BME PARIS
BioMedical Engineering
MASTER'S PROGRAM

# Internship proposition

**Academic Year:** 2025-2026
**Acronym:** MUSCLE_DAMAGE

**Project title:**
Investigating strain-rate dependent behavior in skeletal muscle: uniaxial traction, histology and computational insights on damage mechanisms
**Funding :**
Funding: IUF Institut Universitaire de France

**Supervisors:**
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*Benjamin Wheatley (*Bucknell University, Lewisburg, PA*, USA)*

**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**

The passive mechanical behaviour of skeletal muscle is fundamental for movement, stability, and injury prevention. With ageing or pathological conditions such as immobilization, disuse, and neuromuscular disease, muscle becomes more vulnerable to injury and deep tissue injury (DTI). Prevention and treatment strategies depend on a mechanistic understanding of how muscle microstructure fails under load, yet current clinical tools largely infer "stiffness" without explaining why stiffness changes with strain rate, stretch history, or pathology.

To address this gap, **Benjamin Wheatley (Bucknell University, USA)** and **Pierre-Yves Rohan (ENSAM, France)** are collaborating through a *Transatlantic Research Partnership* (TRP) titled "*Developing a Link Between Muscle Microstructural Form and Function – Towards Improved Treatments for Age-Related Muscle Impairments*" (awarded in 2024). This program combines controlled experiments, multiscale modeling, and histology to bridge the missing link between muscle form and function.

**Preliminary work (2024, 2025)**

In a first study, lapine extensor digitorum longus (EDL) muscle–tendon units (MTUs) were tested in uniaxial tension (n = 15 animals). Samples underwent stress relaxation followed by tensile loading to failure at either 0.1% $s^{-1}$ (slow) or 10% $s^{-1}$ (fast) strain rates (figure 1 (a)). Mechanical descriptors including tangent modulus, stress relaxation, ultimate tensile strength (UTS), and toughness were extracted. Results demonstrated that: UTS and toughness were significantly higher at fast strain rates and that failures consistently localized in muscle near the aponeurosis–muscle junction.

To interpret these findings, we developed a finite element (FE) model in FEBio of a 2D MTU slice (figure 1 (b)). Muscle and tendon were modeled with a hyperelastic ground matrix (Prony viscoelasticity) and tension-only reinforcing fibers subject to strain-dependent damage evolution. The model successfully

reproduced the experimental stress–stretch behaviour and predicted rate-dependent load redistribution between muscle and aponeurosis (figure 1 (b)). This suggested that fluid pressurization and ECM load-sharing may protect muscle fibers at higher rates, delaying failure.

However, the **absence of histological evidence** leaves the underlying mechanisms unresolved. Did fibers themselves rupture less at higher rates? Was the extracellular matrix (ECM) carrying more load? Did sarcolemmal disruption occur earlier than macroscopic failure? Answering these questions is critical both for basic science and for translational contexts (e.g., bed-rest muscle damage, sarcopenia, or rehabilitation loads).

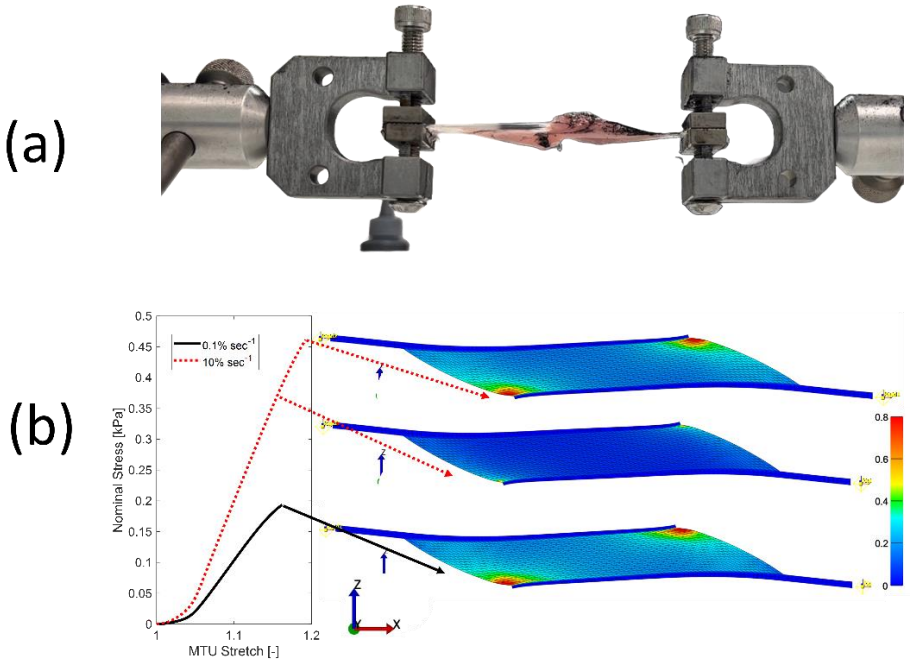


*Figure 1: (a) Uniaxial tensile tests of lapine extensor digitorum longus (EDL) muscle–tendon units showed higher ultimate tensile strength and toughness at fast strain rates, with failures localizing near the aponeurosis–muscle junction. (b) Finite element modeling reproduced the experimental stress–stretch response and predicted rate-dependent load redistribution, suggesting fluid pressurization and ECM load-sharing delay fiber failure at higher rates.*

**Hypothesis.**

We hypothesize that muscle damage initiation and progression under tensile loading are both strain-rate dependent and microstructure-specific. At slow rates, progressive fiber rupture and extracellular matrix (ECM) tearing dominate, producing early softening and reduced toughness. At fast rates, fluid pressurization and ECM load-sharing delay fiber failure, allowing greater energy absorption and toughness. By combining mechanical testing, histology at controlled stages of loading, and constitutive modeling with explicit damage laws, this internship will provide the first experimental validation of these mechanisms.

**Objectives of the Internship**

Building directly upon preliminary work, the new internship will pursue three main objectives:

**1. Mechanical testing (animal experiments)** Reproduce uniaxial tensile tests of lapine extensor digitorum longus (EDL) muscle–tendon units at slow (0.1% $s^{-1}$) and fast (10% $s^{-1}$) strain rates. Quantify stress–stretch behaviour, stress relaxation, ultimate tensile strength (UTS), toughness, and failure location. Record local strain distributions using digital image correlation (DIC).

**2. Histological analysis** Fix and process tissue samples at defined damage stages (pre-damage, onset, post-peak, and post-failure). Apply a panel of stains and markers (H&E, Picrosirius Red/Masson, desmin, IgG/Evans Blue) to characterize fiber rupture, ECM remodeling, and sarcolemmal disruption. Quantify microstructural damage and compare across strain rates and regions (muscle belly vs aponeurosis junction).

**3. Simulation and modeling** Refine finite element (FE) models of MTUs with a viscoelastic ground matrix and fiber-reinforced damage law. Calibrate the models against experimental stress–stretch curves and unloading softening. Validate model-predicted spatial damage distribution against histological evidence, testing solid-damage versus poro/visco-damage formulations.

**Expected Outcomes**

Experimental evidence confirming strain-rate effects on UTS, toughness, and failure location in skeletal muscle. Histological validation of simulation claims, showing distinct microstructural damage pathways at slow versus fast loading. Quantitative correlations between mechanical descriptors (UTS, toughness, relaxation), histology (fiber/ECM damage scores), and model predictions. A validated constitutive damage model that reproduces both rate-dependent behaviour and spatial damage localization. Standardized protocols and datasets enabling reproducibility and integration into the ongoing TRP program.