strain approach

Anna Marina Pandolfi

Politecnico di Milano

The iris is a deformable circular diaphragm that regulates pupil size in response to changes in illumination through the antagonistic actions of sphincter and dilator muscles. While the phenomenological relationship between pupil size and light intensity is well studied, the mechanical interplay between active muscle contraction and passive iris tissue remains poorly understood. In this study, we develop a finite element model of the human iris using an active strain formulation to investigate the mechanics underlying pupil regulation under physiological conditions. The iris is represented as a fiber-reinforced soft tissue, with passive matrix behavior modeled as isotropic, nonlinear elastic and active muscle contraction introduced via contractive strains along fiber directions. Numerical simulations are performed using a dedicated finite element code. By progressively including active and passive tissue components, we analyze how tissue architecture affects pupil kinematics, stress distribution, and interaction with supporting boundaries at the iris root. Results reveal a counterintuitive yet significant role of passive tissues in shaping three-dimensional iris deformation and moderating boundary reactions. This computational framework provides a mechanically consistent basis for understanding iris biomechanics and can support future studies extending to more complex physiological or pathological conditions.

The distance stress

Paolo Podio-Guidugli

Accademia Nazionale dei Lincei

I shall show that the tensorial notion of distance stress has a representation in terms of distance forces which is strongly reminiscent of the Continuum Mechanics representation of contact stress in terms of contact forces.

Modelling cell trans-migration to understand cancer invasion

Luigi Preziosi

Politecnico di Torino

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.

Nucleation of fracture as a mechanical instability

Davide Riccobelli

Scuola Internazionale Superiore di Studi Avanzati

We argue that nucleation of brittle cracks in initially flawless soft elastic solids is preceded by a nonlinear elastic instability, which cannot be captured without accounting for geometrically precise description of finite elastic deformation. As a prototypical problem we consider a homogeneous elastic body subjected to tension and assume that it is weakened by the presence of a free surface which then serves as a location of cracks nucleation. We show that in this maximally simplified setting, brittle fracture emerges from a symmetry breaking elastic instability activated by softening and involving large elastic rotations. The implied bifurcation of the homogeneous elastic equilibrium is highly unconventional for nonlinear elasticity as it exhibits strong sensitivity to geometry, reminiscent of the transition to turbulence in fluids. We trace the post-bifurcational development of this instability beyond the limits of applicability of scale-free continuum elasticity and use a phase-field approach to capture the scale dependent sub-continuum strain localization, signaling the formation of actual cracks.

Dispersion without higher gradients

Giuseppe Saccomandi

Università degli Studi di Perugia

The presence of intrinsic characteristic lengths in materials, such as the hierarchical microstructure of soft biological tissues, typically leads to wave dispersion. Standard continuum theories capture this effect by enriching the model with higher-order deformation gradients, microstructural variables, or nonlocal interactions, thereby moving beyond the classical framework of simple materials. In this work, motivated by the need to model wave propagation in soft tissues—where dispersion is prominent yet a simple, robust continuum description is desirable—we challenge this viewpoint by demonstrating that dispersion can be rigorously described **within** Noll's theory of simple materials.
Through the lens of Edelen's primitive thermodynamics and by establishing an exact correspondence with differential materials of grade 2 (specifically, second-grade fluids), we prove that dispersion may be introduced by using a model belonging entirely to the class of simple materials. For isotropic incompressible materials, the theory reduces to a scalar wave equation of the improved Boussinesq type, which in the linear limit recovers the classical Love equation. Importantly, the nonlinear version admits compactly supported solitary waves (compactons)—a genuinely nonlinear phenomenon that emerges naturally from the constitutive structure. Unlike continualization procedures applied to discrete lattices, this axiomatic approach yields the most general form of the dispersive equations without invoking any microscopic assumptions.
Our results establish that the introduction of an internal characteristic length does **not** force one to abandon the framework of simple materials. A thermodynamically consistent modification of the inertial terms, combined with an appropriate decomposition of the stress, is sufficient to describe nonlinear dispersive phenomena while preserving the conceptual and mathematical elegance of classical continuum mechanics. This framework is particularly relevant for soft tissue biomechanics, where microstructural complexity must be reconciled with the practical need for efficient, low-order continuum models.

Modeling the effect of strain amplitude on orientation spreading in cell ensembles subjected to cyclic stretch

Giuseppe Tomassetti

Università degli Studi Roma 3

Endothelial cells in the cardiovascular system experience cyclic stretching due to pulsatile blood flow, leading to orientation changes that are crucial in vascular remodelling and related pathologies, such as hypertension. Traditional models often describe cell alignment as a deterministic drift toward energy-minimizing configurations. However, experimental observations reveal non-sharp distributions of orientations, with reduced spreading under increased strain amplitude. In recent work by Loy and Preziosi (Bull. Math. Biol., 2023) such spreading is modelled by augmenting the deterministic evolution equation with a noise term. This approach leads to a Fokker–Planck equation whose stationary solutions show qualitative agreement with experimental data. Building on that work, in this talk I adopt the framework of Stochastic Thermodynamics with Internal Vari (Leadbetter et al., PNAS Nexus, 2023) to derive a two-dimensional dynamical system governing the mean orientation and degree of alignment of the cells. Phase-plane analysis confirms that the effect of strain amplitude on the experimentally observed spreading phenomenon stems from the interplay between drift and noise.

Homogenized constrained mixture models for the evolution of fiber distributions in soft tissue

Marcello Vasta

Università degli Studi "G. d'Annunzio" Chieti - Pescara

Soft biological tissues are marked by continuous time-dependent degradation and deposition of tissue fibers. These govern, in particular, growth and remodeling (G&R) of soft tissues. Growth and remodeling in soft tissue changes, in general, the orientation distribution of the collagen fibers in the tissue. So far, the governing principles are still incompletely understood. In this paper, we derive from the homogenized constrained mixture theory a theoretical framework that enables simple analytical solutions that help to understand the evolution of the collagen fiber distribution in soft tissues during growth and remodeling under uniaxial loading. Our analysis suggests a natural tendency of the collagen fiber distribution to form a peak in the direction of loading and a spread increasing with the ratio of the fiber half-life time and the time constant governing loading-related fiber production. This observation helps to understand why in vivo collagen fiber reinforcement is typically organized in the form of (often von Mises-like) distributions with a finite spread.
The proposed analytical solutions can be considered a first stepping stone towards a future extension of the homogenized constrained mixture models in continuous fiber distributions. Moreover, these analytical solutions provide general insights about the factors governing the evolution of fiber distributions in soft tissues. Our analysis also suggests a considerable history dependence of the fiber distribution evolution, which may explain why, in tissues under the same type of loading, sometimes considerably different fiber orientation distributions are observed.

[1] A. Gizzi, C. Cyron, C. Falcinelli, M. Vasta. *Evolution of fiber distributions in homogenized constrained mixture models of soft tissue growth and remodeling: Uniaxial loading*, Journal of Mechanics and Physics of Solids, Volume 183, 2023.