RESEARCH CENTRE

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2024

ACTIVITY REPORT

Project-Team

M3DISIM

Mathematical and Mechanical Modeling with Data Interaction in Simulations for Medicine

IN COLLABORATION WITH: Laboratoire de Mécanique des Solides

DOMAIN

Digital Health, Biology and Earth

THEME

Modeling and Control for Life Sciences

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Project-Team M3DISIM

Creation of the Project-Team: 2016 June 01

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Computer sciences and digital sciences

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1 Team members, visitors, external collaborators

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- Fabrice Vallée [AP/HP]

2 Overall objectives

The research carried out in the MΞDISIM team has a rather global methodological perspective oriented towards biomechanics, encompassing mathematical modeling and analysis, inverse problems arising from model-data coupling, and the formulation and analysis of effective and reliable numerical procedures adapted to this overall program. We are also very keen on demonstrating the effectiveness and relevance of these methods in actual applications, usually by proof-of-concept studies carried out within various collaborations.

3 Research program

3.1 Multi-scale modeling and coupling mechanisms for biomechanical systems, with mathematical and numerical analysis

Over the past decade, we have laid out the foundations of a multi-scale 3D model of the cardiac mechanical contraction responding to electrical activation. Several collaborations have been crucial in this enterprise, see below references. By integrating this formulation with adapted numerical methods, we are now able to represent the whole organ behavior in interaction with the blood during complete heart beats. This subject was our first achievement to combine a deep understanding of the underlying physics and physiology and our constant concern of proposing well-posed mathematical formulations and adequate numerical discretizations. In fact, we have shown that our model satisfies the essential thermo-mechanical laws, and in particular the energy balance, and proposed compatible numerical schemes that – in consequence – can be rigorously analyzed, see [7]. In the same spirit, we have formulated a poromechanical model adapted to the blood perfusion in the heart, hence precisely taking into account the large deformation of the mechanical medium, the fluid inertia and moving domain, and so that the energy balance between fluid and solid is fulfilled from the model construction to its discretization, see [8].

3.2 Inverse problems with actual data – Fundamental formulation, mathematical analysis and applications

A major challenge in the context of biomechanical modeling – and more generally in modeling for life sciences – lies in using the large amount of data available on the system to circumvent the lack of absolute modeling ground truth, since every system considered is in fact patient-specific, with possibly non-standard conditions associated with a disease. We have already developed original strategies for solving this particular type of inverse problems by adopting the observer stand-point. The idea we proposed consists in incorporating to the classical discretization of the mechanical system an estimator filter that can use the data to improve the quality of the global approximation, and concurrently identify some uncertain parameters possibly related to a diseased state of the patient. Therefore, our strategy leads to a coupled model-data system solved similarly to a usual PDE-based model, with a computational cost directly comparable to classical Galerkin approximations. We have already worked on the formulation, the mathematical and numerical analysis of the resulting system – see [6] – and the demonstration of the capabilities of this approach in the context of identification of constitutive parameters for a heart model with real data, including medical imaging, see [3].

4 Application domains

As already emphasized in the team's objectives, we consider experimental studies and clinical applications as crucial, both for motivating our new modeling endeavors, and to validate the global modeling simulation chain, via the numerical simulation and inverse problems (for data-based estimation).

For instance, the translation of the modeling and data assimilation techniques developed in our team into cardiac clinical applications is pursued in two main directions: 1. Cardiac modeling for monitoring purposes in anesthesia and critical care medicine 2. Cardiac modeling in heart diseases. Concerning the clinical applications of lung modeling and data interaction, the team works for a better understanding of pulmonary fibrosis and with recent new research about COVID pulmonary infections. Another example is the clinical relevance of our modeling and characterization of the biomechanical behavior of the cornea.

Beyond medical applications, our general methods have applications in many industrial fields. For instance, our expertise in wave propagation and associated inverse problems have potential applications in non-destructive testing of structure.

5 Social and environmental responsibility

5.1 Impact of research results

5.1.1 AnaestAssist project and impact for anaesthesia

Unstable hemodynamics during general anaesthesia increases the risk of cardiac, renal and brain disfunctions during the postoperative period, thus leading to a higher level of morbidity and mortality. To improve the patient's condition, learned societies therefore recommend monitoring the hemodynamics of the patient and having treatment strategies with quantitative objectives based on this monitoring. Currently, medical doctors have at their disposal some physiological signals (ECG, blood pressure) displayed on their monitor, and must rely on established practices and their experience to act in case of a dangerous drift.

The AnaestAssist project proposes to develop an augmented monitoring tool for anaesthesia. The proposed technology will introduce into the monitoring loop a predictive biophysical model, simulated in real time, and fed by the measured physiological signals. The model will be personalised for the patient, thus creating a digital twin of the patient's cardiovascular system. With this digital twin, physiological information that can cannot be measured or that can only be obtained with highly invasive methods will be computed in real time and treatment recommendations will be made. Our system will thus provide a much more complete vision of the patient's cardiovascular state and allow more informed and faster decisions. Eventually, the effects of drugs will be included in the model, which will make it possible to determine (through predictive modeling) adapted action recommendations, or even a real-time automatic drug administration loop. Our technology is expected to allow the medical staff to deliver a better treatment to the patient, to improve the patient's condition through a reduction of the risk related to general anaesthesia and a wiser exposition to drugs, and to reduce the costs for the health care system due to a lower rate of complications and shorter hospital stays.

The AnaestAssist project is intended to lead to a startup creation in the near future.

6 Highlights of the year

The ambitious i-Démo project MediTwin funded by France 2030, in which the team is involved, started this year.
Philippe Moireau started a new position as Professeur de Classe Exceptionnelle at Ecole Polytechnique in September 2024.

7 New software, platforms, open data

7.1 New software

7.1.1 MoReFEM

Name: Modeling Research with the Finite Element Method

Keywords: HPC, Multiphysics modelling, Data assimilation

Functional Description: MoReFEM is a HPC finite element library for simulating multiphysics evolution problems like the ones encounter in cardiac modeling (electrophysiology, structure and fluid mechanics, transport-diffusion, wave equations)

URL: https://gitlab.inria.fr/MoReFEM

Contact: Sebastien Gilles

Participants: Sebastien Gilles, Jerome Diaz, Patrick Le Tallec, Philippe Moireau, Dominique Chapelle, Chloe Giraudet, Giulia Merlini

7.1.2 CardiacLab

Keywords: Cardiovascular and respiratory systems, Matlab, Real time

Functional Description: CardiacLab is a MATLAB toolbox allowing to perform "real-time" cardiac simulations using 0D models of the cardiovascular systems. Its modular development includes (1) a module integrating the mechanical dynamics of the cavity taking into account its particular geometry, (2) a module allowing to choose a micro-model of the cardiac contraction, (3) a module of phase management, (4) a circulation module based on Windkessel models or more advanced 1D flows models, and (5) a perfusion module. The objective of this code is threefold: (1) demonstrate to students, engineers, medical doctors, the interest of modeling in cardiac applications, (2) unify our original modeling developments with the possibility to evaluate them with previous team developments before integrating them into 3D complex formulations, and (3) explore some avenues pertaining to real-time simulat

Release Contributions: Addition of a mechanical formulation expressed analytically as a function of displacements

URL: https://gitlab.inria.fr/M3DISIM/CardiacLab

Contact: Philippe Moireau

Participants: Philippe Moireau, Dominique Chapelle, François Kimmig, Jerome Diaz, Sebastien Impériale, Martin Genet, Federica Caforio, Radomir Chabiniok, Arthur Le Gall, Matthieu Caruel, Jessica Manganotti

7.1.3 HELEN

Name: Heart Estimator For Live Evaluation in aNesthesia

Keywords: Low rank models, Dimensionality reduction, Cardiovascular and respiratory systems, Kalman filter, Dynamical system

Functional Description: Real-time fractional heartbeat simulation for on-board monitoring devices. Certified models and implementation with respect to numerical errors. Estimation of state and parameters by sequential filtering for model inversion.

Release Contributions: Launching simulations from option files in text format Choice of modeling components from the option file Simulation results exported in csv format and visualization module available. Modules for the direct problem and the inverse problem (Kalman filter type algorithm). Unit tests implemented and workflow implementation on Inria's continuous integration platform. Non-regression tests implemented (integration test) and implementation of the workflow on Inria's continuous integration platform

Contact: Philippe Moireau

Participants: Laurent Steff, Sebastien Gilles, François Kimmig, Dominique Chapelle, Philippe Moireau, Marc Teyssier

7.1.4 AKILLES

Name: Agnostic Kalman Inference parraLLEl Strategies.

Keywords: Kalman filter, Data assimilation

Functional Description: This library concerns sequential data assimilation algorithms and more particularly of the Uscented Kalman Filter type (Normal, Reduced, Transformed etc.). The principle is to communicate the sigma-points representing the model instances via a message exchange library (here ZeroMQ). Thus each particle calculates in parallel with the others, and the core of the algorithm in C ++ can cooperate with models written in any language.

Contact: Philippe Moireau

Participants: Laurent Steff, Sebastien Gilles, Philippe Moireau

8 New results

8.1 Mathematical and Mechanical Modeling

8.1.1 A model of mechanical loading of the lungs including gravity and a balancing heterogeneous pleural pressure

Participants: Alice Peyraut, Martin Genet *(correspondant)*.

In silico models of the lungs have been widely developed in recent years, to improve the care of patients with pulmonary diseases, for example. A wide range of models, with different levels of complexity, can be found in the literature. In particular, the loading considered usually consists solely in the implementation of the pleural pressure (a negative pressure keeping the lungs inflated). Gravity, usually considered to be small in relation to the pleural pressure, has often been neglected. Beyond its supposedly limited impact, gravity has also been neglected due to the complexity of formulating physiological boundary conditions to counterbalance it. Gravity is however known to have many effects on pulmonary functions, e.g. on ventilation. We therefore chose to implement gravity in our model to verify that it is not negligible and therefore improve the accuracy of our model should it be the case. In this article, we propose a formulation of a counterbalancing pressure as boundary condition to implement gravity. We then study the effect of gravity on global and local behavior of our model, such as the pressure-volume response or the porosity. This study shows that, although small, gravity does have an impact on lung response. In particular, implementing gravity in our model induces the appearance of heterogeneities in the deformation and stress distribution, which could be valuable information to predict the evolution of certain pulmonary diseases, by correlating areas subjected to higher deformation and stresses with the evolution patterns of a given disease, for example. This work was published in [23].

8.1.2 Finite strain micro-poro-mechanics: formulation and compared analysis with macro-poro-mechanics

Participants: Mahdi Manoochehrtayebi, Martin Genet *(correspondant)*.

Porous materials are ubiquitous in nature – notably living tissues, which often undergo large deformations – and engineering applications. Poromechanics is an established theory to model the response of such materials; however, it is limited in its description of microscale phenomena, and structure-properties relationships. In this work, we propose a microscopic poromechanical model based on a novel formulation of the micro-poro-mechanics problem, which allows to compute the response of a periodic porous microstructure to any loading involving fluid pressure, macroscopic strain, and/or macroscopic stress. We systematically compare the global response of our micro-model to macro-poromechanics, in both the infinitesimal and finite strain settings, and investigate in particular three mechanisms, namely solid compressibility, strain-pressure coupling and deviatoric-volumetric strain coupling. We notably illustrate how the micro-model can be used to derive macroscopic parameters, and how these parameters depend on microscopic features like pore shape, porosity, material properties, etc. This modeling framework will be the basis for powerful micro-poro-mechanical models of various materials and tissues, where pore-scale phenomena can be incorporated explicitly.

8.1.3 Biomechanical modeling of extraocular muscles for the movement of an eye model applied to optics

Participants: Julien Bonnafé, Jean-Marc Allain *(correspondant)*.

Eye movements are essential for visual integration, from fixational eye movements to saccades. Several studies have shown dependence between eye movements and ocular tissues strain. Integration of large eye movements in Finite Element Model have been addressed previously on simplified geometries. Predicting activations parameters within a continuum extra ocular muscle model is a challenge since in-vivo measures are difficult. We propose a FEM in which we use a mesh of the sclera, optic nerve and medial and lateral rectus muscles to implement a large scale of movements through simulations of extra ocular muscles activations. To perform extra ocular muscle contraction, an Abaqus subroutine has been coded from data and methods available in litterature. State of the art to implement Robin's boundary conditions to represent orbital fat that support the eye globe has been evaluated.

8.1.4 Well-posedness and potential-based formulation for the propagation of hydro-acoustic waves and tsunamis

Participants: Juliette Dubois *(Ange)*, Sébastien Imperiale *(correspondant)*, Anne Mangeney *(Ange)*, Jacques Sainte-Marie *(Ange)*.

We study a linear model for the propagation of hydro-acoustic waves and tsunami in a stratified free-surface ocean. A formulation was previously obtained by linearizing the compressible Euler equations. The new formulation is obtained by studying the functional spaces and operators associated to the model.

The mathematical study of this new formulation is easier and the discretization is also more efficient than for the previous formulation. We prove that both formulations are well posed and show that the solution to the first formulation can be obtained from the solution to the second. Finally, the formulations are discretized using a spectral element method, and we simulate tsunamis generation from submarine earthquakes and landslides. This work [21] is published in M2AN.

8.2 Numerical Methods

8.2.1 Finite Element Neural Network Interpolation. Part I: Interpretable and Adaptive Discretization for Solving PDEs

Participants: Katerina Skardova, Alexandre Daby-Seesaram, Martin Genet *(correspondant)*.

In this work we construct the Finite Element Neural Network Interpolation (FENNI) framework, a sparse neural network architecture extending previous work on Embedded Finite Element Neural Networks (EFENN) introduced with the Hierarchical Deep-learning Neural Networks (HiDeNN). Due to their mesh-based structure, EFENN requires significantly fewer trainable parameters than fully connected neural networks, with individual weights and biases having a clear interpretation. Our FENNI framework, within the EFENN framework, brings improvements to the HiDeNN approach. First, we propose a reference element-based architecture where shape functions are defined on a reference element, enabling variability in interpolation functions and straightforward use of Gaussian quadrature rules for evaluating the loss function. Second, we propose a pragmatic multigrid training strategy based on the framework's interpretability. Third, HiDeNN's combined rh-adaptivity is extended from 1D to 2D, with a new Jacobian-based criterion for adding nodes combining h- and r-adaptivity. From a deep learning perspective, adaptive mesh behavior through rh-adaptivity and the multigrid approach correspond to transfer learning, enabling FENNI to optimize the network's architecture dynamically during training. The framework's capabilities are demonstrated on 1D and 2D test cases, where its accuracy and computational cost are compared against an analytical solution and a classical FEM solver. On these cases, the multigrid training strategy drastically improves the training stage's efficiency and robustness. Finally, we introduce a variational loss within the EFENN framework, showing that it performs as well as energy-based losses and outperforms residual-based losses. This framework is extended to surrogate modeling over the parametric space in Part II of the work.

8.2.2 Finite Element Neural Network Interpolation. Part II: Hybridisation with the Proper Generalised Decomposition for Non-Linear Surrogate Modelling

Participants: Alexandre Daby-Seesaram, Katerina Skardova, Martin Genet *(correspondant)*.

This work introduces a hybrid approach that combines the Proper Generalised Decomposition (PGD) with deep learning techniques to provide real-time solutions for parametrised mechanics problems. By relying on a tensor decomposition, the proposed method addresses the curse of dimensionality in parametric computations, enabling efficient handling of high-dimensional problems across multiple physics and configurations. Each mode in the tensor decomposition is generated by a sparse neural network within the Finite Element Neural Network Interpolation (FENNI) framework presented in Part I, where network parameters are constrained to replicate the classical shape functions used in the Finite Element Method. This constraint enhances the interpretability of the model, facilitating transfer learning, which improves significantly the robustness and cost of the training process. The FENNI framework also enables finding the optimal spatial and parametric discretisation dynamically during training, which accounts to optimising the model's architecture on the fly. This hybrid framework offers a flexible and interpretable solution for real-time surrogate modelling. We highlight the efficiency of the FENNI-PGD approach through 1D and 2D benchmark problems, validating its performance against analytical and numerical reference solutions. The framework is illustrated through linear and non-linear elasticity problems, showing the flexibility of the method in terms of changes in physics.

8.2.3 A time-domain spectral finite element method for acoustoelasticity: modeling the effect of mechanical loading on guided wave propagation

Participants: André Dalmora, Alexandre Imperiale, Sébastien Imperiale *(correspondant)*, Philippe Moireau.

Ultrasonic testing techniques such as guided wave-based structural health monitoring aim to evaluate the integrity of a material with sensors and actuators that operate *in situ*, *i.e.* while the material is in use. Since ultrasonic wave propagation is sensitive to environmental conditions such as pre-deformation of the structure, the design and performance evaluation of monitoring systems in this context is a complicated task that requires quantitative data and the associated modeling effort. In this work, we propose a set of numerical tools to solve the problem of mechanical wave propagation in materials subjected to pre-deformation. This type of configuration is usually treated in the domain of acoustoelasticity. A relevant modeling approach is to consider two different problems: a quasi-static nonlinear problem for the large displacement field of the structure and a linearized time-domain wave propagation problem. After carefully reviewing the modeling ingredients to represent the configurations of interest, we propose an original combination of numerical tools that leads to a computationally efficient algorithm. More specifically, we use 3D shell elements for the quasi-static nonlinear problem and the time-domain spectral finite element method to numerically solve the wave propagation problem. Our approach can represent any type of material constitutive law, geometry or mechanical solicitation. We present realistic numerical results on 3D cases related to the monitoring of both isotropic and anisotropic materials, illustrating the genericity and efficiency of our method. We also validate our approach by comparing it to experimental data from the literature. This work has been published in Wave Motion [18].

8.2.4 Fully explicit numerical scheme for linearized wave propagation in nearly-incompressible soft hyperelastic solids

Participants: Giulia Merlini, Sébastien Imperiale *(correspondant)*, Jean-Marc Allain.

The numerical approximation of wave propagation problems in nearly or pure incompressible solids faces several challenges such as locking and stability constraints. In this work we propose a stabilized Leapfrog scheme based on the use of Chebyshev polynomials to relax the stability condition, which is strongly limited by the enforcement of incompressibility. The scheme is fully explicit, second order accurate and energy-preserving. For the space discretization we use a mixed formulation with high-order spectral elements and mass-lumping. A strategy is proposed for an efficient and accurate computation of the pressure contribution with a new definition of the discrete Grad-div operator. Finally, we consider linear wave propagation problems in nearly-incompressible hyperelastic solids subject to static preload. This work has been submitted to Wave Motion, see preprint [35].

8.2.5 Numerical analysis of fully explicit methods for incompressible elastodynamics

Participants: Zineb Ramiche, Sébastien Imperiale *(correspondant)*.

In this work, we study a fully explicit high-order space-time discretization approach for the computation of elastic field propagation in quasi-incompressible media. For space discretization, our approach relies on, first, the use of high-order continuous finite elements with mass-lumping, and, second, the use of an explicit Chebyshev Leap-frog scheme to deal with time discretization. The Chebyshev Leap-frog scheme [35] is used to overcome the stability constraint (CFL condition) caused by the nearly incompressibility while still maintaining the explicitness. We present an approach that is valid for full hexahedral meshes (where the elastic field is sought in $\mathbb{Q}_k$ and the pressure in $\mathbb{Q}_{k-2}$ or fully tetrahedral meshes. For tetrahedral meshes, new enriched, using higher-degree bubble functions are studied. Furthermore, through the application of the so-called macro-element technique, we provide proof of the stability of the finite element discretization. This allows us to carry out error estimates for the semi-discrete problem in space (accounting in particular for quadrature errors).

8.2.6 Uniform boundary stabilization of a high-order finite element space discretization of the 1-d wave equation

Participants: Tiphaine Delaunay, Sébastien Imperiale *(correspondant)*, Philippe Moireau.

The objective of this work is to propose and analyze numerical schemes for solving boundary control problems or data assimilation problems by observers for wave propagation problems. The efficiency of the considered control or data assimilation strategy relies on the exponentially stable character of the underlying system. Therefore, the aim of our work is to propose a discretization process that allows preserving the exponential stability at the discrete level when using high-order spectral finite element approximation. The main idea is to add a stabilizing term to the wave equation that dampens the spurious oscillatory components of the solutions. This term is based on a discrete multiplier analysis that gives us the exponential stability of the semi-discrete problem at any order without affecting the approximation properties. This work is published in Numerische Mathematik [20].

8.3 Inverse Problems

8.3.1 Finite Strain Formulation of the Discrete Equilibrium Gap Principle: Application to Direct Parameter Estimation from Large Full-Fields Measurements

Participants: Alice Peyraut, Martin Genet *(correspondant)*.

The Equilibrium Gap Method (EGM) is a direct model parameter identification method, i.e., that does not require any resolution of the model. It has been extensively studied in the context of small strains but not thoroughly investigated for large strains. In this work, we propose a novel formulation of the EGM, valid in large strains, and applicable to both boundary and body forces, when full-field measurements are available. Our formulation is based on a recently proposed continuous formulation and consistent discretization of the equilibrium gap principle. Additionally, we developed an estimation pipeline to quantify the robustness of our new EGM formulation to noise, and we compared its performance to other classical estimation methods, namely the Finite Element Model Updating (FEMU) method and the Virtual Fields Method (VFM). Our robustness quantification pipeline involves generating synthetic data from a reference model through two methods: by adding noise to the reference displacement, or by generating noisy images and performing motion tracking with the Equilibrium Gap principle used as mechanical regularization. While the quality of estimation using our new EGM formulation is poor with the first data generation method, it improves drastically with the second method. Since the second method of synthetic data generation closely mimics experimental processes, the EGM, when combined with motion tracking with Equilibrium Gap regularization, demonstrates reasonable noise robustness. Thus, it is a promising option for direct parameter estimation from full-field measurements.

8.3.2 Uncertainty quantification for personalized biomechanical modeling: application to pulmonary poromechanical digital twins

Participants: Alice Peyraut, Martin Genet *(correspondant)*.

The development of personalized models is a key step for addressing various problems, especially in biomechanics. These models typically include many constants, introduced in the model material law or loading definition, and their estimation is crucial for the model personalization. However, performing solely the estimation does not yield any information on the estimation accuracy. Additionally, all parameters can typically not be estimated based only on clinical data: some parameters are identified, while others are fixed at generic values. The question of the identifiability of the parameters, along with the robustness of the estimation, notably to noise (measurement errors) and to bias (model errors), is therefore crucial and should be quantitatively addressed in parallel to the model development. In this work, we propose a general uncertainty quantification pipeline based on the creation of synthetic data –for which the parameters ground-truth values are known–, generated for different noise and bias levels. Estimation is then performed for many realizations of the noise or bias, as well as parameter initializations, until convergence of the estimated parameters error distributions. This pipeline was applied to a poromechanical lung model for illustration and validation purposes. It provides quantitative information on the actual identifiability of the parameters, and any derived quantity of interest, in the clinical setting. In particular, it allows to retrieve a confidence interval for each estimated parameters, which represents valuable information for diagnosis or prognosis use of the estimated values. This work is therefore a step towards improving the reliability of digital twins pipelines.

8.3.3 Kalman-based estimation of loading conditions from ultrasonic guided wave measurements

Participants: André Dalmora, Alexandre Imperiale, Sébastien Imperiale, Philippe Moireau *(correspondant)*.

Ultrasonic guided wave-based Structural Health Monitoring (SHM) of structures can be perturbed by Environmental and Operations Conditions (EOCs) that alter wave propagation. In this work, we present an estimation procedure to reconstruct an EOC-free baseline of the structure suitable for SHM from the only available Ultrasonic guided wave measurements. Our approach is model-based, *i.e.* we use a precise modeling of the wave propagation altered by structure loading conditions. This model is coupled with the acquired data through a data assimilation procedure to estimate the deformation caused by the unknown loading conditions. From a methodological point of view, our approach is original since we have proposed an iterated Reduced-Order Unscented Kalman strategy, which we justify as an alternative to a Levenberg-Marquardt strategy for minimizing the non quadratic least-squares estimation criteria. Therefore, from a data assimilation perspective, we provide a quasi-sequential strategy that can valuably replace more classical variational approaches. Indeed, our resulting algorithm proves to be computationally very effective, allowing us to successfully apply our strategy to realistic 3D industrial SHM configurations. This work has been published in Inverse Problems [19].

8.3.4 Stability analysis of a new curl-based full field reconstruction method in 2D magnetic resonance elastography

Participants: Nagham Chibli, Sébastien Imperiale *(correspondant)*, Martin Genet.

In Magnetic Resonance Elastography, the shear modulus of tissues μ is determined from full-field displacement data by solving an inverse problem based on the time-harmonic, linear, isotropic and nearly incompressible elastodynamic wave equation. The main challenge lies in developing a robust algorithm for handling noisy data. Specifically, the nearly incompressible nature of tissues means that the bulk λ is very high, which often causes straightforward extensions of existing algorithms to fail in maintaining robustness. Following previous works, we study a new formulation for the 2D problem. We reformulate the problem as a non-autonomous hyperbolic system to establish existence, uniqueness, and stability estimates for the inverse problem. To mitigate the impact of noise, we have implemented a regularization technique. Convergence properties of the method is evaluated using in-silico data.

8.3.5 Optimal filtering on manifolds

Participants: Gaël Le Ruz *(COMMEDIA)*, Damiano Lombardi *(COMMEDIA)*, Philippe Moireau *(correspondant)*.

This work is motivated by data assimilation for wildfire propagation, where the state and the observations of the system are naturally modeled in the manifold of contours. Typically, one can use an estimate-then-project method to address this problem. However, this is purely empirical and, in addition, an embedding in the Euclidean space need to be accessed, which is clearly artificial in the case of contours. Writing and solving the filtering problem directly on the manifold (without using the embedding in the ambient space) is a novel promising research direction, as some recent results in optimization and optimal control suggest. In this talk, using the example of a first-order dynamics on the two-sphere Riemannian manifold, we propose to develop a framework for computing optimal filters in a general manifold from the solution of a Hamilton-Jacobi-Bellman equation in the state space. We then reduce the cost of the resulting algorithm by using a quadratic approximation of the value function solution of the Hamilton-Jacobi-Bellman equation.

8.4 Experimental Assessments

8.4.1 Mechanical properties of stromal striae, and their impact on corneal tissue behavior

Participants: Qian Wu, Jean-Marc Allain *(correspondant)*.

Biological tissues have complex mechanical properties, which are deeply related to their function. It is thus needed to quantify the volumetric displacements induced by mechanical load, rather than only surface displacements. In this article, we propose to use Optical Coherence Tomography as a simple and fast method to quantify the volumetric deformation of the cornea under pressure. Indeed, the cornea plays a key role in vision, and any mechanical defect can impact the eye as it is under the intraocular pressure. Our observations show that, in the tangential direction, the cornea deforms more in the posterior than in the anterior region. In the depth direction, we observed a strong compression, with depth-dependent heterogeneity, delineating three distinct regions. This strong compression can be explained only by important outward water fluxes. Our study shows the complexity of human corneal mechanics, highlighting the need of adequate volumetric measure to characterize its strong anisotropy and depth-dependent behavior. This work is available in [33].

8.4.2 Mechanical properties of stromal striae, and their impact on corneal tissue behavior

Participants: Qian Wu, Jean-Marc Allain *(correspondant)*.

Cornea is an essential element of our eye. The refractive power of the cornea is closely related to its shape, which depends on the balance between its mechanical properties and the intraocular pressure. However, in keratoconus, the shape of the cornea is altered, and the mechanical properties (i.e., elastic modulus and viscosity) are reduced. These alterations have been associated with the development of striae within the cornea. Recently, such striae have been observed in healthy corneas as well, but with slightly different shapes. Our study investigated the mechanical role of these striae. To this end, we performed an inflation test under Optical Coherence Tomography: tomographic volumes were acquired in the central zone of eleven human corneas during an inflation test. Striae planes were extracted from the segmented images, and principal deformation maps were obtained by Digital Volume Correlation (DVC). We observe that the pattern of the striae does not change with pressure, even far above physiological pressure. Maximum principal strains are co-localized with the striae and are oriented perpendicular to the striae. We also observe that principal deformations on the striae increase with depth in the cornea. Our results show that striae lead to greater deformability in the direction perpendicular to the striae, especially in the posterior part of the cornea where they are the most visible. This supports the idea that the striae are undulations in the cornea collagenous microstructure, which are progressively unfolded under loading. They decrease the global stiffness of the cornea, in particular in the posterior part, and thus may help in accommodating deformations. This work has been published in [24]

8.4.3 Microrheology and structural quantification of hypercoagulable clots

Participants: Jean-Marc Allain *(correspondant)*, Simon Kouba.

Hypercoagulability is a pathology that remains difficult to explain today in most cases. It is likely due to a modification of the conditions of polymerization of the fibrin, the main clot component. Using passive microrheology, we measured the mechanical properties of clots and correlated them under the same conditions with structural information obtained with confocal microscopy. We tested our approach with known alterations: an excess of fibrinogen and of coagulation Factor VIII. We observed simultaneously a rigidification and densification of the fibrin network, showing the potential of microrheology for hypercoagulability diagnosis.

8.4.4 Using a micro-device with a deformable ceiling to probe stiffness heterogeneities within 3D cell aggregates

Participants: Martin Genet *(correspondant)*.

Recent advances in the field of mechanobiology have led to the development of methods to characterise single-cell or monolayer mechanical properties and link them to their functional behaviour. However, there remains a strong need to establish this link for three-dimensional (3D) multicellular aggregates, which better mimic tissue function. Here we present a platform to actuate and observe many such aggregates within one deformable micro-device. The platform consists of a single polydimethylsiloxane piece cast on a 3D-printed mould and bonded to a glass slide or coverslip. It consists of a chamber containing cell spheroids, which is adjacent to air cavities that are fluidically independent. Controlling the air pressure in these air cavities leads to a vertical displacement of the chamber's ceiling. The device can be used in static or dynamic modes over time scales of seconds to hours, with displacement amplitudes from a few μm to several tens of microns. Further, we show how the compression protocols can be used to obtain measurements of stiffness heterogeneities within individual co-culture spheroids, by comparing image correlations of spheroids at different levels of compression with finite element simulations. The labelling of the cells and their cytoskeleton is combined with image correlation methods to relate the structure of the co-culture spheroid with its mechanical properties at different locations. The device is compatible with various microscopy techniques, including confocal microscopy, which can be used to observe the displacements and rearrangements of single cells and neighbourhoods within the aggregate. The complete experimental and imaging platform can now be used to provide multi-scale measurements that link single-cell behaviour with the global mechanical response of the aggregates.

8.5 Clinical Applications

8.5.1 Digital twins for chronic lung diseases

Participants: Martin Genet *(correspondant)*.

Digital twins have recently emerged in healthcare. They combine advances in cyber-physical systems, modelling and computation techniques, and enable a bidirectional flow of information between the physical and virtual entities. In respiratory medicine, progress in connected devices and artificial intelligence make it technically possible to obtain digital twins that allow real-time visualisation of a patient's respiratory health. Advances in respiratory system modelling also enable the development of digital twins that could be used to predict the effectiveness of different therapeutic approaches for a patient. For researchers, digital twins could lead to a better understanding of the gene- environment - time interactions involved in the development of chronic respiratory diseases. For clinicians and patients, they could facilitate personalised and timely medicine, by enabling therapeutic adaptations specific to each patient and early detection of disease progression. The objective of this review is to allow the reader to explore the concept of digital twins, their feasibility in respiratory medicine, their potential benefits and the challenges to their implementation. This work has been published as [22].

8.5.2 A Clinical-Grade Partially Decellularized Matrix for Tracheal Replacement: Validation In Vitro and In Vivo in a Porcine Model

Participants: Jean-Marc Allain *(correspondant)*.

The management of extensive tracheal resection followed by circumferential replacement remains a surgical challenge. Numerous techniques are proposed with mixed results. Partial decellularization of the trachea with the removal of the mucosal and submucosal cells is a promising method, reducing immunogenicity while preserving the biomechanical properties of the final matrix. Despite many research protocols and proofs of concept, no standardized clinical grade protocol is described. Furthermore, local and systemic biointegration mechanisms of decellularized trachea are not well known. Therefore, in a translational research perspective, this work set up a partial tracheal decellularization protocol in line with Cell and Tissue Products regulations. Extensive characterization of the final product is performed in vitro and in vivo. The results show that the Partially Decellularized Trachea (PDT) is cell-free in the mucosa and submucosa, while the cartilage structure is preserved, maintaining the biomechanical properties of the trachea. When implanted in the muscle in vivo for 28 days, no systemic inflammation is observed, and locally, the PDT shows an excellent biointegration and vascularization. No signs of graft rejection are observed. These encouraging results confirmed the efficacy of the clinical grade PDT production protocol, which is an important step for future clinical applications. This work has been published in [16].

8.5.3 Modeling-based Radial Pressure Waveform Reconstruction using Photoplethysmography Signals

Participants: Jérôme Diaz *(correspondant)*, François Kimmig, Fabrice Vallée, Philippe Moireau.

This work introduces a model linking photoplethysmography (PPG) dynamics to radial pressure waveform (RPW), which could be integrated into digital twins, that enables the reconstruction of RPW from PPG measurements using pulse pressure extrema. Built upon existing literature and supervised symbolic regression on anesthesia data, the model was validated on 581 continuous 10 seconds subsequences from 24 patients. Calibration through an unscented Kalman filter ensured patient-specific accuracy, yielding an averaged Pearson correlation coefficient of 0.955 for the reconstructed signal. The model's ordinary differential equation (ODE) with three parameters showed consistency with existing models. The stable, identifiable parameters underscore the model's robustness. The proposed model gives some insights into the physiology hidden behind the PPG and paves the way for RPW reconstruction using non-invasive measurements. This work has been published as [25].

8.5.4 AnaestAssist project

Participants: François Kimmig *(correspondant)*, Dominique Chapelle, Philippe Moireau, Fabrice Vallée.

See section 5.1.1 for a description of the context and general objectives of the project.

More specifically this year, AnaestAssist contributed to the Diip-Heart project led by the Inserm U942 MASCOT team as part of the PEPR Santé Numérique. The Diip-Heart project aims to set up elements of augmented monitoring in the perioperative period allowing to anticipate all serious cardiovascular events.

Moreover, the MAJOR project prepared by the AnaestAssist team along with the anesthesia department of Lariboisière Hospital (AP-HP) and the Inria team COMMEDIA has been awarded an FHU-Carnot funding by AP-HP. The MAJOR project aims to extend augmented monitoring tools to intensive care, which requires incorporating the pulmonary system into the models.

In addition, in collaboration with the anesthesia department of the Lariboisière Hospital (AP-HP), the AnaestAssist team has designed a clinical study protocol, named CardioTwin, as a clinical validation stage of the AnaestAssist system. This study is an observational study. It aims to demonstrate the performance of the digital twin to characterize the patient's cardiovascular state in situations of hemodynamic instabilities. The clearance to conduct the study has been granted in December 2024 and the study will start in January 2025.

The HΞLEN code constitutes a key element to produce the proof of concept of the AnaestAssist solution functioning in real time. Enhancements of the code were performed during the year: an implementation of a venous return model element, the update of the circulation model elements for more modularity.

Moreover, a Python library named "ToolboxDigitalTwin", has been submitted to the Software Protection Agency (Agence pour la Protection des Programmes). It provides tools to manipulate high-frequency time signals and link them to digital models. These tools are intended to be aggregated in "wrapper" scripts. The main functionalities provided by the library are: data visualization, data preprocessing, execution of simulations, collection and postprocessing of simulation results and the production of output results (figures, tables, ...).

9 Bilateral contracts and grants with industry

9.1 Bilateral contracts with industry

Participants: Jean-Marc Allain, Julien Bonnafé.

- Metyos company. Study of a skin injection device
- Contract with Essilor on the modeling of myopia (75 keuros)

Participants: Andre Dalmora, , Sébastien Imperiale, , Philippe Moireau.

- CEA List. Collaboration contract around A. Dalmora's PhD work (15 keuros)

9.2 Bilateral grants with industry

Participants: Philippe Moireau, Jérôme Diaz, François Kimmig, Dominique Chapelle.

- AMIES Grant the french compagny Withings, specialized in health monitoring solutions through connected devices (watch, balance, etc.). Collaboration on data assimilation from connected devices measurements.

10 Partnerships and cooperations

10.1 National initiatives

10.1.1 MEDITWIN

Participants: Dominique Chapelle, Philippe Moireau, Colin Drieu, Alexis Janin.

MediTwin is an i-Démo project funded by France 2030. It ambitions to offer digital twins for medical applications, for better diagnosis and treatment, in neurology, cardiology and oncology. Coordinated by Dassault-Systèmes, it involves Inria as sole academic partner, together with seven French University Hospital Institutes (IHUs) and a few other private and public actors.

In this project, the team operates within the infrastructure-oriented workpackage (WP5) and will develop software tools that are essential ingredients in the construction of digital twins, namely, for simulation and estimation purposes. All these tools will be shared within the consortium during the project, and a major part of them will also be distributed as opensource software.

The project is funded for 5 years (2024–29, funding for the team 1160 k€).

10.1.2 Sachems

Participants: Sébastien Imperiale, Philippe Moireau, Andre Dalmora.

Structural Health Monitoring (SHM) consists of integrating sensors into a high-stakes structure (aircraft, nuclear power plant, wind turbine, etc.) to monitor its state of health in real time and thus anticipate maintenance operations. The project entitled "SACHEMS" ("SAClay High-end Equipment for the Monitoring of Structures"), as it was funded in 2019 under the SESAME system of the Ile-de-France region, aims to create a federative platform for research and innovation for the SHM, allowing the development of complete SHM systems and to deploy them on the application cases provided by industrial end users. This platform brings together both academic teams and industrial end-users. It offers to the public laboratories involved the possibility of carrying out research in close collaboration with industrial partners.

10.1.3 ANR

- **ANR JCJC LungManyScale (383 k€)**

  Participants: Martin Genet, Philippe Moireau, Dominique Chapelle, Madhi Manoochehrtayebi.

  The lungs architecture and function are well characterized; however, many fundamental questions remain (e.g., there is no quantitative link between tissue- and organ-level material responses), which represent real health challenges (e.g., Idiopathic Pulmonary Fibrosis is a poorly understood disease, for which a mechanical vicious cycle has been hypothesized, but not demonstrated). The general objective of this project is twofold: (i) scientifically, to better understand pulmonary mechanics, from the alveola to the organ in health and disease; (ii) clinically, to improve diagnosis and prognosis of patients through personalized computational modeling. More precisely, This project aims at developing a many-scale model of the pulmonary biomechanics, linked by computational nonlinear homogenization. The model will integrate the experimental and clinical data produced by partners, through an estimation pipeline that will represent augmented diagnosis and prognosis tools for the clinicians.

- **ANR ODISSE, (154 k€)**

  Participants: Philippe Moireau, Sébastien Imperiale, Tiphaine Delaunay.

  Motivated by some recent developments from two different fields of research, that is, observer design for finite-dimensional systems and inverse problems analysis for some PDE systems, the ODISSE project aims at developing rigorous methodological tools for the design of estimation algorithms for infinite-dimensional systems arising from hyperbolic PDE systems.

- **ANR SIMR (97 k€)**

  Participants: Philippe Moireau, Dominique Chapelle, Jérôme Diaz, Martin Genet.

  SIMR is a multi-disciplinary project seeking a better understanding of the biophysical mechanisms involved in mitral valve (MV) regurgitation diseases, to improve decision-making in patients by helping to determine the optimal timing for surgery. This project aims at facing this major issue with the following main two objectives: (1) Evaluate the biophysical consequences of MV repair and (2) Design numerical tools for cardiac hemodynamics, fluid-structure interaction and myocardium biomechanics to provide an in silico counterpart of the in vivo data obtained by tension measurement and imaging.

- **ANR AAP RA-COVID-19 SILICOVILUNG (55k€)**

  Participants: Martin Genet, Colin Laville.

  It is currently impossible to predict the evolution of severe COVID19-induced lung pathologies, in particular towards pulmonary fibrosis. A patient-specific model of lungs at 2-3 months after the acute stage will be used to seek mechanical indicators that may be valuable to predict the lung state after one year.

- **ANR Elastoheart (212k€)**

  Participants: Philippe Moireau, Sébastien Imperiale, Dominique Chapelle.

  The objective of this project is to develop a comprehensive mathematical and numerical modeling (direct and inverse) of 3D Shear-Wave (SW) propagation in cardiac realistic physiological models, and to demonstrate in vivo that shear velocity can assess important cardiac function and characteristics in experimental pathological models and in patients.

- **ANR CorMecha (191k€)**

Participants: Jean-Marc Allain.

This project aims at: (i) setting up an atlas of cornea 3D structure from the sub-micrometer scale (intra-lamellar organization of collagen fibrils) to the millimeter-centimeter scale, (ii) accurately measuring the biomechanical properties linked to this structure in physiological conditions and in various pathological conditions, and (iii) building a model of corneal biomechanics based on these microstructural and macroscopic data in order to provide insight into the role of specific stromal structures. It relies on the highly original combination of well-controlled inflation device and state-of-the-art imaging setups, mainly polarization-resolved second harmonic generation microscope. Specific bioimage informatics tools and pipelines will be developed to process the very large data sets (Gb to Tb) generated by this new device and quantify clinically-relevant parameters of interest. Advanced statistical analysis of the series of clinical, structural and mechanical data obtained on the same cornea will then be performed for normal, keratoconic and photo-ablated corneas. The ultimate goals are twofold: (i) to translate the structural features observed with advanced research microscopes into easily-detectable features using commonly used techniques in clinical ophthalmology, in order to enable the diagnosis of structural defects related to defective mechanical properties; (ii) to develop a patient-specific simplified model to serve as a predictive tool by clinicians, mainly to improve refractive surgery procedures.

- **ANR MLQ-CT (140k€)**

Participants: Martin Genet.

High-Resolution Computed Tomography (HRCT) scans have a pivotal role in revolutionizing pulmonary medicine, particularly in the classification of Interstitial Lung Diseases (ILDs). However, predicting the prognosis of fibrosing ILDs, such as Idiopathic Pulmonary Fibrosis (IPF), remains a challenge despite advancements in HRCT analysis. The project aims to develop qualitative and quantitative biomarkers from routine HRCT scans for fibrosing ILDs, focusing on those with a Progressive Pulmonary Fibrosis (PPF) phenotype. Two anti-fibrotic drugs, Pirfenidone and Nintedanib, show promise, but there is a lack of specific data on patient selection and timing of prescription. The research hypothesizes that real-time analysis of HRCT scans can yield significant candidate biomarkers for fibrosis progression. The objective is to advance existing software tools to a Technology Readiness Level 6, creating an implantable prototype for hospital use and testing it on ILDs patient data to identify potential biomarkers for PPF characterization.

- **ANR KAYO (200k€)**

Participants: Jean-Marc Allain.

KAYO project aims to determine which hyper coagulability conditions can be detected through microrheoglogy measurements, and at which selectivity and sensitivity. The main underlying hypothesis is that hypercoagulability is associated with a change of the fibrin network, as it modifies the coagulation factors. Thus, the project will explore the impact of different known hypercoagulability conditions on the structure of the fibrin network (through confocal or SEM images) and on its microscopic rheological properties. Once the effects of known conditions will be determine, it will be tested on real blood samples.

10.1.4 Other funding

- PEPR santé numérique - DiipHeart project (253k€)

Participants: François Kimmig, Philippe Moireau, Dominique Chapelle.

This project is led by the Inserm team U942 MASCOT. It aims to set up elements of augmented monitoring in the perioperative period allowing to anticipate all serious cardiovascular events (total grant: 1.8M euros).

- AP-HP FHU-Carnot - MAJOR project (72k€)

Participants: François Kimmig, Alexis Janin, Dominique Chapelle.

The MAJOR project is led by the anesthesia department of Lariboisière Hospital (AP-HP) and also involves the Inria team COMMEDIA. The project MAJOR aims to extend to the augmented monitoring tools developed in the AnaestAssist project to intensive care, which requires to incorporate the pulmonary system into the models (total grant: 250k euros).

- AMIES Project WithCardiacModels, in partnership with Withings company (98k€)

Participants: Philippe Moireau, Jérôme Diaz, François Kimmig.

Connected objects are now emerging as an effective tool for non-invasive monitoring of the general state of health day and night. In order to process the generated data streams, many signal processing and learning algorithms are required to reconstruct actionable outputs about the user's health. Many objects providing interesting cardiovascular information for the general public already exist on the market, such as the Withings Scanwatch, which measures an ECG and detects atrial fibrillation.

In this project, we propose to process the measurements collected by data assimilation approaches based on the modeling of the underlying biophysical processes. These models of the cardiovascular system and the real-time estimation methods developed by the M3DISIM team are ideally suited to the distal data on cardiovascular functioning collected by Withings. New algorithms for estimating the physiology of subjects respecting the constraints of optimal regularization of signals, detection of defects by searching for causality, privacy on shared data will make it possible tomorrow to detect deterioration in the cardiovascular health of heart failure patients, for example.

- **RheCa Labex (70k€)**

Participants: Jean-Marc Allain.

The RheCa project focuses on the multi-scale study of venous blood clots for the diagnosis of thrombosis. It aims at building an original device for the microrheological of blood clot, usable for clinical studies.

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

General chair, scientific chair

- J.M. Allain, Session chair at ESB2024
- M. Genet, Session chair on Biomechanics and Biomedical Engineering at the 16th national workshop on computational mechanics (CSMA), Giens, France
- M. Genet, Session chair on Lung Modeling at the 2024 Virtual Physiological Human Conference (VPH2024), Stuttgart, Germany
- S. Imperiale, Session chair, Waves conference, Berlin, Germany
- P. Moireau, Session chair, SIAM UQ, Trieste, Italy

Member of the organizing committees

- J.M. Allain, Member of Journée de la F2M committee

11.1.2 Scientific events: selection

Member of the conference program committees

- J.M. Allain, Member of the PhysBio2024 program committee

Reviewer

- J.M. Allain, reviewer for the ESB2024 conference
- J.M. Allain, reviewer for the Societe de Biomechanics conference
- M. Genet, reviewer for the 49ème Congrès de la Société de Biomécanique (SB2024), Grenoble, France

11.1.3 Journal

Member of the editorial boards

- D. Chapelle, member of the editorial board of journal *ESAIM:M2AN*
- P. Le Tallec , Member of the editorial board of journal *Computer Methods in Applied Mechanics and Engineering*
- P. Le Tallec , Member of the editorial board of journal *Computer and Structures*

Reviewer - reviewing activities

- M. Genet, reviewer for “Computer Methods in Applied Mechanics and Engineering” and “Computational Mechanics” and “Biomechanics and Modeling in Mechanobiology” and “Journal of the Mechanical Behavior of Biomedical Materials”
- J.M. Allain, reviewer for “Acta Biomateriala”
- S. Imperiale, reviewer for SIAM, IJNME, M2AN, MATCOM
- P. Moireau, reviewer for COCV, Cambridge Press, IMA

11.1.4 Invited talks

- L.P. Chaintron, invited seminar at IHES (May 2024), “Constrained dynamics on measures”, Bures sur Yvette, France
- L.P. Chaintron, invited seminar at EPFL (November 2024), “Quasi-continuity methods for mean-field systems”, Lausanne, Swritzerland
- M. Genet, invited keynote at the BIOREME (Biophysical Modelling in Respiratory Medicine) Network Conference 2024, Nottingham, United Kingdom
- M. Genet, invited keynote at the RT Math-Bio-Santé 2024 workshop, Nantes, France
- P. Moireau, invited seminar at Imperial-UCL Numerics seminar (Jan 2024), London, UK

11.1.5 Leadership within the scientific community

- J.M. Allain, Member of the Société de Biomécanique
- J.M. Allain, Member of the European Society of Biomechanics
- M. Genet, Board Member of the PhotoMechanics Association (PMa)
- M. Genet, Board Member of the French Computational Mechanics Association (CSMA)

11.1.6 Scientific expertise

- M. Genet and J.M. Allain, reviewers for ANR
- J.M. Allain, reviewer for the ERC
- J.M. Allain, reviewer for SNSF (Switzerland funding agency)

11.1.7 Research administration

- J.M. Allain, responsible of the axis “mécanique et matériaux pour le bio” at the Fédération Francilienne de Mécanique
- D. Chapelle, scientific head of the joint AP-HP–Inria laboratory “Daniel Bernoulli”
- D. Chapelle, member of the steering committee of the interdisciplinary center “Engineering for Health” (E4H) of IPP
- P. Le Tallec, Dean of the bachelor programme at Ecole Polytechnique, until July 1st, 2024
- P. Moireau, member of the steering committee of the Mathematics Departement, Institut Polytechnique de Paris
- P. Moireau, member of the steering committee of the Commission des carrières scientifiques, Corps des Mines

11.2 Teaching - Supervision - Juries

11.2.1 Teaching

- Bachelor: Z. Ramiche, “Statistiques”, 36h, B1, Université Paris-Saclay
- Bachelor: Z. Ramiche, “Mathématiques”, 64h, B1 et B2, Université Paris-Saclay
- Bachelor; N. Chibli, “Linear Algebra”, 56h, École Polytechnique.
- Bachelor: G. Le Ruz, “Linear algebra and ODEs”, 38h, B3, Polytech Sorbonne, Sorbonne Université

- Bachelor: G. Le Ruz, “Fourier analysis”, 14h, B3, Polytech Sorbonne, Sorbonne Université
- Bachelor: G. Le Ruz, “Numerical Analysis for PDEs”, 12h, B3, Polytech Sorbonne, Sorbonne Université
- All-levels: J.M. Allain, referent for disability at Ecole polytechnique, France
- Bachelor: J.M. Allain, Academic advisor for mechanics at the Bachelor program Ecole Polytechnique, France
- Bachelor: J.M. Allain, “Classical mechanics”, 24h, B2, Ecole Polytechnique, France
- Master: J.M. Allain, “Statistical mechanics: application to cell motility”, 20h, M2, Ecole Polytechnique, France
- Master: J.M. Allain, “Introduction à la mécanique des milieux continus”, 30h, M2, Ecole Polytechnique, France
- Master: J.M. Allain, “Biosolids”, 20h, M2, Ecole Polytechnique, France
- Master: D. Chapelle, “MSE303 - Modélisation mathématique et estimation en biomécanique cardiaque – De la théorie aux applications médicales”, 16h, M2, Université Paris-Saclay and Institut Polytechnique de Paris, France
- Master: D. Chapelle, “MSE303 - Modélisation mathématique et estimation en biomécanique cardiaque – De la théorie aux applications médicales”, 9h, M2, Université Paris-Saclay and Institut Polytechnique de Paris, France
- Master: M. Genet, “Numerical methods in (solid) mechanics”, 54h, M1, École Polytechnique, France
- Master: M. Genet, “Model-Data interaction in mechanics”, 40h, M1, École Polytechnique, France
- Master: M. Genet, “Ingénierie biomédicale basée sur la simulation mécanique : application à la fibrose pulmonaire”, 2h, (M2 B2PRS), Université Paris-Saclay
- Master: S. Imperiale, “AMS306 – Techniques de discrétisation avancées pour les problèmes d’évolutions”, 18h, M2, Université Paris-Saclay
- Master: P. Moireau, “MAP431 — Variational formulations”, 40h, M1, École Polytechnique
- Master: P. Le Tallec, “Mécanique des Milieux Continus”, 24h, M1, Ecole Polytechnique France.
- Master: P. Le Tallec, “Solid and Continuum Mechanics”, 12h, M1, Master of Nuclear Energy, Université Paris-Saclay, France
- Master: P. Moireau, “AMS305 – Complétion de données et identification dans les problèmes gouvernés par des équations aux dérivées partielles”, 16h, M2, Université Paris-Saclay, France
- Master: P. Moireau, “MSE303 - Modélisation mathématique et estimation en biomécanique cardiaque – De la théorie aux applications médicales”, 16h, M2, Université Paris-Saclay and Institut Polytechnique de Paris, France

11.2.2 Supervision

- PhD defended: Giulia Merlini, “Simulation of Dynamical Optical Coherent Elastography with applications in cornea”, defended 01/2025; supervisor: J.M. Allain and S. Imperiale
- PhD defended: Louis-Pierre Chaintron, “Finite-dimensional and measure-valued constrained dynamics, through the lens of large deviation and control theory”, defended 12/2024; supervisor: J. Reygner (Materials) and P. Moireau
- PhD defended: A. Peyraut, “Modeling and estimation of lung poromechanics”, defended 12/2024, supervisors: M. Genet

- PhD defended: Matheus de Lorenzo, Approches multi-échelles de l'adhérence des pneumatiques sur route mouillée, defended 06/2024; supervisor: P. Le Tallec
- PhD defended: M. Manoochertayebi, "Manyscale modeling of lung poromechanics", defended 03/2024, supervisors: M. Genet, A. Bel-Brunon (INSA-Lyon)
- PhD in progress: Qian Wu, "Cornea biomechanics", started 10/2022, supervisor: J.M. Allain
- PhD in progress: Juilen Bonnafé, "Biomechanical modeling of the eye movements", started 09/2023; supervisor: J.M. Allain
- PhD in progress: Simon Kouba, "Microrheology of blood clot", started 10/2023; supervisor: J.M. Allain and N. Westbrook (Université Paris-Saclay)
- PhD in progress: N. Chibli, "Mathematical & numerical analysis of inverse problems methods for soft tissue quasi-static elastography", started 11/2023, supervisors: S. Imperiale and M. Genet
- PhD in progress: Z. Ramiche, "Mathematical and numerical modeling of shear-wave propagation in the heart in the context of elastography", started 10/2022, supervisor: S. Imperiale
- PhD in progress: F. Alvarez-Barrientos, "Modeling and Estimation of Pulmonary Dynamics", started 09/2024, supervisor: M. Genet
- PhD in progress: H. Xiao, "Modeling and estimation of combined tissue deformation, air and blood flow in the lung", started 10/2024, supervisors: M. Genet

11.2.3 Juries

- J.M. Allain, Habilitation Jury of S. Le Floch, Université de Montpellier, President Y. Monerie, 07/10
- J.M. Allain, PhD Jury of E. Saadat, Sissa (Trieste, Italy), PhD Advisor: Stefano Ruffo, 12/16
- D. Chapelle, Habilitation jury (rapporteur) of Francesco Bonaldi, Univ. Perpignan, 18/10
- M. Genet, PhD jury (rapporteur) for Nibaldo Aviles-Rojas, Pontificia Universidad Catolica de Chile, Santiago, Chile, 03/2024
- M. Genet, PhD jury (examinateur) for Sokratis Xenos, École Polytechnique, Palaiseau, France, 06/2024
- M. Genet, PhD jury (examinateur) for Enrico Lorenzetti, École Polytechnique, Palaiseau, France, 06/2024
- S. Imperiale, PhD jury (examinateur) for Houdan Mouhcine, Université Paris-Saclay, 12/2024
- P. Moireau, PhD jury (president) for Gabriel Victorino Cardoso, Sorbonne Université , 04/2024
- P. Moireau, PhD jury (examinateur) for Willy Hallik, Sorbonne Université , 10/2024
- P. Moireau, PhD jury (examinateur) for Fabien Pourre, Institut Polytechnique de Paris, 12/2024

11.3 Popularization

11.3.1 Participation in Live events

- N. Chibli, Fête de la Science, Ecole polytechnique

11.3.2 Others science outreach relevant activities

- N. Chibli, Médiation scientifique, Inria Saclay

12 Scientific production

12.1 Major publications

[1] J. Albella Martínez, S. Imperiale, P. Joly and J. Rodríguez. 'Solving 2D linear isotropic elastodynamics by means of scalar potentials: a new challenge for finite elements'. In: *Journal of Scientific Computing* (2018). DOI: 10.1007/s10915-018-0768-9. URL: https://hal.inria.fr/hal-01803536.

[2] M. Caruel, P. Moireau and D. Chapelle. 'Stochastic modeling of chemical-mechanical coupling in striated muscles'. In: *Biomechanics and Modeling in Mechanobiology* (2018). DOI: 10.1007/s10237-018-1102-z. URL: https://hal.inria.fr/hal-01928279.

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