Skin as a Sponge

How pressure kills blood flow,

and how patient-specific modeling can stop it.

Thomas Lavigne[123], PhD

Supervisors: S.P.A Bordas[1], P-Y. Rohan[2], G. Sciumè[3]

1: University of Luxembourg, Faculty of Science, Technology and Medicine (FSTM), Doctoral School in Science and Engineering (DSSE)

2: IBHGC, ENSAM (France), Ecole Doctorale Sciences et Métiers de l'ingénieur (ED SMI)

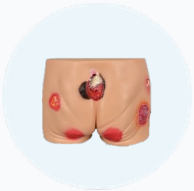
3: I2M, CNRS, ENSAM (France), Ecole Doctorale Sciences et Métiers de l'ingénieur (ED SMI)

AFR-FNR Grant #17013812

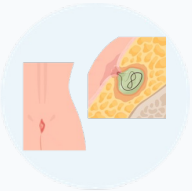
th0maslavigne.github.io

Why Study Skin?

Diabetic Foot Ulcer



Wheelchair User



Pilonidal Cyst

Faculty of Science, Technology and Medicine

Curriculum

2016 – 2018 — **Classes Préparatoires (PCSI/PSI*)**
Lycée Hoche, Versailles

2018 – 2020 — **M1 & Bachelor's in Mechanical Engineering**
ENS Paris-Saclay

2020 – 2021 — **MSc in Biomechanics**
ENSAM Paris

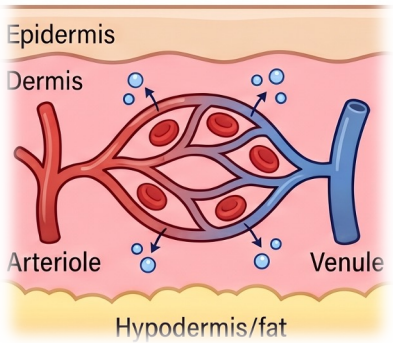
2021 – 2022 — **Pre-Doctoral Research Year**
Univ. Luxembourg / ENS Paris-Saclay

2022 – 2025 — **PhD in Engineering Sciences (Biomechanics)**
Univ. Luxembourg & DSSE / ENSAM & ED SMI / I2M · AFR-FNR

2025 – 2025 — **Post-Doctoral Researcher**
Univ. Bordeaux, I2M

2025 – 2027 — **Post-Doctoral Researcher**
École Polytechnique, CNRS, ANR ROSALY

Pressure Ulcers: What are they?



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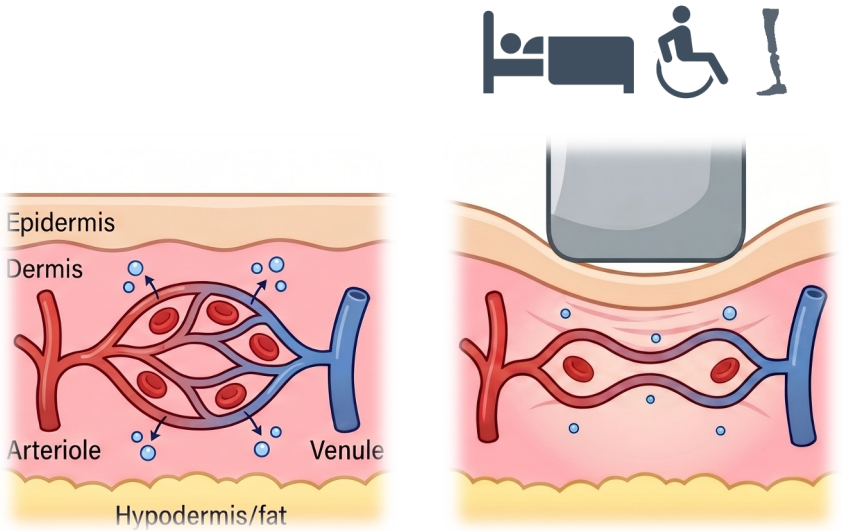

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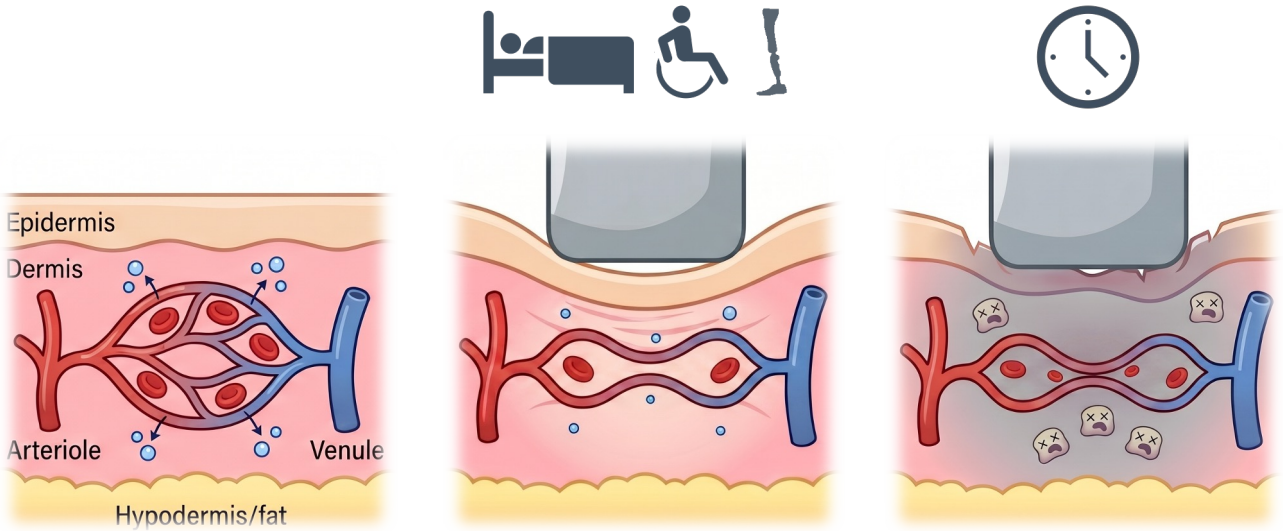

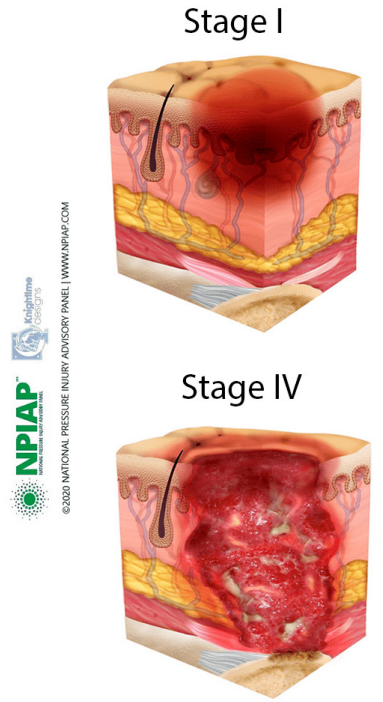

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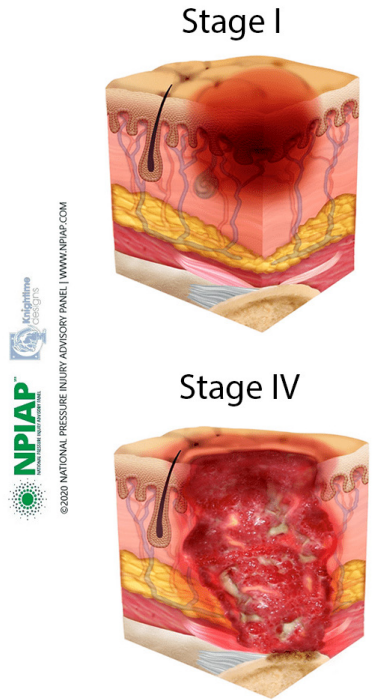
Pressure Ulcers: The Silent Epidemic

1 in 5

European hospital patients affected

[Vanderwee et al., 2007]



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Pressure Ulcers: The Silent Epidemic

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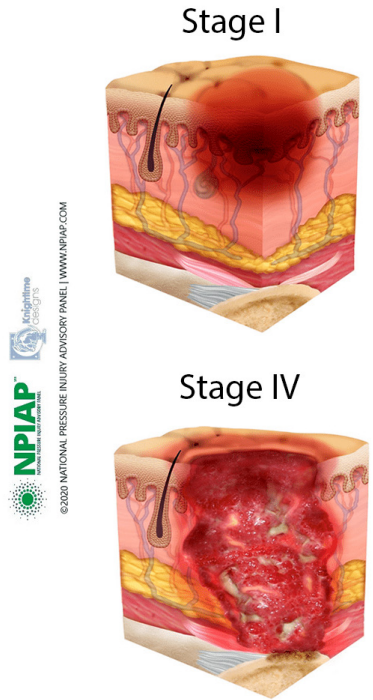
[Vanderwee et al., 2007]

50%

Incidence worldwide

[Lyder & Ayello, 2008]



A Life-Threatening Reality

Pressure ulcers are not just "sores." They are systemic failures.

Painful

- massive, chronic **pain**,
- severely **reduced independence**.

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Isolating

- extremely **long healing**,
- long term **hospitalization**,
- limited **social** interactions.

Consequences

- risk of **amputation**,
- significant **mortality** rates,
- massive healthcare **costs**.

The Clinician's Dilemma

What would you do?

You are the clinician.

You have a bedridden patient in front of you.

Your must prevent an ulcer.

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Current Tools: An Illusion of Control

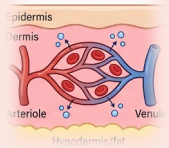
Surface Level Assessment (the illusion)

Day 0

Pressure Mapping

Snapshot only

The Diagnostic Blind Spot



Healthy microcirculation

Normal oxygen flow

Internal tissue reality

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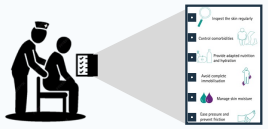
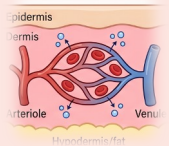
Progression



Clinical Scoring

Norton/Braden

The Diagnostic Blind Spot



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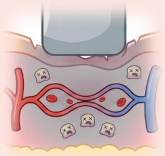

Silent ischemia

Vessels pinched, cell death

Internal tissue reality

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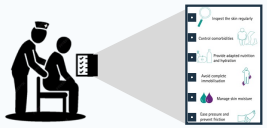
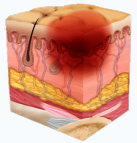
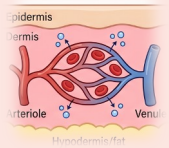
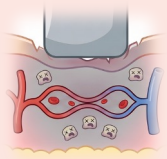
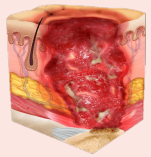
Day 0	Progression	Outcome
		
Pressure Mapping	Clinical Scoring	Visual Detection
Snapshot only	Norton/Braden	Too Late

The Diagnostic Blind Spot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	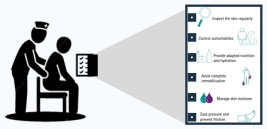	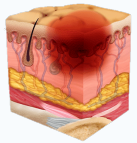
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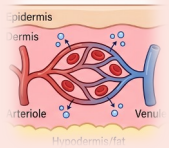	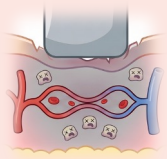	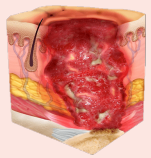
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Internal tissue reality

A Missing tool

Dynamic, internal tissue assessment

Faculty of Science, Technology and Medicine

The Core Research Question

How do we dynamically link the mechanics of pressure with the underlying biology?

The Core Research Question

Bridging mechanics, biology, and the clinic

PhD

Theoretical Mechanics

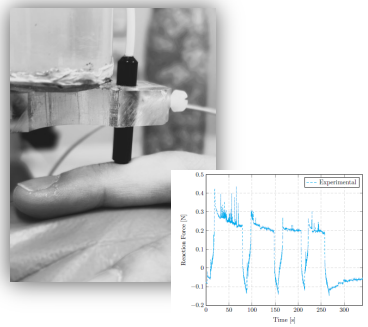
Mass is conserved

Fundamental laws of physics

Reproduce Reality?

PhD

Experimental Data



In-vivo validation

Predict Outcomes?

Clinical Reality

Helping the patient

Faculty of Science, Technology and Medicine

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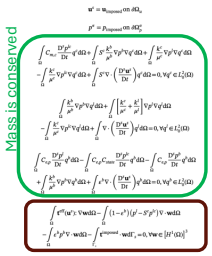

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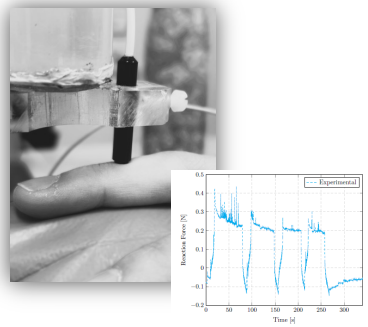

In-vivo validation

Predict Outcomes?

Clinical Reality

Helping the patient

The Ultimate Goal

To quantitatively predict patient-specific risk before tissue breakdown occurs.

Faculty of Science, Technology and Medicine

The Modelling Challenge

Limited access to data => **Comprehensive** modelling.

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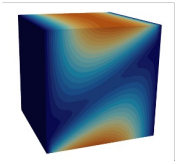

Over simplified models

- ✕ Ignores structural complexity
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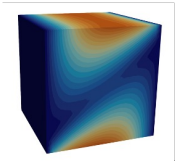

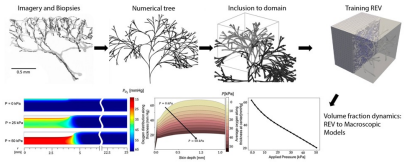

[Sree et al., 2019]

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- ✕ Computationally heavy
- ✕ Too many unknown parameters

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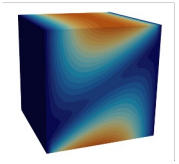

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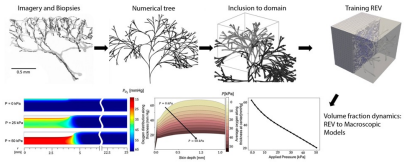

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Need for a comprehensive and clinically relevant model.

Back to Physics: Skin as a Sponge

- Solid scaffold & Cells
- Interstitial Fluid
- Blood & Oxygen

Some images are AI generated

Back to Physics: Skin as a Sponge

- Solid scaffold & Cells
- Interstitial Fluid
- Blood & Oxygen

Squeeze → Fluid forced out
Hold → Fluid still moves
Release → Fluid rushes back

Some images are AI generated

Poromechanics

Structural Integrity

Captures **tissue stiffness**, **mechanical behaviour** of the solid scaffold.

Vascular Coupling

Integrates **blood flux** and **oxygen transport** directly into the mechanical solver.

Patient-Specific

Average theory at **organ scale** enables **patient-specific** simulation.

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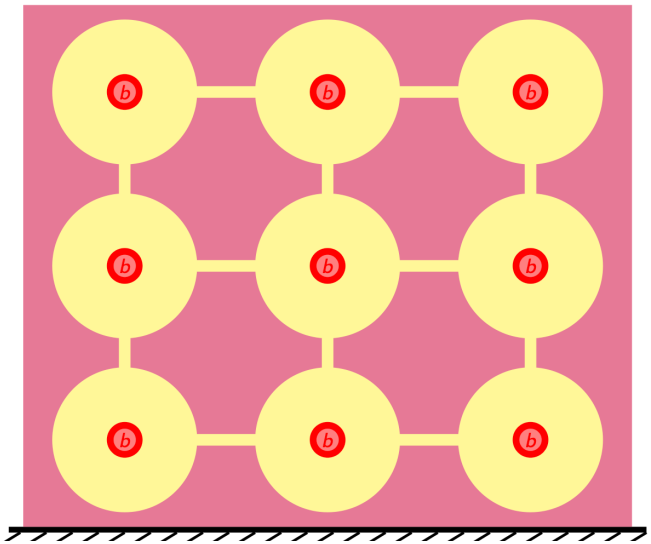
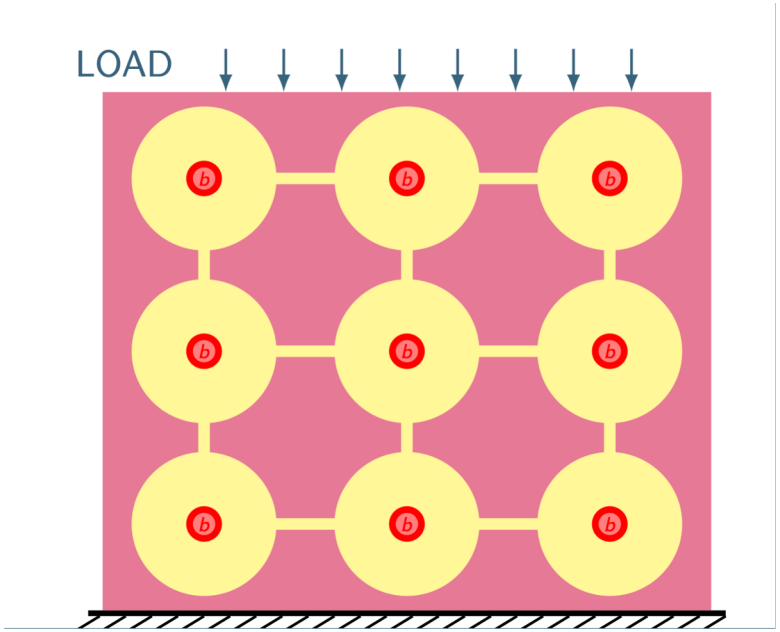


T. Lavigne et al., *J. Mech. Behav. Biomed. Mater.*, 2023

Bi-Compartment Porous Model



How does it work?

⇩

Increasing force on the **solid**

⇩

Increased pressure in the **pores**

⇩

Squeezed **blood vessels**

T. Lavigne et al., *J. Mech. Behav. Biomed. Mater.*, 2023

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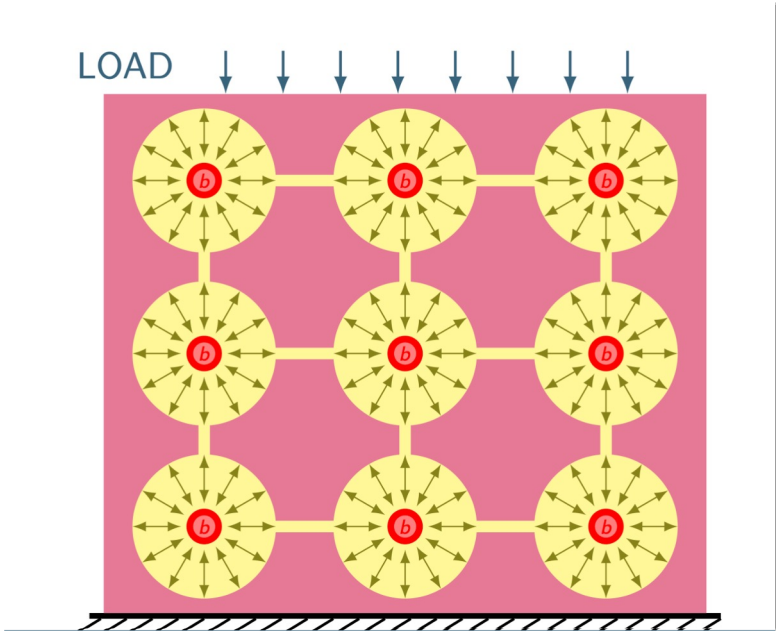

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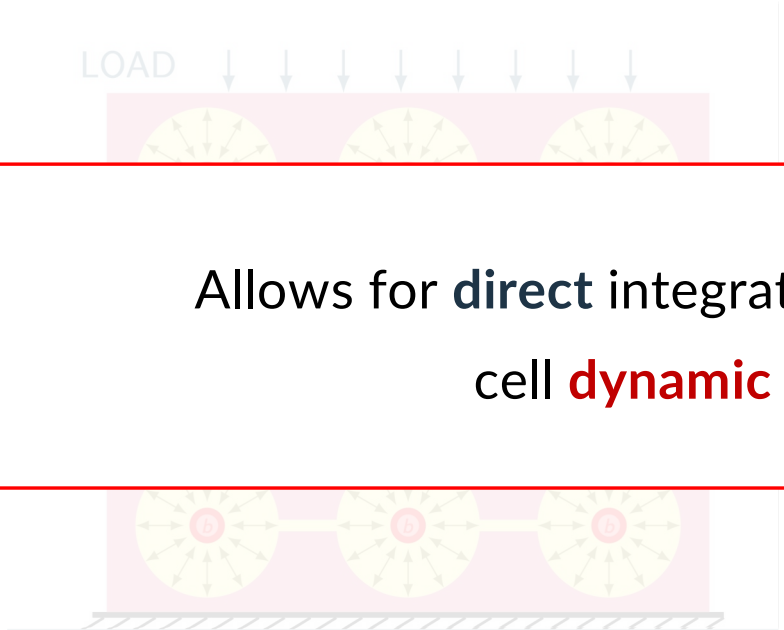
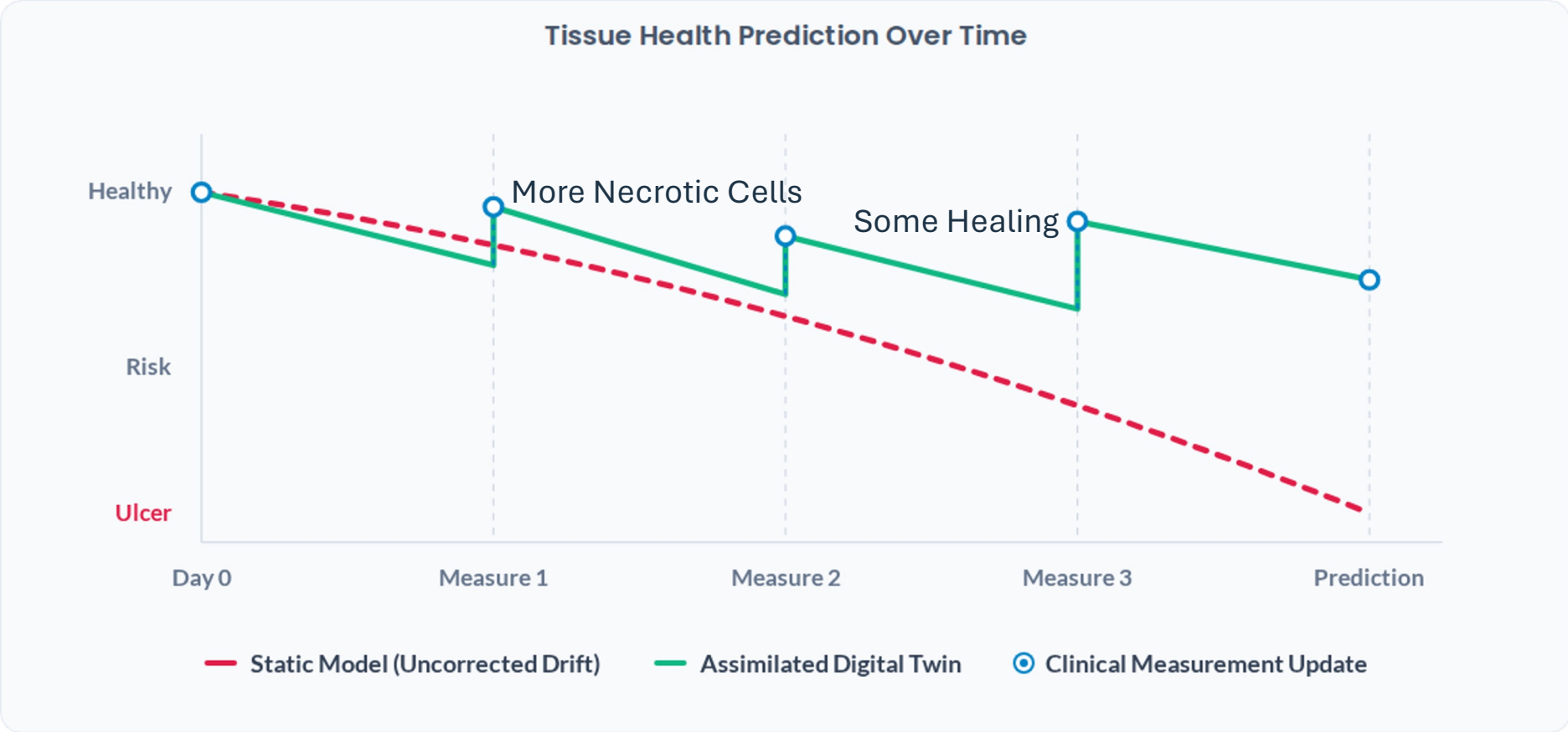


Allows for **direct** integration of **biological exchanges** and cell **dynamic death/healing** rates.

Squeezed blood vessels

T. Lavigne et al., *J. Mech. Behav. Biomed. Mater.*, 2023

Data Assimilation: The Weather Forecast Analogy



Towards Dynamic Digital Physical Twins

Data Assimilation

- **Baseline**: Patient-specific anatomy & mechanics.
- **Updates**: Periodic clinical evaluations.
- **Goal**: Prevent model divergence,
  Assess individual parameters.

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Biomechanical Simulation

- **Dynamics**: Tissue response over **hours/days.**
- **Precision**: **Exact** location of ischemia.
- **Action**: Predicts collapse **before it happens**.

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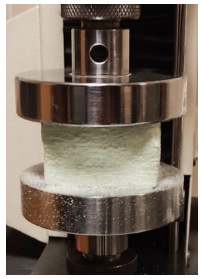
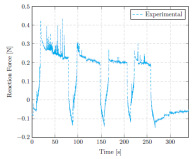
The Overall Framework

Real World





T. Lavigne et al., *JMBBM*, 2023
T. Lavigne et al., *IJNMBE*, 2024
T. Lavigne et al., *IJNMBE*, 2025

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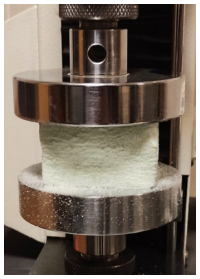
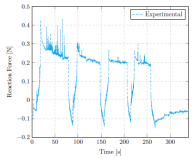
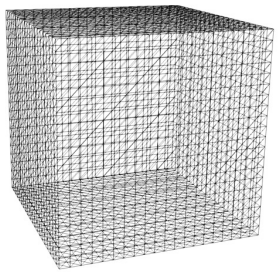




Discretized Domain



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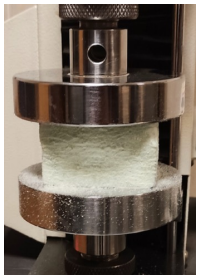
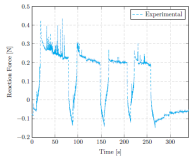
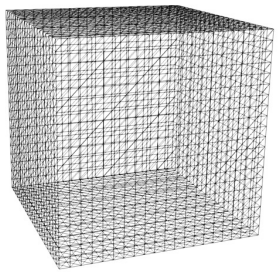




Discretized Domain



Model

$$\mathbf{u}^s = \mathbf{u}_{\text{imposed}} \text{ on } \partial\Omega_u$$

$$p^a = p_{\text{imposed}} \text{ on } \partial\Omega_p^a$$

Mass is conserved

$$\int_\Omega C_{m,c}\frac{\mathrm{D}^s p^c}{\mathrm{D}t}q^c\,\mathrm{d}\Omega + \int_\Omega S^c\frac{k^b}{\mu^b}\nabla p^b\nabla q^c\,\mathrm{d}\Omega + \int_\Omega \frac{k^c}{\mu^c}\nabla p^l\nabla q^c\,\mathrm{d}\Omega$$
$$-\int_\Omega \frac{k^c}{\mu^c}\nabla p^{lc}\nabla q^c\,\mathrm{d}\Omega + \int_\Omega S^c\nabla\cdot\left(\frac{\mathrm{D}^s\mathbf{u}^s}{\mathrm{D}t}\right)q^c\,\mathrm{d}\Omega = 0, \forall q^c \in L_0^2(\Omega)$$

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$$\int_\Omega C_{\epsilon,p}\frac{\mathrm{D}^s p^l}{\mathrm{D}t}q^b\,\mathrm{d}\Omega - \int_\Omega C_{\epsilon,p}C_{state}\frac{\mathrm{D}^s p^{lc}}{\mathrm{D}t}q^b\,\mathrm{d}\Omega - \int_\Omega C_{\epsilon,p}\frac{\mathrm{D}^s p^b}{\mathrm{D}t}q^b\,\mathrm{d}\Omega$$
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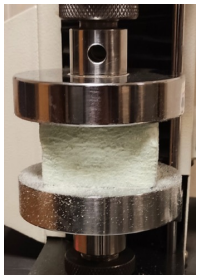
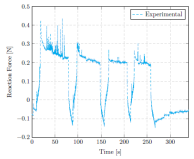
T. Lavigne et al., *JMBBM*, 2023
T. Lavigne et al., *IJNMBE*, 2024
T. Lavigne et al., *IJNMBE*, 2025

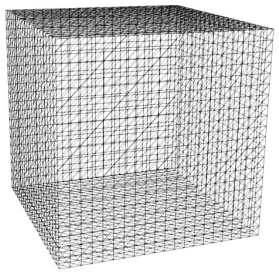
The Overall Framework

Real World





Discretized Domain



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Mass is conserved

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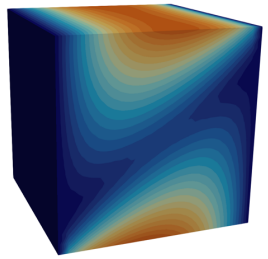
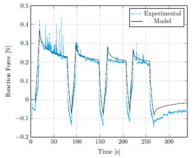
Computed Fields





New set of Parameters

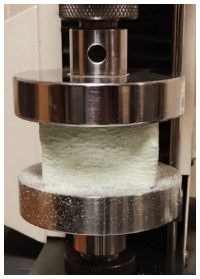
Patient-Specific Calibration

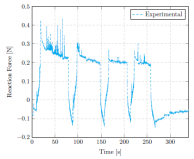
Sensitivity Analysis

T. Lavigne et al., *JMBBM*, 2023
T. Lavigne et al., *IJNMBE*, 2024
T. Lavigne et al., *IJNMBE*, 2025

The Overall Framework

Real World





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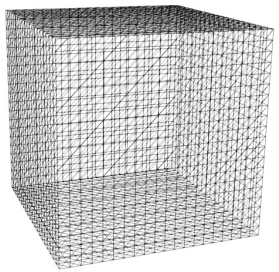

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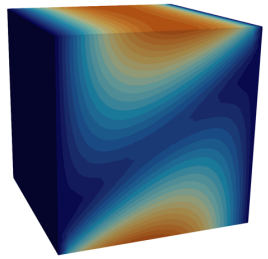
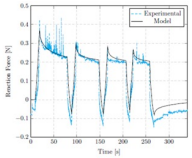




Future Outlook

Quantitative Risk Assessment

New set of Parameters

Patient-Specific Calibration

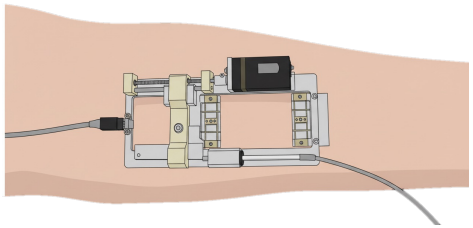
Sensitivity Analysis

T. Lavigne et al., *JMBBM*, 2023
T. Lavigne et al., *IJNMBE*, 2024
T. Lavigne et al., *IJNMBE*, 2025

In Vivo Validation

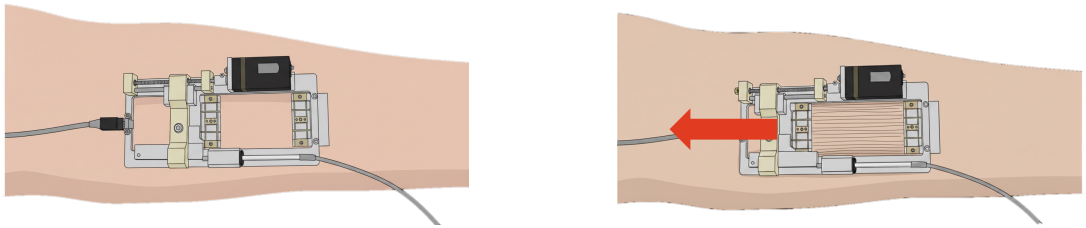
Does the **abstract math** match **real human tissue**?

In Vivo Evaluation: Hold Phase



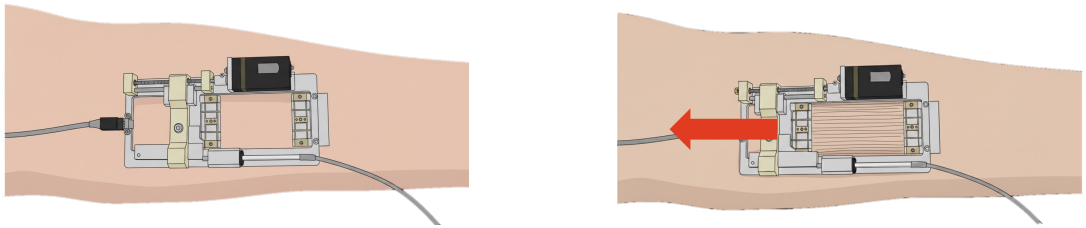
T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025a

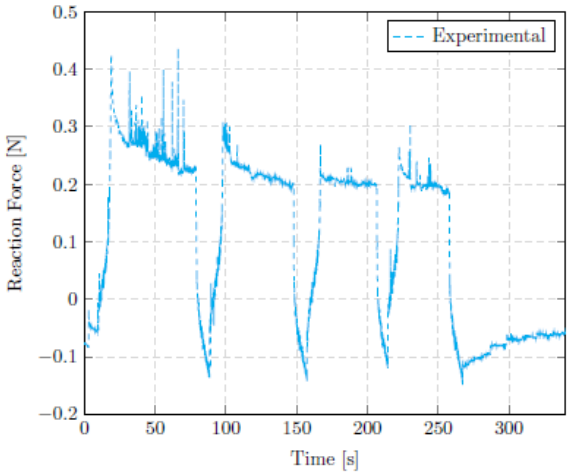
In Vivo Evaluation: Hold Phase



T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025a

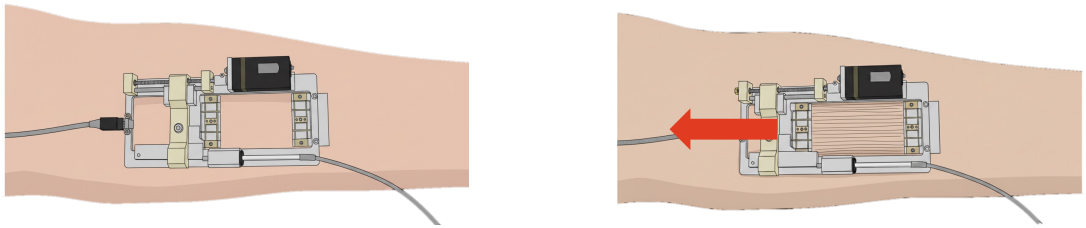
In Vivo Evaluation: Hold Phase

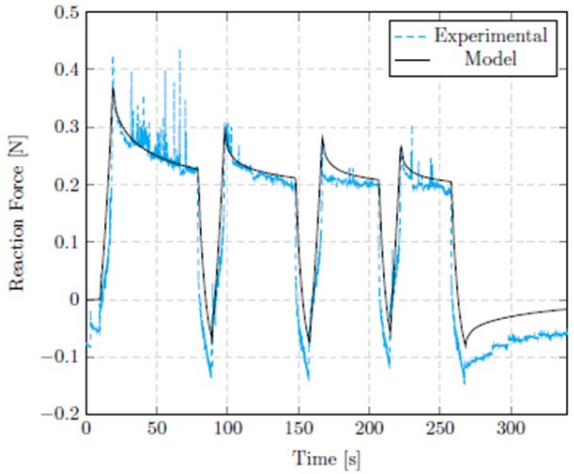




T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025a

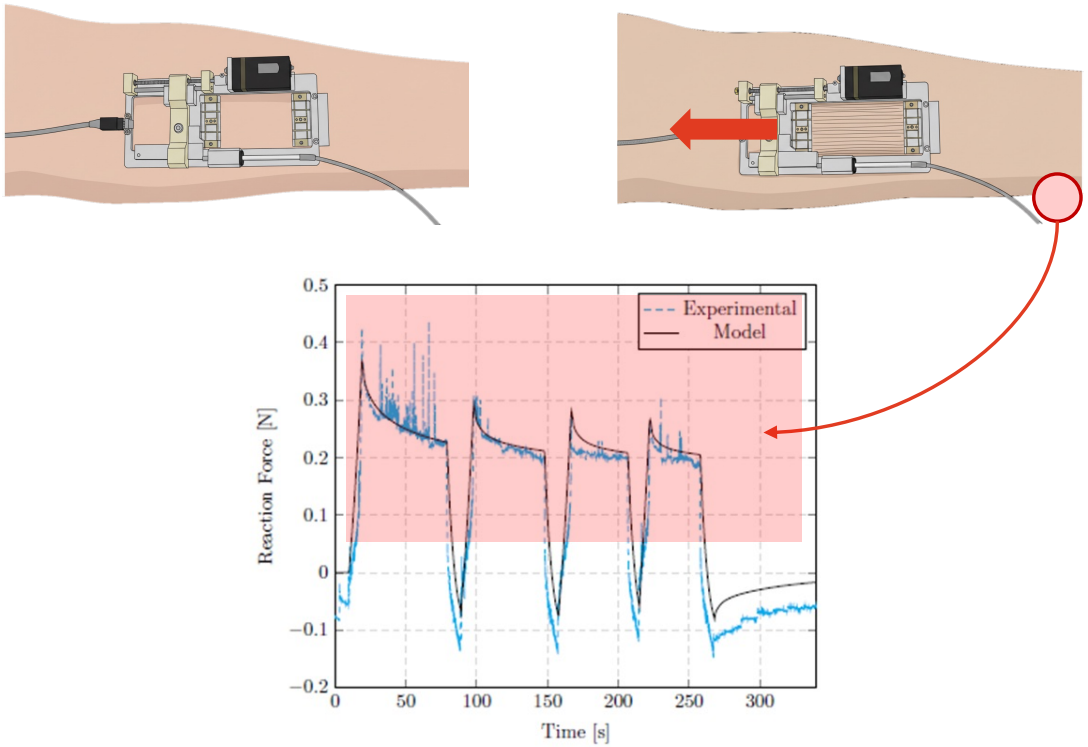
In Vivo Evaluation: Hold Phase





T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025a

In Vivo Evaluation: Hold Phase



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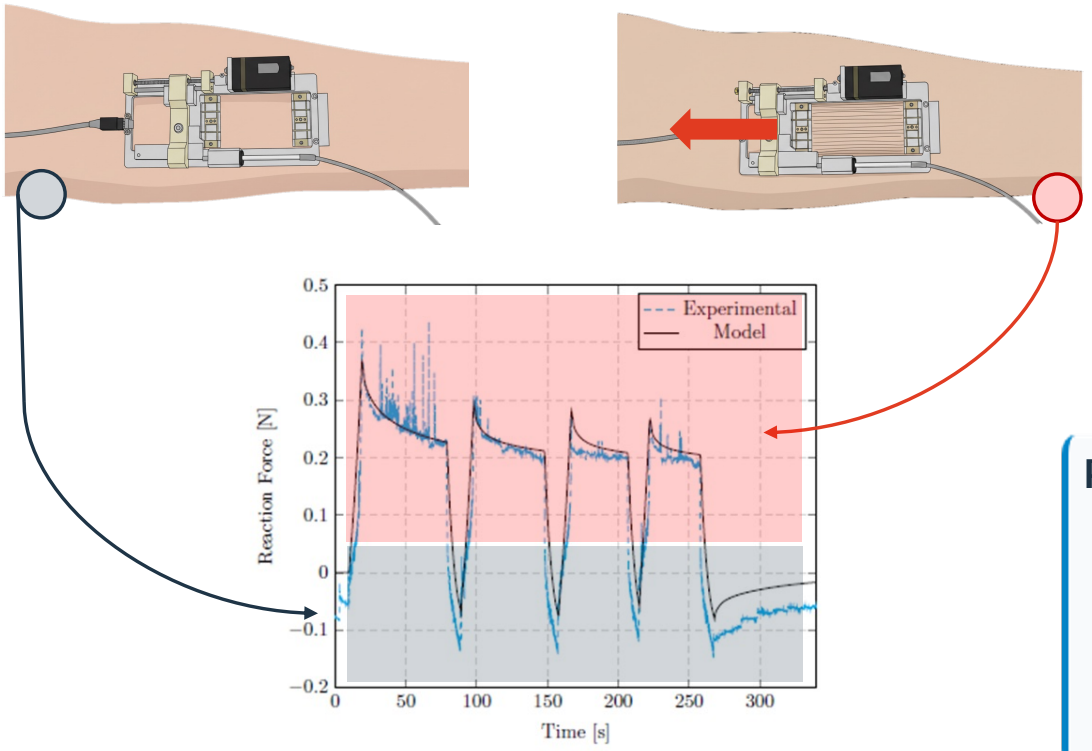
In Vivo Evaluation: Hold Phase



Physics matches reality.

- **Patient specific** mechanical properties.
- **Fluid** redistribution is a **primary physical driver** of skin relaxation.

T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025a

New *In Vivo* Evaluation: Perfusion vs Mechanics

Ethical approval (national registration number RCB: 2023- A00418- 37)

11 Human Volunteers

T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025b

Some images are AI generated

New *In Vivo* Evaluation: Perfusion vs Mechanics

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Gender-Inclusive Cohort

T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025b

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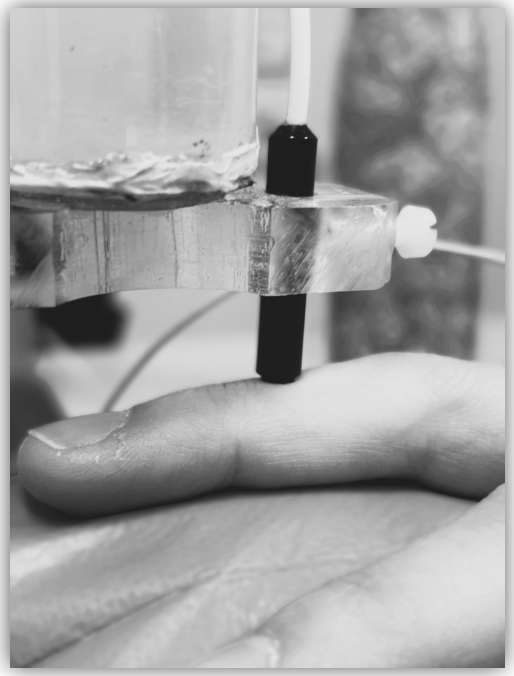
New *In Vivo* Evaluation: Perfusion vs Mechanics

Ethical approval (national registration number RCB: 2023- A00418- 37)

- 11 Human Volunteers
- Gender-Inclusive Cohort
- Controlled Finger Indentation



T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025b

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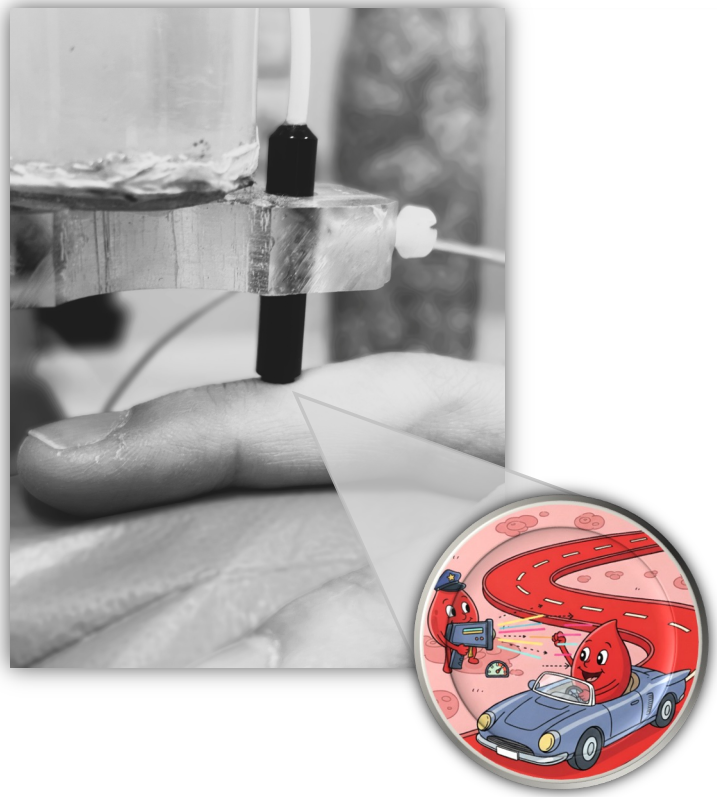
New *In Vivo* Evaluation: Perfusion vs Mechanics

Ethical approval (national registration number RCB: 2023- A00418- 37)

- 11 Human Volunteers
- Gender-Inclusive Cohort
- Controlled Finger Indentation
- Real-Time LDF Blood Flux



T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025b

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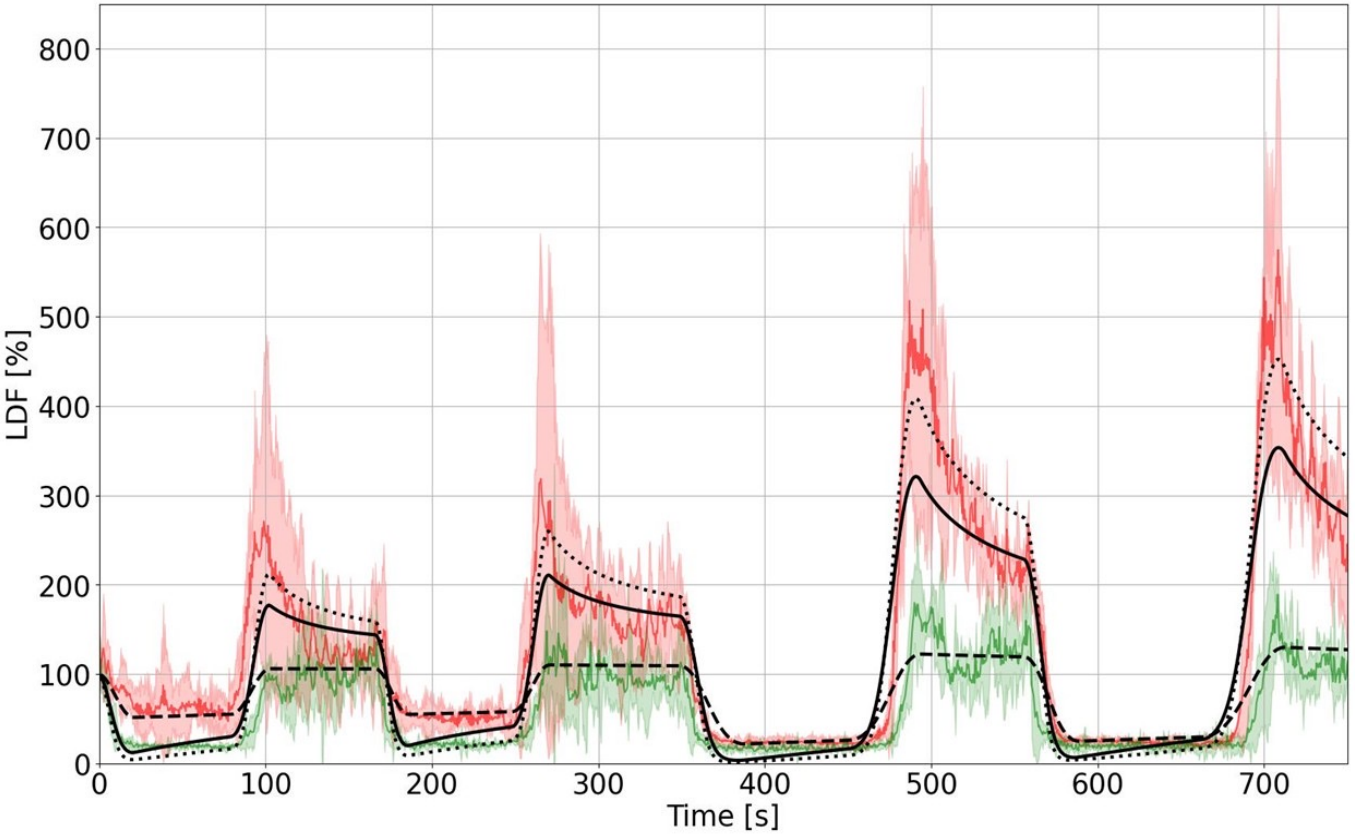
New *In Vivo* Evaluation: Perfusion vs Mechanics

LDF signals & model outputs



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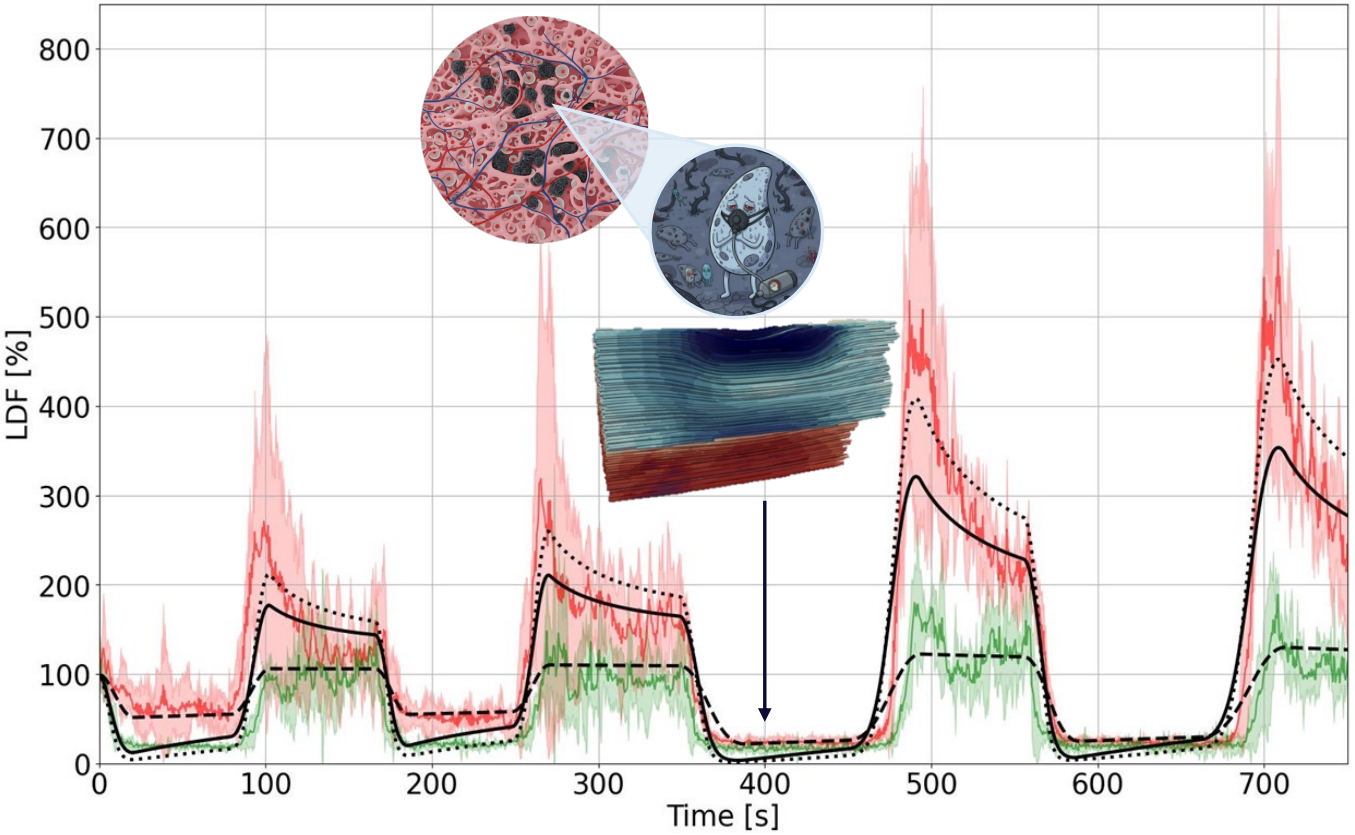

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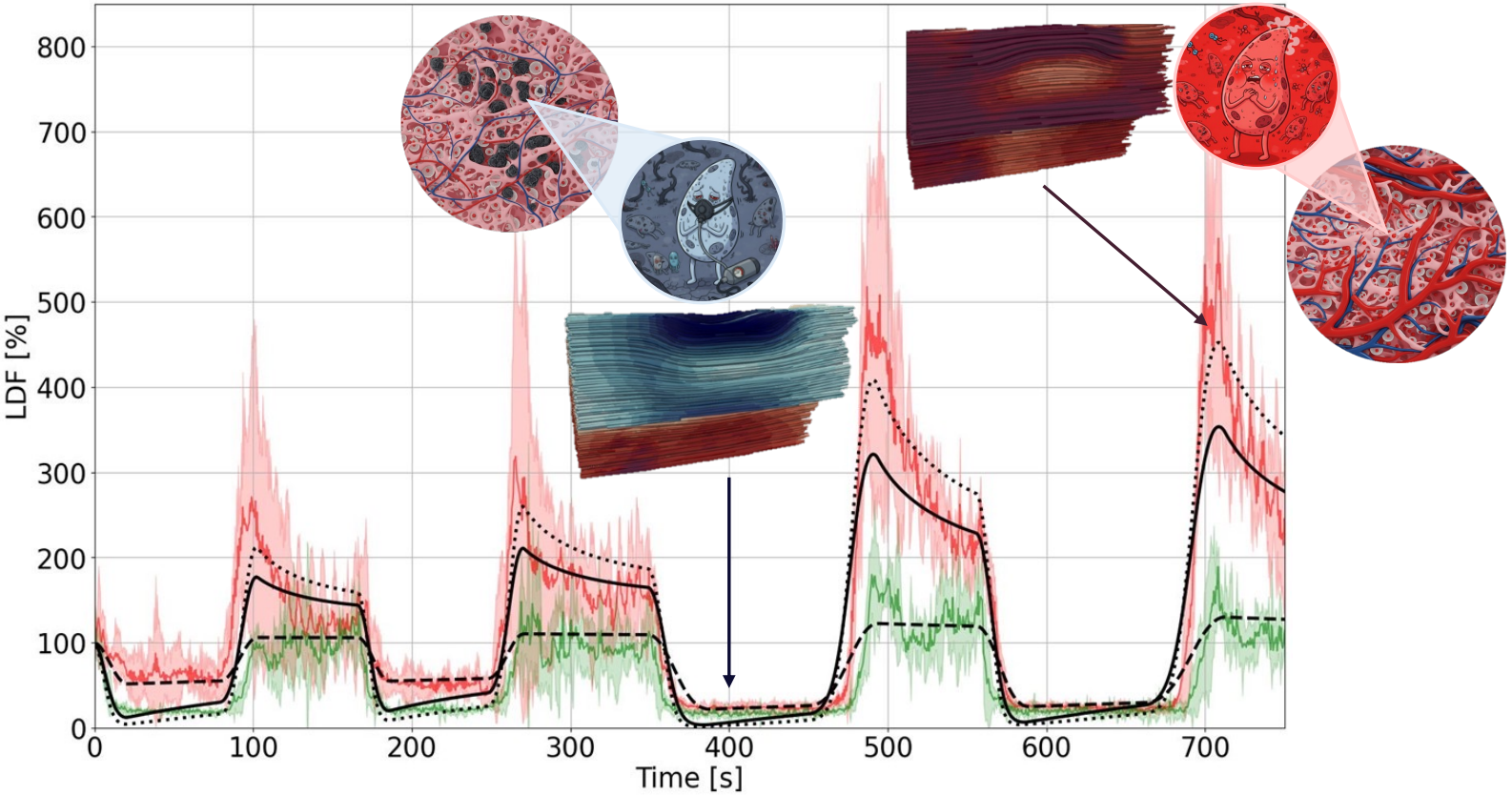

T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025b

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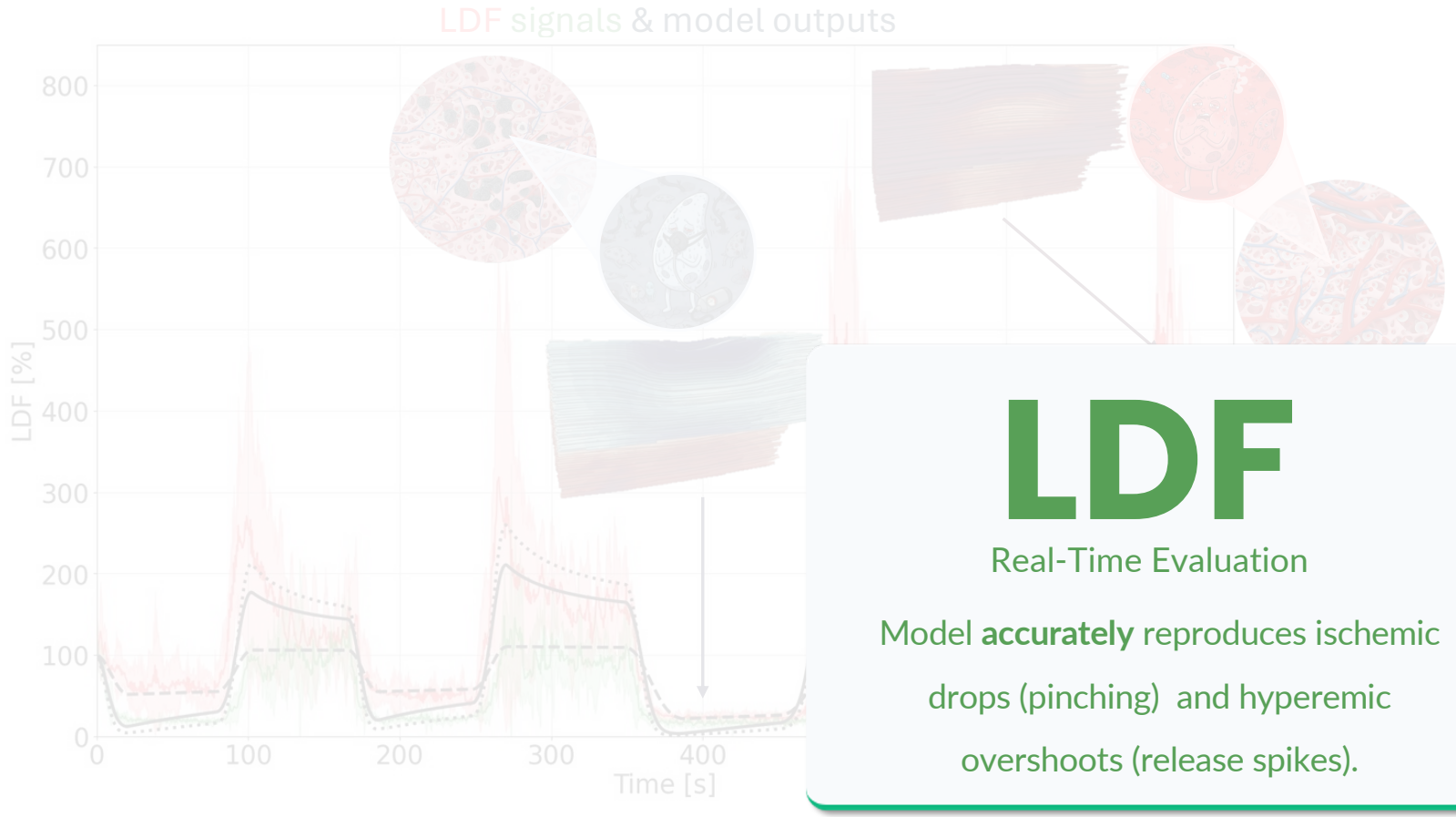


LDF

Real-Time Evaluation

Model **accurately** reproduces ischemic drops (pinching) and hyperemic overshoots (release spikes).

T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025b

Some images are AI generated

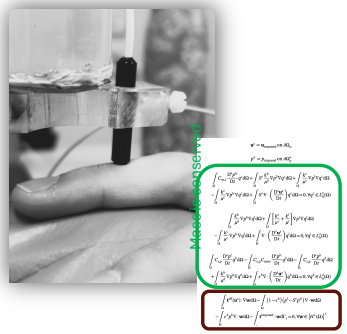
In Vivo Validation

What is the link between these **healthy** volunteer tests and a real **hospital** bed?

What do these patient-specific parameters actually tell us?

From Validation to Prediction

Laboratory

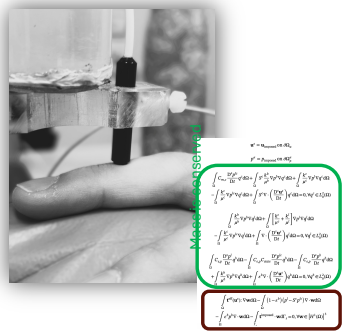


In-vivo validation: our math is correct.

Faculty of Science, Technology and Medicine

From Validation to Prediction

Laboratory



In-vivo validation: our math is correct.

A personalized countdown timer.

By inputting unique parameters like skin stiffness, we start predicting.

Hospital

Predicting pressure ulcers onset.

From Validation to Prediction

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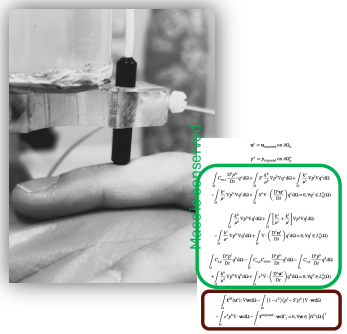

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Hospital

Predicting pressure ulcers onset.

> *"Given this specific patient's tissue state, if you do not turn them in 2 hours, deep tissue death will begin.*

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Impact & Open Science

Output

6 Journal Articles

2025 Excellent Thesis Award

Open Source

FEniCSx & GitHub

Inria: "Reproducible Research"
Anonymised and available data

Impact & Open Science

Output

6 Journal Articles

2025 Excellent Thesis Award

Open Source

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An **openly available comprehensive** and **evaluated toolbox** to go towards **patient-specific** pressure ulcer risk assessment and digital twins.

Faculty of Science, Technology and Medicine

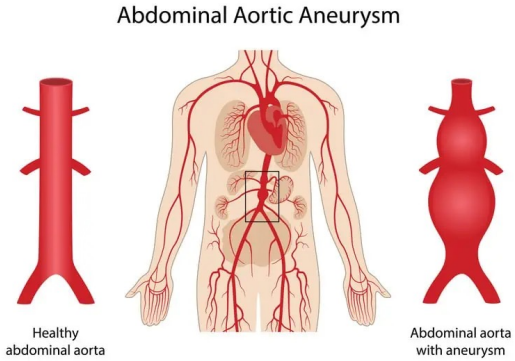
Invited Talks and Conferences, & Collaborations.

Collaborations

From Foundation to Multi-Organ Application

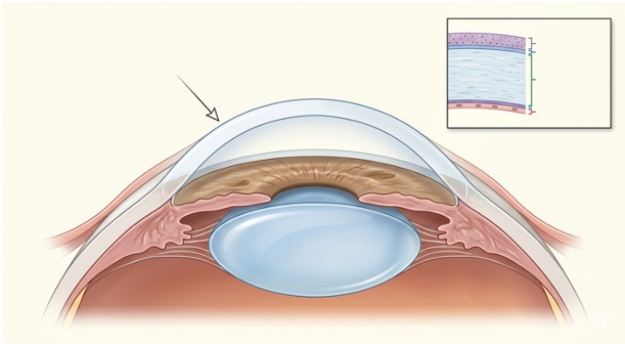
Brain Glioblastoma

Porous frameworks to account for cancer cells diffusion.



Aneurysm Risks

Embedding smooth muscle cells in collagen hydrogels.



Ophthalmology

Computational models to improve myopia surgery outcomes.

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The Take-Home Message

Bridging mechanics, biology, and the clinic

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Bridging mechanics, biology, and the clinic

Clinical Problem

Doctors are blind to what happens under the skin.

Faculty of Science, Technology and Medicine

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Bridging mechanics, biology, and the clinic

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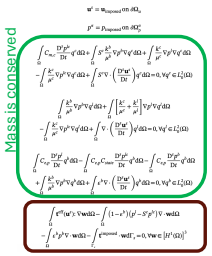
Theoretical Mechanics



Using physics to treat the skin as a sponge

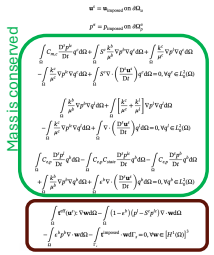
The Take-Home Message

Bridging mechanics, biology, and the clinic

Clinical Problem

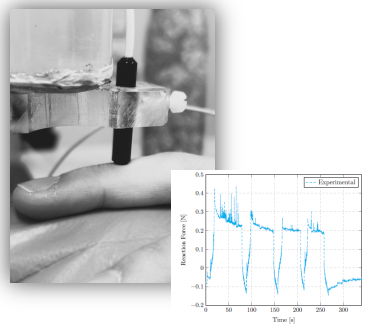
Doctors are blind to what happens under the skin.

Theoretical Mechanics



Using physics to treat the skin as a sponge

Experimental Data



Validated in real life on human volunteers.

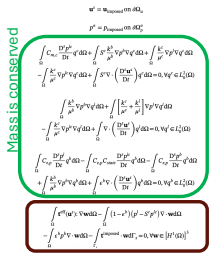
The Take-Home Message

Bridging mechanics, biology, and the clinic

Clinical Problem

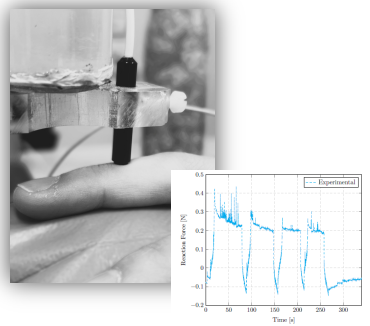
Doctors are blind to what happens under the skin.

Theoretical Mechanics



Using physics to treat the skin as a sponge

Experimental Data



Validated in real life on human volunteers.

> "We are providing a blueprint to **predict ulcers before the tissue dies**.
>
> - Finally putting an end to the 'one-size-fits-all' approach.

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Thank You!

"Predict ulcers before the tissue dies."

https://th0maslavigne.github.io

Connect & explore my research

AFR-FNR Grant #17013812

University of Luxembourg, Faculty of Science, Technology and Medicine (FSTM),
Doctoral School in Science and Engineering (DSSE)

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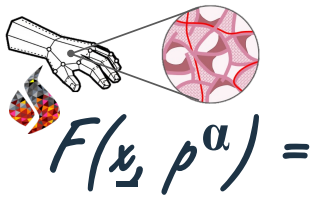
The Model: what is behind?



$F(x, \rho^{\alpha}) =$

Conservation Laws

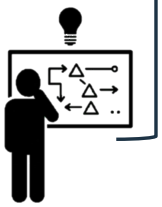
Mass Conservation

$$\begin{cases} \sum_{\alpha} \varepsilon_{\alpha} = 1 \\ \dot{\varepsilon}_{\alpha} + \nabla \cdot (\varepsilon_{\alpha} \boldsymbol{v}_{\boldsymbol{\alpha}}) = \mathbf{0} \end{cases}$$

Force Equilibrium

$$\nabla \cdot \sigma_{tot} = 0$$

Constitutive Laws



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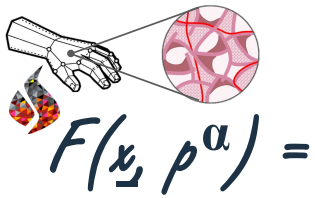
The Model: what is behind?



Conservation Laws

Mass Conservation

Solid

IF

$$\begin{cases} \sum_{\alpha} \varepsilon_{\alpha} = 1 \\ \dot{\varepsilon}_{\alpha} + \nabla \cdot (\varepsilon_{\alpha} \boldsymbol{v}_{\boldsymbol{\alpha}}) = \mathbf{0} \end{cases}$$

Force Equilibrium

Total stress

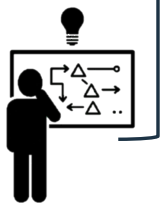
Darcy IF

$$\nabla \cdot \sigma_{tot} = 0$$

Constitutive Laws

Solid

Stress-Strain law



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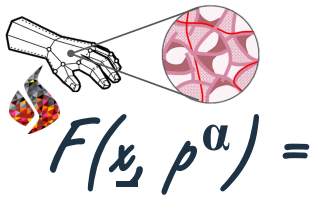

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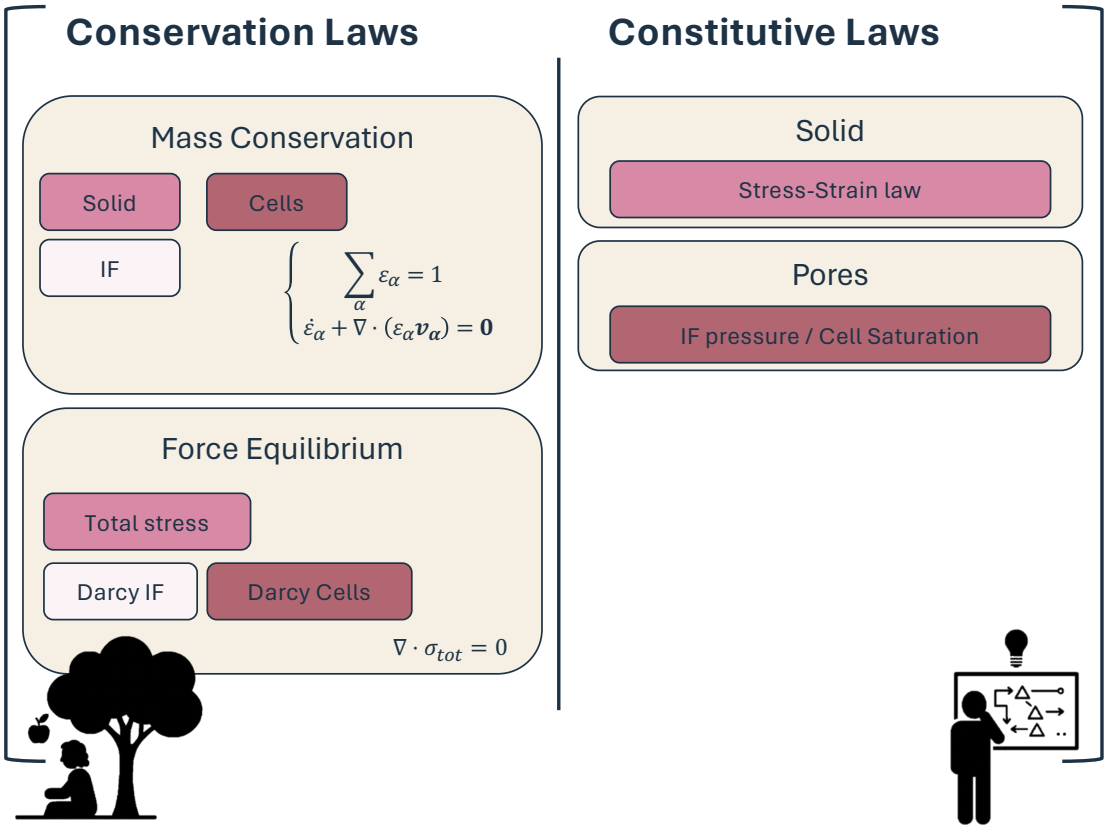

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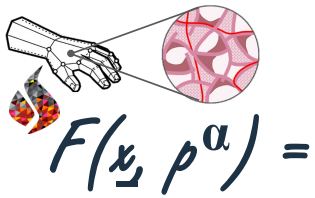

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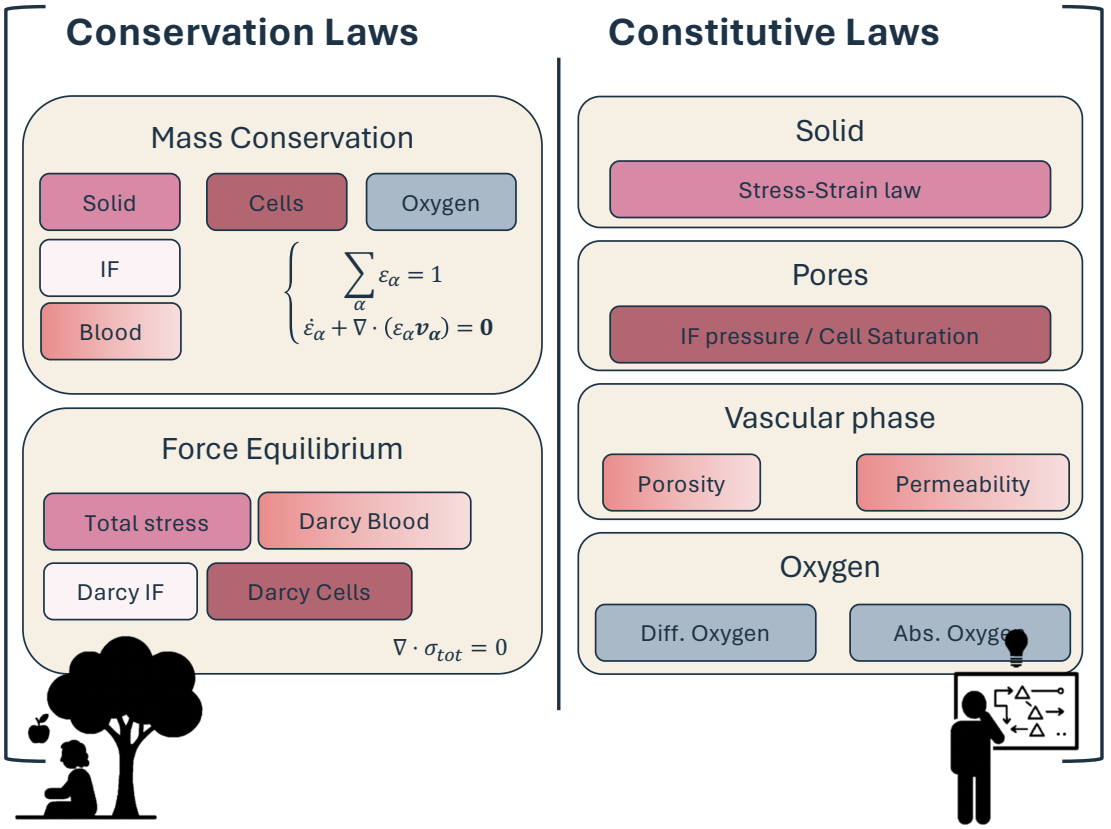

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The Ecosystem

University of Luxembourg (Central Hub)

Driving open-source numerical frameworks and international PhD co-tutelle.

IBHGC & I2M (Core Co-tutelle Partners)

Bridging experimental biomechanics in Paris with theoretical poromechanics in Bordeaux.

FEMTO-ST & LBTI (Experimental Partners)

Collaborating on advanced mechanical testing and tissue biology characterization.

External Collaborations (Leeds, IMT, FAU)

Expanding reach into Breast Cancer modeling, Fetal Brain development, and Brain mechanics.

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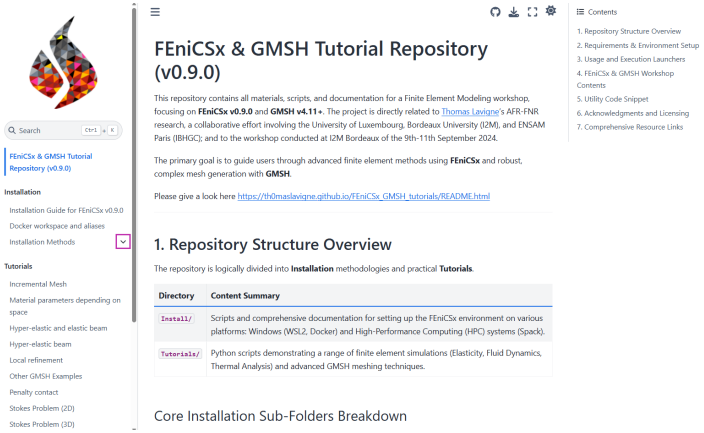
Open Access Tools

FEniCSx & GMSH Repository

v0.9.0

Lowering barriers to poromechanical modeling.

- **Single and bi-compartment models** completely open-sourced for the community.
- **HPC Deployment Guides** providing practical instructions for cluster implementation (Spack).
- **Full Reproducibility** ensuring all materials, codes, and documentation are accessible for soft tissue modeling.



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Impact

Systematic Open-Source Approach

*"Ce travail a par ailleurs été réalisé dans un souci constant de **validation** des simulations numériques proposées et de partage des développements informatiques avec une approche **open-source** systématique. Cette thèse place ainsi sans conteste Thomas Lavigne parmi les scientifiques qui feront **référence** dans ce champ..."*

— Official Jury Member Report

Knowledge Transmission

*"...he demonstrated strong qualities in **knowledge transmission** through teaching, mentoring, and the development of reusable training material. Given his outstanding scientific production and the quality of his work, Thomas clearly **ranks among the most productive and promising young researchers**."*

— Official Jury Member Report

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Visibility Multiplier

Open Source Code

International Community Hub

Makes the University of Luxembourg a recognized international hub for cutting-edge, transparent biomechanical tools, attracting new talent and establishing leadership in reproducibility.

Cotutelle Partnerships

Cross-border Knowledge Transfer

Significantly strengthens the strategic positioning and visibility of the University of Luxembourg within European research networks, as explicitly noted by the jury.

Clinical Relevance

Addressing Societal Challenges

Fulfills the public university mission by translating fundamental computational mechanics into direct public healthcare benefits, demonstrating tangible societal ROI.

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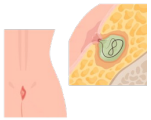

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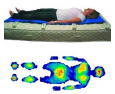

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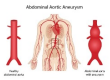

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