BME PARIS
BioMedical Engineering
MASTER'S PROGRAM

Internship proposition

Academic Year: 2025-2026
Acronym: CALF-IN

Project title:
Investigating the Apparent Incompressible Behaviour of Calf Soft Tissue under Compression: An Experimental–Numerical Investigation
Funding :
Funding: IUF Institut Universitaire de France

Supervisors:
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International mobility:
A **one-week visit to Bucknell University (Lewisburg, PA) is planned in February–March 2026** to harmonize high-strain-rate tensile protocols, run a short validation campaign, and calibrate our computational damage model on joint datasets.

Project description:

Research rational and hypothesis

To gain deeper insights into various aspects of human health, disease, injury, and their treatment, it is essential to develop a quantitative understanding of how biological cells, tissues, and organs respond to applied loads. The **quasi-incompressibility of biological soft tissues** has emerged as a key area of focus, particularly in the context of their interaction with external medical devices. These interactions often involve significant mechanical loading under compression, such as in cases where immobilized individuals are confined to beds (Mukhina et al., 2025, 2022) or wheelchairs (Macron et al., 2020, 2018; Rohan et al., 2023), amputees use prostheses (Fougeron et al., 2022; Matray et al., 2025), or patients are fitted with orthotics or other medical devices attached to the skin. In these scenarios, maintaining tissue integrity while ensuring load transmission is crucial to prevent tissue damage, such as pressure ulcers or deep tissue injuries

Within the framework of the **ANR IMPRINT project** (Individualized Manufacturing from fully digital PRocesses: human/orthopedic device INTerfaces), experimental work in the PhD of **Maialen Matray** revealed the **time-dependent accommodation of transtibial residual limbs in sockets**. Analysis of 309 gait cycles showed that, during the first 5–15 minutes after fitting, peak pressures decreased proximally (lateral, anterior, posterior sensors) while increasing distally (anterior and lateral). After 40–50 minutes, when residual limb volume appeared stabilized, cycle duration was also significantly reduced. These findings demonstrate a **proximal-to-distal redistribution of loads over time**, reflecting biological accommodation processes that cannot be captured by purely elastic formulations

Attempts to describe such time-dependent response of soft tissues often rely on viscoelastic formulations. While these models can reproduce stress-relaxation and creep phenomenologically, they lack a mechanistic basis, as they ignore the bi-phasic nature of skin (Lavigne et al., 2025) and skeletal muscle (Lavigne et al., 2022). The load-bearing response of muscle thus depends not only on the deformation of the solid phase but also on fluid pressurization and redistribution within the tissue. Consequently, its apparent compressibility evolves with time.

Hypothesis.

We hypothesize that the apparent incompressibility of soft tissues arises from different mechanisms depending on the timescale of loading. At short times, tissues behave as nearly incompressible because of rapid interstitial fluid pressurization. Over longer times, however, permeability of the solid matrix and vasculo-lymphatic compliance allow fluid drainage and redistribution, which results in pressure relaxation, creep, and an increase in apparent compressibility. These mechanisms provide a physiological explanation for the accommodation phenomena observed clinically in transtibial sockets, where pressures progressively shift from proximal to distal regions within minutes. Such signatures cannot be reproduced with hyperelastic or viscoelastic models alone, but can be described by a biphasic poroelastic continuum combining a solid matrix and an interstitial fluid phase. The temporal evolution of interface pressures and distal depressurization reported in the PhD of Maialen Matray's thesis strongly supports this hypothesis.

Objectives of the Internship

Building directly on the observations of time-dependent socket accommodation, the CALF-IN internship aims to investigate the **apparent incompressibility of calf soft tissues under compression**, combining **in vivo experiments**, **ultrasound imaging**, and **numerical modelling**. The specific objectives are:

1. **Experimental characterization (*in vivo* calf):** Quantify the time- and rate-dependent mechanical response of calf tissues in compression, including force–displacement curves, stress-relaxation, creep, hysteresis, and apparent Poisson's ratio, across multiple loading amplitudes and speeds.
2. **Functional imaging:** Use portable ultrasound (B-mode, speckle-tracking, optionally Doppler) during controlled loading to measure tissue thickness, local displacement fields, and indirect indicators of fluid redistribution.
3. **Numerical modelling:** Develop, calibrate, and validate a **poroelastic finite element model** (and a visco-poroelastic variant) against the experimental data. Benchmark the predictions against quasi-incompressible hyperelastic formulations in order to delineate the conditions where hyperelastic models suffice and where poroelasticity becomes indispensable.
4. **Clinical translation:** Relate the in vivo calf compression results to the temporal pressure redistribution observed in prosthetic sockets, identifying characteristic time constants and defining a **time–scale criterion** for constitutive model selection in digital socket design.

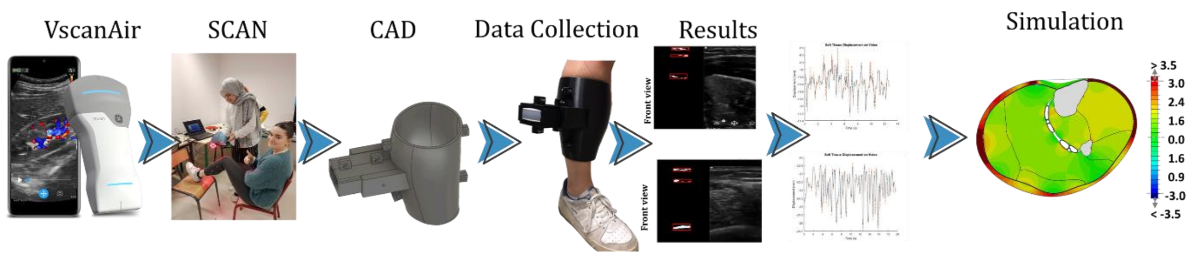

Figure 1: Experimental–numerical workflow: in vivo calf compression with portable ultrasound, data acquisition and analysis, and calibration of poroelastic finite element models for comparison with hyperelastic predictions.

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