RESEARCH CENTRE

Inria Saclay Centre at Institut Polytechnique de Paris

IN PARTNERSHIP WITH:

Institut Polytechnique de Paris

2023 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

Inria

Contents

Project-Team M3DISIM

Creation of the Project-Team: 2016 June 01

Keywords

Computer sciences and digital sciences

A6.1.1. – Continuous Modeling (PDE, ODE)

A6.1.2. – Stochastic Modeling

A6.1.4. – Multiscale modeling

A6.1.5. – Multiphysics modeling

A6.2.1. – Numerical analysis of PDE and ODE

A6.3.1. – Inverse problems

A6.3.2. – Data assimilation

A6.3.4. – Model reduction

A6.4.1. – Deterministic control

A6.4.2. – Stochastic control

A6.4.3. – Observability and Controlability

A6.4.4. – Stability and Stabilization

A6.4.6. – Optimal control

A6.5.1. – Solid mechanics

A6.5.2. – Fluid mechanics

A6.5.4. – Waves

A9.2. – Machine learning

Other research topics and application domains

B1.1.8. – Mathematical biology

B1.1.9. – Biomechanics and anatomy

B2.2.1. – Cardiovascular and respiratory diseases

B2.6.2. – Cardiac imaging

B2.6.3. – Biological Imaging

1 Team members, visitors, external collaborators

Research Scientists

- Philippe Moireau [Team leader, INRIA, Senior Researcher, Team Leader from 01/07/2023 to 31/12/2023, HDR]
- Dominique Chapelle [INRIA, Senior Researcher, Team Leader from 01/01/2023 to 30/06/2023, HDR]
- Sebastien Impériale [INRIA, Researcher, HDR]

Faculty Members

- Jean-Marc Allain [Ecole Polytechnique, Professor, HDR]
- Martin Genet [Ecole Polytechnique, Professor, HDR]
- Patrick Le Tallec [Ecole Polytechnique, Professor, HDR]

Post-Doctoral Fellows

- Andre Luiz Dalmora [INRIA, from Oct 2023]
- Elise Grosjean [INRIA, Post-Doctoral Fellow, from Oct 2023]
- Lionel Lartigue [CNRS, Post-Doctoral Fellow, from Feb 2023]
- Benjamin Memmi [AP/HP, Post-Doctoral Fellow, from Nov 2023]
- Katerina Skardova [Ecole Polytechnique, Post-Doctoral Fellow, from Aug 2023]

PhD Students

- Mathieu Barre [INRIA, until Oct 2023]
- Julien Bonnafe [Essilor, CIFRE, from Sep 2023]
- Louis-Pierre Chaintron [ENS PARIS]
- Nagham Chibli [Ecole Polytechnique, from Nov 2023]
- Andre Luiz Dalmora [CEA, until Sep 2023]
- Tiphaine Delaunay [INRIA]
- Simon Kouba [Ecole Polytechnique, from Oct 2023]
- Mahdi Manoochehrtayebi [Ecole Polytechnique]
- Giulia Merlini [Ecole Polytechnique]
- Alice Peyraut [CNRS]
- Zineb Ramiche [INRIA]
- Qian Wu [Ecole Polytechnique]

Technical Staff

- Jerome Diaz [INRIA, Engineer]
- François Kimmig [INRIA, Engineer, from Sep 2023]
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Interns and Apprentices

- Nagham Chibli [INRIA, Intern, from Apr 2023 until Sep 2023]
- Marion Lautier [Ecole Polytechnique, Intern, from Apr 2023 until Jul 2023]
- Louis Pade [INRIA, Intern, from May 2023 until Aug 2023]
- Adrian Padilla Segarra [INRIA, Intern, from Apr 2023 until Aug 2023]
- Yifan Wu [Ecole Polytechnique, Intern, from Apr 2023 until Jul 2023]

Administrative Assistant

- Bahar Carabetta [INRIA]

External Collaborators

- Jeanne Brionnet [AP/HP, from Sep 2023]
- Matthieu Caruel [UNIV PARIS XII]
- Radomir Chabiniok [UT SOUTHWESTERN]
- Alexandre Imperiale [CEA]
- François Kimmig [self-employed, from May 2023 until Aug 2023]
- Didier Lucor [CNRS]
- Adrian Padilla Segarra [ONERA, from Nov 2023]
- 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 thermomechanical laws, and in particular the energy balance, and proposed compatible numerical schemes that – in consequence – can be rigorously analyzed, see [6]. 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 [7].

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 [5] – 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 [2].

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 dysfunctions 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.

5.1.2 COVID research

In response to the ongoing COVID-19 pandemic caused by SARS-CoV-2, governments are taking a wide range of non-pharmaceutical interventions (NPI). These measures include interventions as stringent as strict lockdown but also school, bar and restaurant closures, curfews and barrier gestures, i.e. social distancing. Disentangling the effectiveness of each NPI is crucial to inform response to future outbreaks. To this end, we propose to develop a multi-level estimation of the French COVID-19 epidemic over a period of one year. This work performed with colleagues from project-teams Sistm and Monc among others has been published in [10] for the methodological aspects and in [8] for the applications to the COVID-19 pandemic.

More specifically in this work, we rely on a global extended Susceptible-Infectious-Recovered (SIR) mechanistic model of the infection including a dynamical (over time) transmission rate containing a Wiener process accounting for modeling error. Random effects are integrated following an innovative population approach based on a Kalman-type filter where the log-likelihood functional couples data across French regions. We then fit the estimated time-varying transmission rate using a regression model depending on NPI, while accounting for vaccination coverage, apparition of variants of concern (VoC) and seasonal weather conditions. We show that all NPI considered have an independent significant effect on the transmission rate. We additionally demonstrate a strong effect from weather conditions which decrease transmission during the summer period, and also estimate increased transmissibility of VoCs.

5.1.3 Withings

With the french compagny Withings, specialized in health monitoring solutions through connected devices (watch, balance, etc.), we propose to process the collected measurements by our 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 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 in the future to detect deterioration in the cardiovascular state of patients.

6 Highlights of the year

Philippe Moireau participated to the Programme "The mathematical and statistical foundation of future data-driven engineering" at Isaac Newton Institute for Mathematical Sciences, Cambridge from January to end of june.

6.1 Awards

Martin Genet has been promoted Associate Professor at Polytechnique.

A former PhD student of the team, Federica Caforio, received this year L'Oréal-UNESCO For Women in Science, partly her work in the team.

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

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

As part of Julien Bonnafé's PhD, which began this year, we have carried out a literature review on the different components of the eye, and in particular on their mechanical roles. A specific question is the importance of the muscle and the surrounding tissues. Our aim is to predict the mechanical loadings due to major eye movements, and their possible impact on the optical capacity of the eye. This state of the art consisted of an evaluation of the models present in the literature, an identification of feasible simulation methods, a biometric assessment of anatomical features, as well as the collection of mechanical parameters of the various tissues of the ocular system.

8.1.2 Upscaling of nonlinear multiscale structures

Participants: Patrick Le Tallec.

The numerical simulation of multiscale and multiphysics problems requires efficient tools for spatial localization and model reduction. A general strategy combining Domain Decomposition and Nonuniform Transformation Field Analysis (NTFA) was proposed in [29] for the simulation of nuclear fuel assemblies at the scale of a full nuclear reactor. The model at subdomain level solves the full elastic problem but with a reduced nonlinear loading, based on simplified boundary conditions, reduced creep flow rules, projected sign preserving contact conditions, and a NTFA like reduced friction law to get the evolution of each slipping mode. With this loading reduction, the local solution can be explicitly obtained from a small set of precomputed elementary elastic solutions.

8.1.3 Modeling actin-myosin interaction: beyond the Huxley-Hill framework

Participants: Louis-Pierre Chaintron *(correspondant)*, Matthieu Caruel *(UPEC)*, François Kimmig.

Contractile force in muscle tissue is produced by myosin molecular motors that bind and pull on specific sites located on surrounding actin filaments. The classical framework to model this active system was set by the landmark works of A.F. Huxley and T.L. Hill. This framework is built on the central assumption that the relevant quantity for the model parametrization is the myosin head reference position. In this paper, we present an alternative formulation that allows to take into account the current position of the myosin head as the main model parameter. The actin-myosin system is described as a Markov process combining Langevin drift-diffusion and Poisson jumps dynamics. We show that the corresponding system of Stochastic Differential Equation is well-posed and derive its Partial Differential Equation analog in order to obtain the thermodynamic balance laws. We finally show that by applying standard elimination procedures, a modified version of the original Huxley-Hill framework can be obtained as a reduced version of our model. Theoretical results are supported by numerical simulations where the model outputs are compared to benchmark experimental data. This work was published as [17].

8.1.4 A jump-diffusion stochastic formalism for muscle contraction models at multiple timescales

Participants: Louis-Pierre Chaintron, François Kimmig, Matthieu Caruel *(UPEC)*, Philippe Moireau *(correspondant)*.

Muscle contraction at the macro level is a physiological process that is ultimately due to the interaction between myosin and actin proteins at the micro level. The actin-myosin interaction involves slow attachment and detachment responses and a rapid temporal change in protein conformation called power-stroke. Jump-diffusion models that combine jump processes between attachment and detachment with a mechanical description of the power-stroke have been proposed in the literature. However, the current formulations of these models are not fully compatible with the principles of thermodynamics. To solve the problem of coupling continuous mechanisms with discrete chemical transitions, we rely on the mathematical formalism of Poisson random measures. First, we design an efficient stochastic formulation for existing muscle contraction PDE models. Then, we write a new jump- diffusion model for actin-myosin interaction. This new model describes both the behavior of muscle contraction on multiple time scales and its compatibility with thermodynamic principles. Finally, following a classical calibration procedure, we demonstrate the ability of the model to reproduce experimental data characterizing muscle behavior on fast and slow time scales. This work was published as [19].

8.1.5 Reduced left ventricular dynamics modeling based on a cylindrical assumption

Participants: Martin Genet *(correspondant)*, Jérôme Diaz, Dominique Chapelle, Philippe Moireau.

Biomechanical modeling and simulation is expected to play a significant role in the development of the next generation tools in many fields of medicine. However, full-order finite element models of complex organs such as the heart can be computationally very expensive, thus limiting their practical usability. Therefore, reduced models are much valuable to be used, for example, for pre-calibration of full-order models, fast predictions, real-time applications, and so forth. In this work, focused on the left ventricle, we develop a reduced model by defining reduced geometry & kinematics while keeping general motion and behavior laws, allowing to derive a reduced model where all variables & parameters have a strong physical meaning. More specifically, we propose a reduced ventricular model based on cylindrical geometry & kinematics, which allows to describe the myofiber orientation through the ventricular wall and to represent contraction patterns such as ventricular twist, two important features of ventricular mechanics. Our model is based on the original cylindrical model of Guccione, McCulloch, & Waldman (1991); Guccione, Waldman, & McCulloch (1993), albeit with multiple differences: we propose a fully dynamical formulation, integrated into an open-loop lumped circulation model, and based on a material behavior that incorporates a fine description of contraction mechanisms; moreover, the issue of the cylinder closure has been completely reformulated; our numerical approach is novel aswell, with consistent spatial (finite element) and time discretizations. Finally, we analyze the sensitivity of the model response to various numerical and physical parameters, and study its physiological response. This work was published in [23].

8.1.6 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 paper, 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. This work has just been submitted to the Journal of Mechanics and Physics of Solids.

8.1.7 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 is about to be submitted to the Biomechanics and Modeling in Mechanobiology journal.

8.2 Numerical Methods

8.2.1 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, 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.

8.2.2 A numerical scheme for linear elastic wave propagation in nearly-incompressible tissues

Participants: Giulia Merlini, Sébastien Imperiale, Jean-Marc Allain.

Dynamic elastography is a fundamental technique to study the local mechanical property of biological tissues, such as the cornea. It is based on in-vivo tracking of shear waves propagation as a result of a transient stimulation. Due to high water content, the cornea is a nearly incompressible tissue where the shear waves are 150 times slower than the compressional waves. The incompressibility and the double-scale of the phenomena make the finite element (FE) approximation difficult. The objective of this study is to propose an efficient scheme to obtain a reliable modelling of transient elastography measurements applied to the cornea and to improve tissue characterization techniques.

In order to model the resulting shear-wave propagation phenomenon, we propose a FE approximation with high-order spectral elements together with Mass Lumping approach. This allows to avoid the inversion of mass matrix at each time-step by computing an approximated value of the mass integrals with a numerical integration formula (Gauss-Lobatto rule).

Incompressibility is a well-known problem in FE approximation with pure displacement method, due to locking, ill-conditioning of the stiffness matrix and incorrect pressures approximations. To overcome these limitations, we use a mixed formulation with the introduction of the pressure as a local variable defined on each element. The approximation of the displacement and the pressure field are performed with $\mathcal{Q}_4$-$\mathcal{Q}_2^{disc}$ elements .

For the time discretization, the explicit leapfrog (LF) scheme shows high efficiency and second order accuracy. However, the time-step is strongly decreased by the velocity of the compressional wave. In this study, we propose a strategy inspired by local time-stepping method. The contribution of pressure wave is computed explicitly in an inner loop. While maintaining stability and accuracy, we obtain a fully explicit algorithm that is more efficient in terms of CPU time compared to the standard LF scheme.

We have performed simulations of elastic wave propagation on a homogeneous isotropic cornea with a CPU time of 75 minutes. In preliminary simulations we achieve a computational time three times lower, with a $L^\infty(L^2)$ -error on the displacement of the order of 4% compared to the LF scheme. The natural extension of this work is to perform simulations taking into account the pre-stress state with a non-linear law and then integrate the model with the anisotropic behavior related to the lamellar structure of the cornea.

8.2.3 Numerical analysis of fully explicit methods for incompressible elastodynamics

Participants: Zineb Ramiche, Sébastien Imperiale.

The objective of this work is first to analyze the numerical method for the shear wave propagation in tissues developped in a previous work and second to extend the method to other types of finite elements strategy. In particular we use enriched finite element space on tetrahedrals in order to construct provably inf-sup stable finite elements of order 2 and 3 that allow using a mass lumping strategy.

8.2.4 An implicit-explicit time discretization for elastic wave propagation problems in plates

Participants: Sébastien Imperiale *(corespondant)*, Alexandre Imperiale.

In this work we propose a new implicit-explicit scheme to address the challenge of modeling wave propagation within thin structures using the time-domain finite element method. Compared to standard explicit schemes, our approach renders a time marching algorithm with a time step independent of the plate thickness and its associated discretization parameters (mesh step and order of approximation). Relying on the standard three dimensional elastodynamics equations, our strategy can be applied to any type of material, either isotropic or anisotropic, with or without discontinuities in the thickness direction. Upon the assumption of an extruded mesh of the plate-like geometry, we show that the linear system to be solved at each time step is partially lumped thus efficiently treated. We provide numerical evidence of an adequate convergence behavior, similar to a reference solution obtained using the well-known leapfrog scheme. Further numerical investigations show significant speed up factors compared to the same reference scheme, proving the efficiency of our approach for the configurations of interest. This work is published in [30]

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

Participants: Tiphaine Delaunay, Sébastien Imperiale, 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 submitted and the preprint is available at [47].

8.2.6 The T-coercivity approach for mixed problems

Participants: Mathieu Barré, Patrick Ciarlet *(POEMS)*.

Classically, the well-posedness of variational formulations of mixed linear problems is achieved through the inf-sup condition on the constraint. In this work, we propose an alternative framework to study such problems by using the T-coercivity approach to derive a global inf-sup condition. Generally speaking, this is a constructive approach that, in addition, drives the design of suitable approximations. As a matter of fact, the derivation of the uniform discrete inf-sup condition for the approximate problems follows easily from the study of the original problem. To support our view, we solve a series of classical mixed problems with the T-coercivity approach. Among others, the celebrated Fortin Lemma appears naturally in the numerical analysis of the approximate problems.

8.2.7 Numerical analysis of an incompressible soft material poromechanics model using T-coercivity

Participants: Mathieu Barré, Céline Grandmont *(COMMEDIA)*, Philippe Moireau *(correspondant)*.

This work is devoted to the numerical analysis of the full discretization of a generalized poromechanical model resulting from the linearization of an initial model fitted to soft tissue perfusion. Our strategy here is based on the use of energy-based estimates and T-coercivity methods, so that the numerical analysis benefits from the essential tools used in the existence analysis of the continuous-time and continuous-space formulation. In particular, our T-coercivity strategy allows us to obtain the necessary inf-sup condition for the global system from the inf-sup condition restricted to a subsystem having the same structure as the Stokes problem. This allows us to prove that any finite element pair adapted to the Stokes problem is also suitable for this global poromechanical model regardless of porosity and permeability, generalizing previous results from the literature studying this model. This work is now published in [16].

8.3 Inverse Problems

8.3.1 Mortensen Observer for a class of variational inequalities - Lost equivalence with stochastic filtering approaches

Participants: Louis-Pierre Chaintron, Philippe Moireau *(correspondant)*.

We address the problem of deterministic sequential estimation for a nonsmooth dynamics governed by a variational inequality. An example of such dynamics is the Skorokhod problem with a reflective boundary condition. For smooth dynamics, Mortensen introduced in 1968 a nonlinear estimator based on likelihood maximisation. Then, starting with Hijab in 1980, several authors established a connection between Mortensen?s approach and the vanishing noise limit of the robust form of the so-called Zakai equation. In this paper, we investigate to what extent these methods can be developed for dynamics governed by a variational inequality. On the one hand, we address this problem by relaxing the inequality constraint by penalization: this yields an approximate Mortensen estimator relying on an approximating smooth dynamics. We verify that the equivalence between the deterministic and stochastic approaches holds through a vanishing noise limit. On the other hand, inspired by the smooth dynamics approach, we study the vanishing viscosity limit of the Hamilton-Jacobi equation satisfied by the Hopf-Cole transform of the solution of the robust Zakai equation. In contrast to the case of smooth dynamics, the zero-noise limit of the robust form of the Zakai equation cannot be understood in our case from the Bellman equation on the value function arising in Mortensen?s procedure. This unveils a violation of equivalence for dynamics governed by a variational inequality between the Mortensen approach and the low noise stochastic approach for nonsmooth dynamics. This work was published as [18].

8.3.2 Mathematical analysis of an observer for solving inverse source wave problem

Participants: Tiphaine Delaunay, Sébastien Imperiale, Philippe Moireau.

The objective of this work is to propose a method using observers to estimate a source term of a wave equation from internal measurements in a subdomain. The first part of the work consists in proving an identifiability result from classical observability conditions for wave equations. We show that the source reconstruction is an ill-posed inverse problem of degree 1 or 2 depending on the measurements type. This inverse problem is solved using observers – a sequential strategy – that is proven to be equivalent to a minimization of a cost functional with Tikhonov regularization.

8.3.3 Flow recovery from distal pressure in linearized hemodynamics: an optimal control approach

Participants: Sébastien Imperiale, Philippe Moireau.

The goal of this work is to derive a reliable stable and accurate inverse problem strategy for reconstructing cardiac output blood flow entering the ascending aorta from pressure measurements at a distal site of the arterial tree, assumed here to be the descending aorta. We assume that a reduced one-dimensional model of the aorta can be linearized around its steady state, resulting in a wave system with absorbing boundary condition at the outlet. Using this model, we attempt to reconstruct the inlet flow from a pressure measurement at the distal outlet. First, we investigate the observability of the problem and prove that the inversion of the input-output operator for the flow and pressure in the space of time-periodic solutions is ill-posed of degree one. We then develop a variational approach where we minimize the discrepancy between measurements and a simulated state and penalize the error with respect to a periodic state. It is shown that the penalty strategy is convergent and provides an efficient solution for the minimization. Numerical results illustrate the robustness of our approach to noise and the potential of our method to reconstruct inlet flow from real pressure recordings during anesthesia. This work is publised in [27].

8.3.4 Finite strain formulation of the discrete equilibrium gap principle: application to mechanically-consistent regularization for large motion tracking

Participants: Martin Genet *(correspondant)*.

The equilibrium gap principle offers a good trade-off between robustness and accuracy for regularizing motion tracking, as it simply enforces that the tracked motion corresponds to a body deforming under arbitrary loadings. This paper introduces an extension of the equilibrium gap principle in the large deformation setting, a novel regularization term to control surface tractions, both in the context of finite element motion tracking, and an inverse problem consistent reformulation of the tracking problem. Tracking performance of the proposed method, with displacement resolution down to the pixel size, is demonstrated on synthetic images representing various motions with various signal-to-noise ratios. This work has been accepted for publication in the Comptes Rendus Mécanique de l'Académie des Sciences journal [22].

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

Participants: André Dalmora, Alexandre Imperiale, Sébastien Imperiale, Philippe Moireau.

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.

8.3.6 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.

8.3.7 A study of the robustness of different full-field measurements identification methods for hyperelastic problems

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

Parameter identification in Finite Element models is a key issue in many mechanical problems, when direct testing is not possible, e.g. in biomechanics to identify *in vivo tissue* properties. Many identification methods based on full-field displacement measurements have been developed, such as the Finite Element Model Updating (FEMU) method, the Equilibrium Gap Method (EGM) or the Virtual Fields Method (VFM). If the accuracy and efficiency of each method have already been investigated in the literature, there is no quantitative study to our knowledge relative to the impact of the noise and/or model errors on the efficiency of these methods. Studies available in the literature also focus on simple elastic problems, which does not allow a comprehensive understanding of the accuracy of the estimation of the different methods for more complex problems. This article proposes a quantitative study of the impact of the noise and of model errors on the estimation of a parameter of a hyperelastic law when using the FEMU method, the EGM and the VFM. In particular, we compare here the accuracy of each method and their robustness to noise and model errors. The study is based on the creation synthetic images, from which a displacement field is extracted, and then used for the estimation. The estimated parameter is then compared to its ground truth value, which is here known. The method to introduce noise on the displacement field is also discussed: (i) by introducing noise directly on the displacement field and (ii) by introducing noise on the images. This article aims at providing information on the accuracy of each method for complex problems and help choose the best compromise between computational efficiency and accuracy for inverse problems.

8.3.8 Computer-implemented method for determining behavior and loading parameters of soft tissue from a plurality of images acquired in different vertical orientations

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

A computer-implemented method of determining parameters includes a soft tissue stiffness field and a loading parameter applied to the soft tissue, in particular a pressure field, in which the values are determined from at least two images of this soft tissue oriented in at least two different respective positions relative to the vertical direction, making it possible to minimize a difference between the deformations of at least part of the soft tissue observed from the images and the corresponding deformations determined by a model of the soft tissue which depends on said parameters. This patent was submitted in June 2023.

8.4 Experimental Assessments

8.4.1 Identification of PCPE-2 as a inhibitor of proteinases

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

In this work, we have studied the alterations of the mice skin mechanical properties linked to the role of PCPE-2. More precisely, BMP-1/tolloid-like proteinases (BTPs) are major players in tissue morphogenesis, growth and repair. They act by promoting the deposition of structural extracellular matrix proteins and by controlling the activity of matricellular proteins and TGF-β superfamily growth factors. They have also been implicated in several pathological conditions such as fibrosis, cancer, metabolic disorders and bone diseases. Despite this broad range of pathophysiological functions, the putative existence of a specific endogenous inhibitor capable of controlling their activities could never be confirmed. Our study shows that procollagen C-proteinase enhancer-2 (PCPE-2), a protein previously reported to bind fibrillar collagens and to promote their BTP-dependent maturation, is primarily a potent and specific inhibitor of BTPs which can counteract their proteolytic activities through direct binding. PCPE-2 therefore differs from the cognate PCPE-1 protein and extends the possibilities to fine-tune BTP activities, both in physiological conditions and in therapeutic settings. This work has been published in [32].

8.4.2 Development and qualification of clinical grade decellularized and cryopreserved human esophagi

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

Tissue engineering is a promising alternative to current full thickness circumferential esophageal replacement methods. The aim of our study was to develop a clinical grade Decellularized Human Esophagus (DHE) for future clinical applications. After decontamination, human esophagi from deceased donors were placed in a bioreactor and decellularized with sodium dodecyl sulfate (SDS) and ethylendiaminetetraacetic acid (EDTA) for 3 days. The esophagi were then rinsed in sterile water and

SDS was eliminated by filtration on an activated charcoal cartridge for 3 days. DNA was removed by a 3-hour incubation with DNase. A cryopreservation protocol was evaluated at the end of the process to create a DHE cryobank. The decellularization was efficient as no cells and nuclei were observed in the DHE. Sterility of the esophagi was obtained at the end of the process. The general structure of the DHE was preserved according to immunohistochemical and scanning electron microscopy images. SDS was efficiently removed, confirmed by a colorimetric dosage, lack of cytotoxicity on Balb/3T3 cells and mesenchymal stromal cell long term culture. Furthermore, DHE did not induce lymphocyte proliferation in-vitro. The cryopreservation protocol was safe and did not affect the tissue, preserving the biomechanical properties of the DHE. Our decellularization protocol allowed to develop the first clinical grade human decellularized and cryopreserved esophagus. This work has been published in [25].

8.4.3 Microrheology and structural quantification of hypercoagulable clots

Participants: Jean-Marc Allain *(correspondant)*, Lionel Lartigue, 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. This first work has been published in [33]. It is now continued by Lionel Lartigue (post-doc), and Simon Kouba (PhD student).

8.4.4 Mechanical properties of the cornea

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

Cornea is the outermost layer of the eye. Healthy human cornea is spherical-shaped. However, in patients with keratoconus, the cornea becomes thinner and gradually swells outward into an irregular cone shape. Stroma is the thickest layer of the cornea. It is formed of stacked lamellae made of collagen fibrils. The stroma is responsible for corneal biomechanical stability. Weakened biomechanical properties are believed to cause steepening and thinning in keratoconus eyes. We have recently published a review on the mechanical properties of the cornea [24], as well as a book chapter on the structure, the mechanics and the possible biomaterials associated with the cornea [39]. Qian Wu (Ph.D) is now continuing this work, focussing on both the control of osmotic flows in the cornea, and on the role of Vogt's striae in the cornea mechanics. Benjmain Memmi (M.D) is working on the link between the errors in laser surgery and patient-specific mechanical properties.

8.5 Clinical Applications

8.5.1 Comparison of optimization parametrizations for regional lung compliance estimation using personalized pulmonary poromechanical modeling

Participants: Colin Laville, Martin Genet *(correspondant)*.

Interstitial lung diseases, such as idiopathic pulmonary fibrosis (IPF) or post-COVID-19 pulmonary fibrosis, are progressive and severe diseases characterized by an irreversible scarring of interstitial tissues that affects lung function. Despite many efforts, these diseases remain poorly understood and poorly treated. In this paper, we propose an automated method for the estimation of personalized regional lung compliances based on a poromechanical model of the lung. The model is personalized by integrating routine clinical imaging data – namely, computed tomography images taken at two breathing levels in order to reproduce the breathing kinematic – notably through an inverse problem with fully personalized boundary conditions that is solved to estimate patient-specific regional lung compliances. A new parametrization of the inverse problem is introduced in this paper, based on the combined estimation of a personalized breathing pressure in addition to material parameters, improving the robustness and consistency of estimation results. The method is applied to three IPF patients and one post-COVID-19 patient. This personalized model could help better understand the role of mechanics in pulmonary remodeling due to fibrosis; moreover, patient-specific regional lung compliances could be used as an objective and quantitative biomarker for improved diagnosis and treatment follow up for various interstitial lung diseases. This work was published in [28].

8.5.2 A biomechanics-based parametrized cardiac end-diastolic pressure-volume relationship for accurate patient-specific calibration and estimation

Participants: Dominique Chapelle *(correspondant)*, Arthur Le Gall *(Lariboisière Hospital)*.

A simple power law has been proposed in the pioneering work of Klotz et al. (Am J Physiol Heart Circ Physiol 291(1):H403-H412, 2006) to approximate the end-diastolic pressure-volume relationship of the left cardiac ventricle, with limited inter-individual variability provided the volume is adequately normalized. Nevertheless, we use here a biomechanical model to investigate the sources of the remaining data dispersion observed in the normalized space, and we show that variations of the parameters of the biomechanical model realistically account for a substantial part of this dispersion. We therefore propose an alternative law based on the biomechanical model that embeds some intrinsic physical parameters, which directly enables personalization capabilities, and paves the way for related estimation approaches. This work was published in [20].

8.5.3 AnaestAssist project

Participants: François Kimmig *(correspondant)*, Dominique Chapelle, Philippe Moireau, , Fabrice Vallée *(AP-HP Hôpital Lariboisière, Inserm U942 MASCOT)*.

Unstable hemodynamics during general anesthesia 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 anesthesia. The proposed technology will introduce into the monitoring loop a predictive biophysical model, simulated in real time, and fed by the routinely measured physiological signals. The model will be personalized for the patient 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 possible to determine (through predictive modelling) 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 condition through a reduction of the risk related to general anesthesia 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 stays of the patients at the hospital.

The AnaestAssist project is intended to lead to a startup creation.

The AnaestAssist team presented project for the national innovation competition iLab organised by Bpifrance. The project was selected for the oral hearings but did not win the competition.

The AnaestAssist contributed to set up the Diip-Heart projet led by the Inserm U942 MASCOT team in response to the call for proposal 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. The Diip-Heart proposal has been award a PEPR Santé numérique grant.

The AnaestAssist team also presented the MAJOR project in response to a call of AP-HP research and innovation department along with the anesthesia department of Lariboisière Hospital (AP-HP) and the Inria team COMMEDIA. The projet MAJOR aims to extend to AnaestAssist augmented monitoring tools to intensive care, which requires to incorporate the pulmonary system into the models. The evaluation phase of this call is ongoing.

The HΞLEN code constitutes a step towards the realization of the proof of concept of the AnaestAssist solution functioning in real time. Enhancements of the code were performed during the year : an implementation of one-dimensional blood vessel has been added allowing to use a representation of the arterial tree encompassing wave propagation phenomena.

9 Bilateral contracts and grants with industry

9.1 Bilateral contracts with industry

Participants: Jean-Marc Allain, Julien Bonnafe.

- Metyos company. Study of a skin injection device
- Contract with Essilor on the modeling of the 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 with Withings compagny. Collaboration on data assimilation from connected devices measurements.

10 Partnerships and cooperations

10.1 International research visitors

10.1.1 Visits to international teams

Sabbatical programme

Participant: Philippe Moireau

Visited institution: Isaac Newton Institute for Mathematical Sciences, Cambridge

Country: Great Britain

Dates: 01/01/2023 to 30/06/2023

Context of the visit: Participation to the Programme “The mathematical and statistical foundation of future data-driven engineering”

Mobility program/type of mobility: sabbatical

10.2 European initiatives

10.2.1 Spiro3D (200 k€)

Participants: Martin Genet.

Lung function is a central concern in the fight against covid-19. Beyond the pandemic heavy losses and long-term health implications, respiratory diseases represent a major threat for the World Health Organisation. It is one of the leading causes of death worldwide, associated with our way of living and impacting all of society. In V|LF-Spiro3D, reference datasets are being acquired at standard MRI field to produce large sets of normative and training data covering six major respiratory diseases: asthma, chronic obstructive pulmonary diseases, bronchopulmonary dysplasia, cystic fibrosis, and bronchiolitis obliterans syndrome in transplant recipients. V|LF-Spiro3D will then redesign the current MRI architecture to perform 3D MR spirometry at low and very low field by highly-processed MRI throughout the lung while the patient is freely breathing, either lying, sitting, or standing in a light V|LF-MRI system. By prioritizing both technology transfer and innovation, V|LF-Spiro3D aims to build up a one-stop-shop imaging standard for the unrestricted assessment of lung pathophysiology.

10.3 National initiatives

10.3.1 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.

10.3.2 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.

10.3.3 Other funding

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

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

  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.

  RheCa project focusses 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 on ESB2023
- J.M. Allain, Session chair on CMBBE2023
- M. Genet: Session co-chair at the 18th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering (CMBBE2023), Paris, France

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
- D. Chapelle, member of the FIMH'23 program committee

Reviewer

- J.M. Allain, reviewer for the ESB2023 conference
- J.M. Allain, reviewer for the Societe de Biomechanics conference
- M. Genet, reviewer for the 18th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering (CMBBE2023), Paris, France
- M. Genet, reviewer for the 48ème congrès de la Société de Biomécanique (SB2023), Grenoble, France

11.1.3 Journal

Member of the editorial boards

- D. Chapelle, member of the editorial board of journal *Computers & Structures*
- 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 & Structures*
- P. Moireau, invited editor for the special issue about Mathematical Biology at “Maths In Action”,

Reviewer - reviewing activities

- J. M. Allain, reviewer for “Acta Biomateriala”, “Experimental Eye Research” and “Prooceedings of the Royal Society A”
- D. Chapelle, reviewer for “Computers & Structures”
- M. Genet, reviewer for the “Journal of the Mechanical Behavior of Biomedical Materials”
- S. Imperiale, reviewer for “Nonlinear Dynamics”, “Journal of Computational Physics”, “Mathematics of computations” and “SIAM Journal on Mathematical Analysis”
- F. Kimmig, reviewer for “Communications Biology”
- P. Moireau, reviewer for “ESAIM:COCV” “Cardiovascular Engineering and Technology”, “International Journal of Biostatistics”

11.1.4 Invited talks

- D. Chapelle, moderator of roundtable on “Digital twins for medicine” in colloquium “Jumeaux numériques” organised by Île de Science Paris-Saclay et S[cube], Febr. 9th
- D. Chapelle, moderator of roundtable on “Digital twins for medicine” at E4H (IPP), July 5th
- P. Le Tallec:“POD Approximations for Muliscale Friction Problems”, Workshop in Honor of Leszek F. Demkowicz’s 70th Birthday Oden Institute, The University of Texas at Austin, April 11th, 2024.
- P. Moireau, Invited talk at Deep dive on Control and Inference Workshop, DDE Programme, Newton Institute, Cambridge

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, member of the Francophone Biomechanics Society
- M. Genet, member of the French Computational Mechanics Association (CSMA)

11.1.6 Scientific expertise

- J.M. Allain, member of a HCERES evaluation panel
- J.M. Allain, reviewer for the ERC
- J.M. Allain, reviewer for SNSF (Switzerland funding agency)
- D. Chapelle, member of Bpifrance i-Nov evaluation panel

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
- P. Moireau, member of the steering committee of the Mathematics Department of IPP

11.2 Teaching - Supervision - Juries

11.2.1 Teaching

- Journée clinique du GdR MécaBio: M. Genet, “Mécanique des tissus durs et mous”, 2h, INSA, Lyon
- All-level: 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
- Bachelor: Z. Ramiche, “Mathématiques 2”, 24h, B2, Economie, Droit et Gestion à l’Université Paris-Saclay, France
- Bachelor: M. Barré and T. Delaunay, "MA103 – Introduction aux EDP et à la méthode des différences finies", 14h, B3, ENSTA Paris, France
- Bachelor: S. Imperiale, “MA102 – Analyse pour les EDP”, 24h, B3, ENSTA ParisTech, France
- Bachelor: G. Merlini, “Physics I: Mechanics and Heat’, B1, École Polytechnique, France
- Bachelor: G. Merlini, “Modal de mécanique”, Xh, B1, École Polytechnique, France
- Bachelor: A. Peyraut, “PHY101 — Physics I: Mechanics and Heat”, 32h, B1, École Polytechnique
- Bachelor: A. Peyraut, “Maths in Practice Calculus”, 32h, B1, Ecole Polytechnique, France

- Bachelor: M. Manoochehrtayebi, “PHY101 — Physics I: Mechanics and Heat”, 32h, B1, École Polytechnique
- Master: G. Merlini, “Mécanique des milieux déformables”, M1, École Polytechnique, France
- Master: G. Merlini, “Biomechanics in Health and Disease”, M1, École Polytechnique, France
- Master: M. Manoochehrtayebi, “MEC/BIO586-Biomechanics in Health & Disease”, 32h, M1, École Polytechnique
- 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: M. Barré and T. Delaunay, “ANN201 – La méthode des éléments finis”, 14h, M1, ENSTA Paris, 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: 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, “MAP-ANA1 – Introduction à l’analyse fonctionnelle”, 12h, M1, ENSTA ParisTech, France
- Master: S. Imperiale, “AMS306 – Techniques de discrétisation avancées pour les problèmes d’évolutions”, 18h, M2, Université Paris-Saclay, France
- Master: P. Moireau, “MAP431 — Variational formulations”, 40h, M1, École Polytechnique
- 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”, 9h, M2, Université Paris-Saclay and Institut Polytechnique de Paris, France
- Master: A. Peyraut, “Collective Scientific Projects (PSC)”, 16h, M1, Ecole Polytechnique, France
- 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.

11.2.2 Supervision

- PhD in progress: Giulia Merlini, Simulation of Dynamical Optical Coherent Elastography with applications in cornea, started 10/2021; supervisor: J.M. Allain and S. Imperiale
- 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: M. Manoochertayebi, "Manyscale modeling of lung poromechanics", started 11/2020, supervisors: M. Genet, A. Bel-Brunon (INSA-Lyon) and D. Chapelle
- PhD in progress: A. Peyraut, "Modeling and estimation of lung poromechanics", started 10/2021, supervisors: M. Genet
- 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, supervisors: S. Imperiale
- PhD in progress: Matheus de Lorenzo, "Approches multi-échelles de l'adhérence des pneumatiques sur route mouillée", started 04/2022, supervisor: P. Le Tallec
- PhD defended: T. Delaunay, "Adaptative observers for propagative systems and associated discretization: formulation and analysis", defended 12/2023, supervised by S. Imperiale and P. Moireau.
- PhD defended: A. Dalmora, " Modeling and estimation by data-assimilation of pre-stresses in non destructive testing experiments", started 2020, supervised by A. Imperiale, S. Imperiale and P. Moireau.
- PhD defended: M. Barré, "Mathematical framework for biological tissue perfusion modeling and simulation",started 2020, supervised by C. Grandmont from Inria-Paris - Commedia and P. Moireau.

11.2.3 Juries

- J.M Allain, Habilitation Jury of C. Morin, Université Jean Monnet - Saint-Etienne, President Pr. Laurence Vico, 5/23
- J.M Allain, PhD Jury of L. Wolff-Trombini, Université de Bordeaux, PhD Advisor: Pr. Chloé James, 01/23
- M. Genet, PhD Jury (rapporteur) of Ariane Martin, ENS Paris-Saclay, 01/2023
- M. Genet, PhD Jury (examinateur) of Mahdi Daei-Daei, École Polytechnique, 01/2023
- M. Genet, PhD thesis reviewer for Juliet Nagawa, University of Cape Town, South Africa, 08/2023
- S. Imperiale, PhD Jury (rapporteur) of Morgane Steins, Ecole des ponts, 12/2023
- S. Imperiale, PhD Jury (examinateur) of Guillaume Castera, Université de Pau et des pays de l'Adour, 12/2023
- P. Moireau, PhD Jury (rapporteur) of Niami Nassr, Université de Bordeaux, 12/2023
- P. Moireau, PhD Jury (rapporteur) of Colin Parellier, PSL Université et Ecole des Mines, 12/2023

11.3 Popularization

11.3.1 Interventions

- Z. Ramiche, Fêtes de la science, Ecole polytechnique, FRance.

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] R. Chabiniok, P. Moireau, P.-F. Lesault, A. Rahmouni, J.-F. Deux and D. Chapelle. 'Estimation of tissue contractility from cardiac cine-MRI using a biomechanical heart model'. English. In: *Biomechanics and Modeling in Mechanobiology* 11.5 (2012), pp. 609–630. DOI: 10.1007/s10237-011-0337-8. URL: http://hal.inria.fr/hal-00654541.

[3] L.-P. Chaintron, F. Kimmig, M. Caruel and P. Moireau. 'A jump-diffusion stochastic formalism for muscle contraction models at multiple timescales'. In: *Journal of Applied Physics* (21st Nov. 2023). DOI: 10.1063/5.0158191. URL: https://hal.science/hal-04264293.

[4] D. Chapelle and K. Bathe. *The Finite Element Analysis of Shells - Fundamentals - Second Edition*. English. Computational Fluid and Solid Mechanics. Springer, 2011, p. 410. DOI: 10.1007/978-3-642-16408-8. URL: http://hal.inria.fr/hal-00654533.

[5] D. Chapelle, N. Cîndea and P. Moireau. 'Improving convergence in numerical analysis using observers - The wave-like equation case'. English. In: *Mathematical Models and Methods in Applied Sciences* 22.12 (2012). DOI: 10.1142/S0218202512500406. URL: http://hal.inria.fr/inria-00621052.

[6] D. Chapelle, P. Le Tallec, P. Moireau and M. Sorine. 'An energy-preserving muscle tissue model: formulation and compatible discretizations'. English. In: *International Journal for Multiscale Computational Engineering* 10.2 (2012), pp. 189–211. DOI: 10.1615/IntJMultCompEng.2011002360. URL: http://hal.inria.fr/hal-00678772.

[7] D. Chapelle and P. Moireau. 'General coupling of porous flows and hyperelastic formulations – From thermodynamics principles to energy balance and compatible time schemes'. In: *European Journal of Mechanics - B/Fluids* 46 (2014). Updated version of previously published research report, pp. 82–96. DOI: 10.1016/j.euromechflu.2014.02.009. URL: https://hal.inria.fr/inria-00520612.

[8] A. Collin, B. P. Hejblum, C. Vignals, L. Lehot, R. Thiébaut, P. Moireau and M. Prague. 'Using Population Based Kalman Estimator to Model COVID-19 Epidemic in France: Estimating the Effects of Non-Pharmaceutical Interventions on the Dynamics of Epidemic'. In: *The international journal of biostatistics* (2023). DOI: 10.1515/ijb-2022-0087. URL: https://hal.science/hal-04151651.

[9] A. Collin and S. Imperiale. 'Mathematical analysis and 2-scale convergence of a heterogeneous microscopic bidomain model'. In: *Mathematical Models and Methods in Applied Sciences* (2018). URL: https://hal.inria.fr/hal-01759914.

[10] A. Collin, M. Prague and P. Moireau. 'Estimation for dynamical systems using a population-based Kalman filter – Applications in computational biology'. In: *MathematicS In Action* (11th Apr. 2022). DOI: 10.5802/msia.25. URL: https://inria.hal.science/hal-02869347.

[11] B. Lynch, S. Bancelin, C. Bonod-Bidaud, J.-B. Gueusquin, F. Ruggiero, M.-C. Schanne-Klein and J.-M. Allain. 'A novel microstructural interpretation for the biomechanics of mouse skin derived from multiscale characterization'. In: *Acta Biomaterialia* 50 (2017), pp. 302–311. DOI: 10.1016/j.actbio.2016.12.051. URL: https://hal.archives-ouvertes.fr/hal-01531321.

[12] P. Moireau. 'A Discrete-time Optimal Filtering Approach for Non-linear Systems as a Stable Discretization of the Mortensen Observer'. In: *ESAIM: Control, Optimisation and Calculus of Variations* (2017). URL: https://hal.inria.fr/hal-01671271.

[13] P. Moireau. 'Discrete-time formulations as time discretization strategies in data assimilation'. In: *Handbook of Numerical Analysis, Numerical Control: Part B*. Handbook of Numerical Analysis. Elsevier, 2022. DOI: 10.1016/bs.hna.2022.11.005. URL: https://hal.inria.fr/hal-03921465.

[14] M. Sermesant, R. Chabiniok, P. Chinchapatnam, T. Mansi, F. Billet, P. Moireau, J.-M. Peyrat, K. C. Wong, J. Relan, K. S. Rhode, M. Ginks, P. Lambiase, H. Delingette, M. Sorine, C. A. Rinaldi, D. Chapelle, R. Razavi and N. Ayache. 'Patient-Specific Electromechanical Models of the Heart for Prediction of the Acute Effects of Pacing in CRT: a First Validation'. English. In: *Medical Image Analysis* 16.1 (2012), pp. 201–215. DOI: 10.1016/j.media.2011.07.003. URL: http://hal.inria.fr/inria-00616191.

12.2 Publications of the year

International journals

[15] M. Barré and P. Ciarlet. 'The T-coercivity approach for mixed problems'. In: *Comptes Rendus. Mathématique* (2023). URL: https://hal.science/hal-03820910.

[16] M. Barré, C. Grandmont and P. Moireau. 'Numerical analysis of an incompressible soft material poromechanics model using T-coercivity'. In: *Comptes Rendus. Mécanique* 351.S1 (2023), pp. 1–36. DOI: 10.5802/crmeca.194. URL: https://hal.science/hal-04098153.

[17] L.-P. Chaintron, M. Caruel and F. Kimmig. 'Modeling acto-myosin interaction: beyond the Huxley–Hill framework'. In: *MathematicS In Action* 12.1 (26th Sept. 2023), pp. 191–226. DOI: 10.5802/msia.38. URL: https://hal.science/hal-03699263.

[18] L.-P. Chaintron, Á. M. González, L. Mertz and P. Moireau. 'Mortensen Observer for a class of variational inequalities - Lost equivalence with stochastic filtering approaches'. In: *ESAIM: Proceedings and Surveys* 73 (30th Aug. 2023), pp. 130–157. DOI: 10.1051/proc/202373130. URL: https://inria.hal.science/hal-03659066.

[19] L.-P. Chaintron, F. Kimmig, M. Caruel and P. Moireau. 'A jump-diffusion stochastic formalism for muscle contraction models at multiple timescales'. In: *Journal of Applied Physics* (21st Nov. 2023). DOI: 10.1063/5.0158191. URL: https://hal.science/hal-04264293.

[20] D. Chapelle and A. Le Gall. 'A biomechanics-based parametrized cardiac end-diastolic pressure–volume relationship for accurate patient-specific calibration and estimation'. In: *Scientific Reports* 13 (2023), p. 9. DOI: 10.1038/s41598-023-38196-5. URL: https://inria.hal.science/hal-04159524.

[21] J. Dubois, S. Imperiale, A. Mangeney, F. Bouchut and J. Sainte-Marie. 'Acoustic and gravity waves in the ocean: a new derivation of a linear model from the compressible Euler equation'. In: *Journal of Fluid Mechanics* 970 (Sept. 2023), A28. DOI: 10.1017/jfm.2023.595. URL: https://hal.science/hal-03880423.

[22] M. Genet. 'Finite Strain Formulation of the Discrete Equilibrium Gap Principle: Application to Mechanically Consistent Regularization for Large Motion Tracking'. In: *Comptes Rendus. Mécanique* 351 (8th Dec. 2023), pp. 429–458. DOI: 10.5802/crmeca.228. URL: https://hal.science/hal-04132311.

[23] M. Genet, J. Diaz, D. Chapelle and P. Moireau. 'Reduced left ventricular dynamics modeling based on a cylindrical assumption'. In: *International Journal for Numerical Methods in Biomedical Engineering* (2023). DOI: 10.1002/cnm.3711. URL: https://hal.science/hal-03832575.

[24] C. Giraudet and J.-M. Allain. 'The healthy and keratoconic human cornea: structure, imaging, mechanical characterization and modeling'. In: *Revue ouverte d'ingénierie des systèmes d'information* (21st Sept. 2023). URL: https://hal.science/hal-04259713.

[25] W. Godefroy, L. Faivre, C. Sansac, B. Thierry, J.-M. Allain, P. Bruneval, R. Agniel, S. Kellouche, O. Monasson, E. Peroni, N. Setterblad, M. Braik, B. Even, S. Cheverry, T. Domet, P. Albanese, J. Larghero, P. Cattan and L. Arakelian. 'Development and qualification of clinical grade decellularized and cryopreserved human esophagi'. In: *Scientific Reports* 13 (25th Oct. 2023). DOI: 10.1038/s41598-023-45610-5. URL: https://hal.science/hal-04269788.

[26] M. Gusseva, D. Castellanos, J. Greer, M. Hussein, K. Hasbani, G. Greil, S. Reddy, M. Hussain, D. Chapelle and R. Chabiniok. 'Time-synchronization of interventional cardiovascular magnetic resonance data using a biomechanical model for pressure-volume loop analysis'. In: *Journal of Magnetic Resonance Imaging* 57.1 (1st Jan. 2023), pp. 320–323. DOI: 10.1002/jmri.28216. URL: https://hal.science/hal-03651166.

[27] S. Imperiale, J. Manganotti and P. Moireau. 'Flow recovery from distal pressure in linearized hemodynamics: an optimal control approach'. In: *Inverse Problems* 39.7 (31st May 2023), p. 075004. DOI: 10.1088/1361-6420/acd274. URL: https://inria.hal.science/hal-04178851.

[28] C. Laville, C. Fetita, T. Gille, P.-Y. Brillet, H. Nunes, J.-F. Bernaudin and M. Genet. 'Comparison of optimization parametrizations for regional lung compliance estimation using personalized pulmonary poromechanical modeling'. In: *Biomechanics and Modeling in Mechanobiology* 22 (13th Mar. 2023), pp. 1541–1554. DOI: 10.1007/s10237-023-01691-9. URL: https://hal.science/hal-04199401.

[29] B. Leturcq and P. Le Tallec. 'From domain decomposition to model reduction for Large nonlinear structures'. In: *Comptes Rendus. Mécanique* 351.S1 (2023), pp. 1–17. DOI: 10.5802/crmeca.168. URL: https://cea.hal.science/cea-04149398.

[30] H. Methenni, A. Imperiale and S. Imperiale. 'An implicit–explicit time discretization for elastic wave propagation problems in plates'. In: *International Journal for Numerical Methods in Engineering* 125 (16th Nov. 2023), e7393. DOI: 10.1002/nme.7393. URL: https://inria.hal.science/hal-04291680.

[31] D. Sabbagh, J. Cartailler, C. Touchard, J. Joachim, A. Mebazaa, F. Vallée, É. Gayat, A. Gramfort and D. A. Engemann. 'Repurposing electroencephalogram monitoring of general anaesthesia for building biomarkers of brain ageing: an exploratory study'. In: *British Journal of Anaesthesia open* 7 (Sept. 2023), p. 100145. DOI: 10.1016/j.bjao.2023.100145. URL: https://hal.science/hal-04191894.

[32] S. Vadon-Le Goff, A. Tessier, M. Napoli, C. Dieryckx, J. Bauer, M. Dussoyer, P. Lagoutte, C. Peyronnel, L. Essayan, S. Kleiser, N. Tueni, E. Bettler, N. Mariano, E. Errazuriz-Cerda, C. Fruchart Gaillard, F. Ruggiero, C. Becker-Pauly, J.-M. Allain, L. Bruckner-Tuderman, A. Nyström and C. Moali. 'Identification of PCPE-2 as the endogenous specific inhibitor of human BMP-1/tolloid-like proteinases'. In: *Nature Communications* 14.1 (4th Dec. 2023). DOI: 10.1038/s41467-023-43401-0. URL: https://hal.science/hal-04350568.

[33] L. Wolff-Trombini, A. Ceripa, J. Moreau, H. Galinat, C. James, N. Westbrook and J.-M. Allain. 'Microrheology and structural quantification of hypercoagulable clots'. In: *Biomedical optics express* 14.8 (2023), pp. 4179–4189. DOI: 10.1364/BOE.492669. URL: https://hal.science/hal-04054272.

International peer-reviewed conferences

[34] M. Diego, M. Gandolfi, S. Giordano, A. Casto, F. M. Belussi, A. Crut, F. Vialla, S. Roddaro, M. Fasano, F. Vallée, P. Maioli, N. D. Fatti and F. Banfi. 'CLEO®/Europe-EQEC 2023, One Page Summary Template Ultrafast Nano Generation of Acoustic Waves in Water: Thermophone Versus Mechanophone'. In: 2023 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC). Munich, Germany: IEEE, 26th June 2023, pp. 1–1. DOI: 10.1109/CLEO/EUROPE-EQEC57999.2023.10231581. URL: https://hal.science/hal-04292052.

[35] K. Škardová, T. Hussain, M. Genet and R. Chabiniok. 'Effect of Spatial and Temporal Resolution on the Accuracy of Motion Tracking Using 2D and 3D Cine Cardiac Magnetic Resonance Imaging Data'. In: *Lecture Notes in Computer Science*. FIMH 2023 - The 12th International Conference on Functional Imaging and Modeling of the Heart. Vol. LNCS-13958. Functional Imaging and Modeling of the Heart. Lyon, France: Springer Nature Switzerland, 16th June 2023, pp. 235–244. DOI: 10.1007/978-3-031-35302-4_24. URL: https://inria.hal.science/hal-04360493.

Conferences without proceedings

[36] A. Dalmora, A. Imperiale, S. Imperiale and P. Moireau. 'Estimating the effect of operational loading condition from ultrasonic guided wave measurements using an iterated Unscented Kalman Filter'. In: 3ème colloque du GDR MecaWave. Porquerolles, France, 2023. URL: https://cea.hal.science/cea-04272530.

[37] A. Dalmora, A. Imperiale, S. Imperiale and P. Moireau. 'Solveur numérique générique pour la modélisation de l'influence des contraintes mécaniques sur la propagation des ondes guidées pour les applications SHM'. In: Journées COFREND 2023. Marseille, France, 2023. URL: https://cea.hal.science/cea-04410161.

[38] A. Sergent, Y. Fraigneau and D. Lucor. 'Plumes and large scale circulation in turbulent thermal convection with a rough plate'. In: RBC 2023 - 9th International Conference on Rayleigh-Bénard Turbulence. Xi'an, China, 16th Oct. 2023. URL: https://hal.science/hal-04400263.

Scientific book chapters

[39] C. Giraudet and J.-M. Allain. 'Biomécanique de la cornée'. In: *Mécanique des tissus vivants*. 27th Sept. 2023. URL: https://hal.science/hal-04259749.

Doctoral dissertations and habilitation theses

[40] M. Barré. 'Mathematical framework for biological tissue perfusion modeling and simulation'. Institut Polytechnique de Paris, 2nd Oct. 2023. URL: https://theses.hal.science/tel-04375138.

Reports & preprints

[41] D. Bernoulli and D. Chapelle. *Essai d'une nouvelle analyse de la mortalité causée par la petite vérole, et des avantages de l'inoculation pour la prévenir*. 2023. URL: https://inria.hal.science/hal-04100467.

[42] F. Blanqui, A. Canteaut, H. de Jong, S. Imperiale, N. Mitton, G. Pallez, X. Pennec, X. Rival and B. Thirion. *Recommandations sur les « éditeurs de la zone grise »*. Inria, 25th Jan. 2023, pp. 1–3. URL: https://inria.hal.science/hal-04001505.

[43] F. Blanqui, A. Canteaut, H. D. Jong, S. Imperiale, N. Mitton, G. Pallez, X. Pennec, X. Rival and B. Thirion. *Recommendations on "Grey-Zone Publishers": Recommendations from the Inria Evaluation Committee, translated from https://hal.inria.fr/hal-04001505*. Inria, 25th Jan. 2023, pp. 1–3. URL: https://inria.hal.science/hal-04201298.

[44] A. L. Dalmora, A. Imperiale, S. Imperiale and P. Moireau. *A time-domain spectral finite element method for acoustoelasticity: modeling the effect of mechanical loading on guided wave propagation*. 25th Jan. 2024. URL: https://inria.hal.science/hal-04417255.

[45] A. L. Dalmora, A. Imperiale, S. Imperiale and P. Moireau. *Kalman-based estimation of loading conditions from ultrasonic guided wave measurements*. 25th Jan. 2024. URL: https://inria.hal.science/hal-04417270.

[46] T. Delaunay, S. Imperiale and P. Moireau. *Mathematical analysis of an observer for solving inverse source wave problem*. 14th Dec. 2023. URL: https://inria.hal.science/hal-04344193.

[47] T. Delaunay, S. Imperiale and P. Moireau. *Uniform boundary stabilization of a high-order finite element space discretization of the 1-d wave equation*. 27th July 2023. URL: https://inria.hal.science/hal-04172229.