Skin as a Sponge

How pressure kills blood flow,

and how patient-specific modeling can stop it.

Thomas Lavigne[123], PhD

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2: IBHGC, ENSAM (France), Ecole Doctorale Sciences et Métiers de l'ingénieur (ED SMI)
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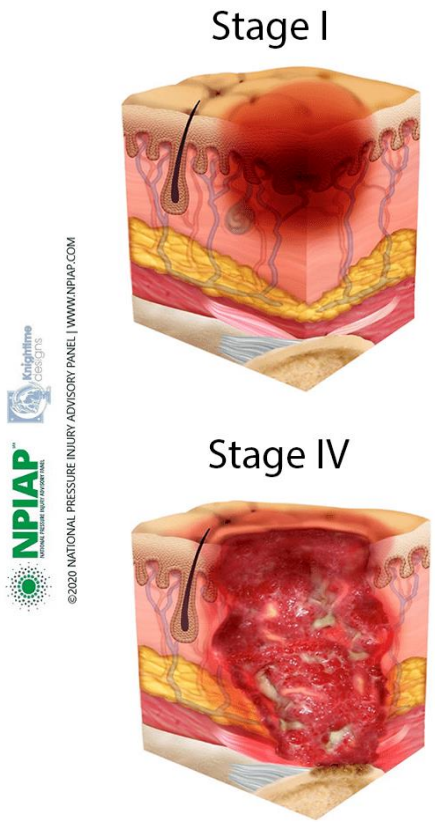
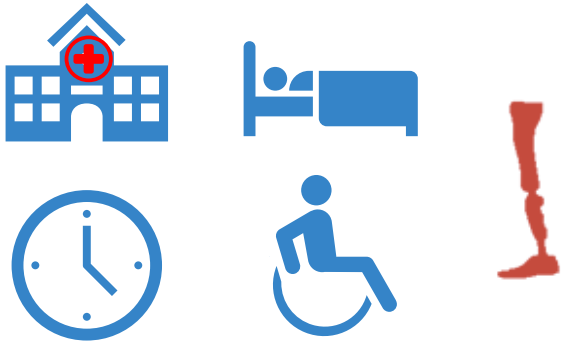
AFR-FNR Grant #17013812

th0maslavigne.github.io

Pressure Ulcers: The Silent Epidemic





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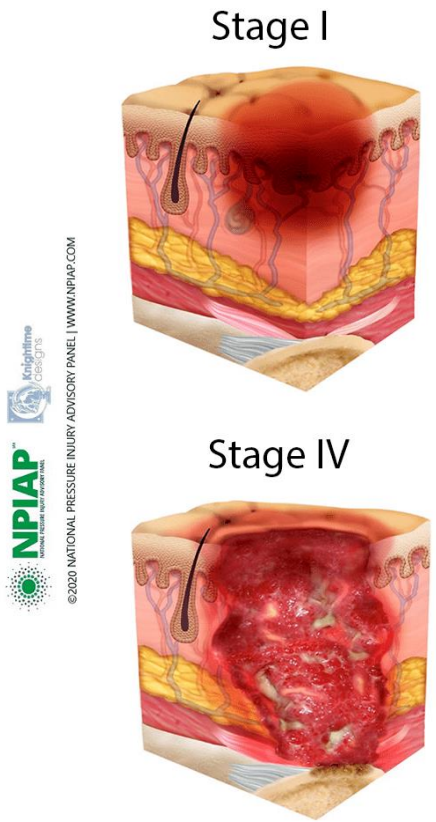

1 in 5

European hospital patients affected

[Vanderwee et al., 2007]

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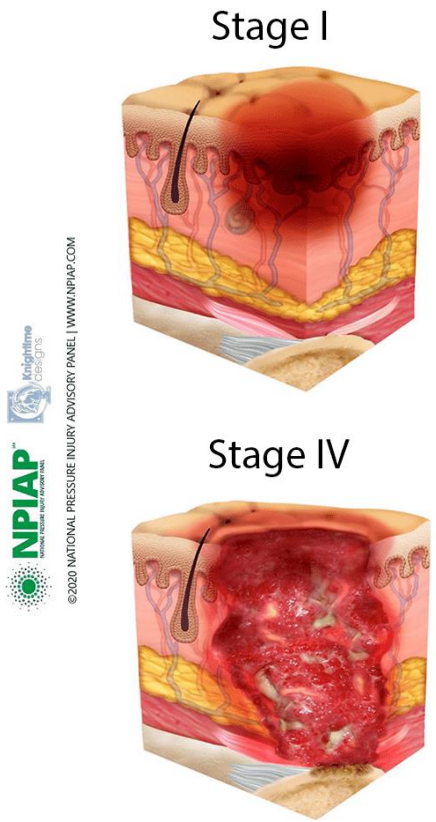

1 in 5

European hospital patients affected

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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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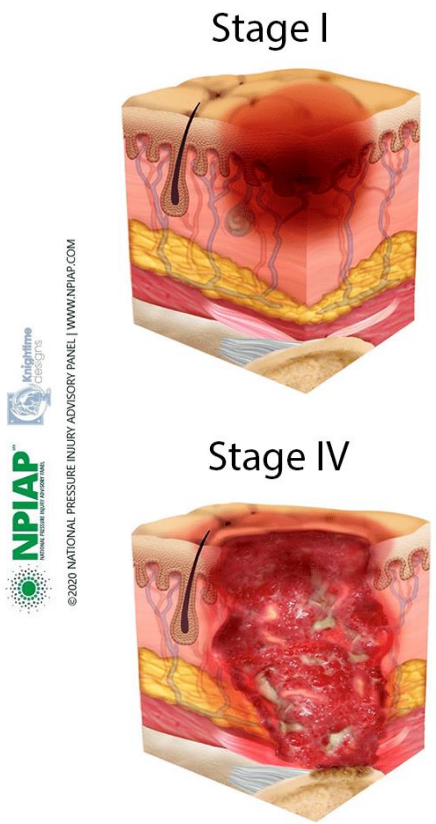
- limited **social** interactions.

Consequences

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

The "Guilty" Factors: Etiology of Ulcers



External Forces

Prolonged mechanical loading structurally compresses the tissue architecture.

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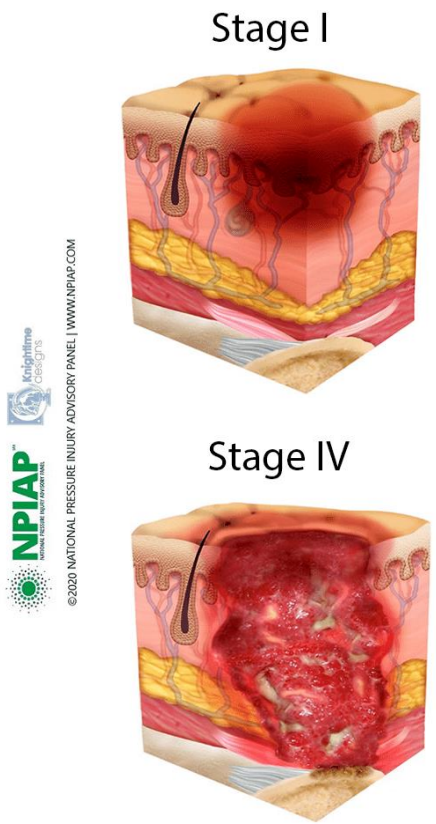

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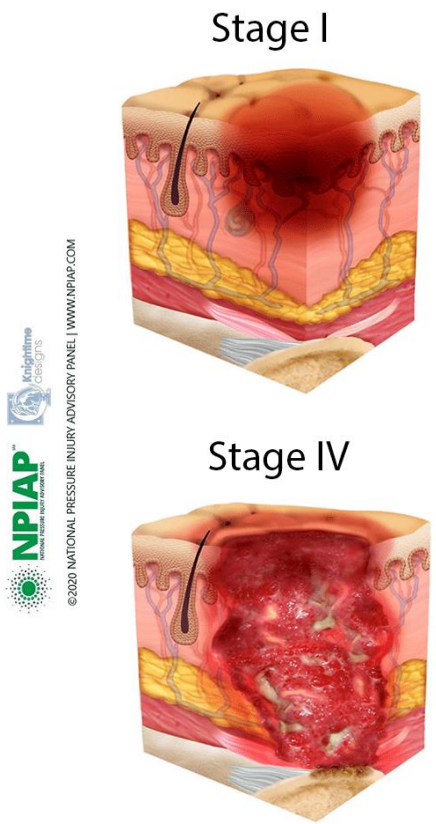

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State of the Tissue

Patient-specific vulnerability, and inherent stiffness, determine the overall biological tolerance.

The Clinician's Dilemma

What would you do? 🧑‍⚕️

You are the attending doctor or nurse.

You have a bedridden patient in front of you.

Your absolute priority is to prevent their tissue from breaking down and forming an ulcer.

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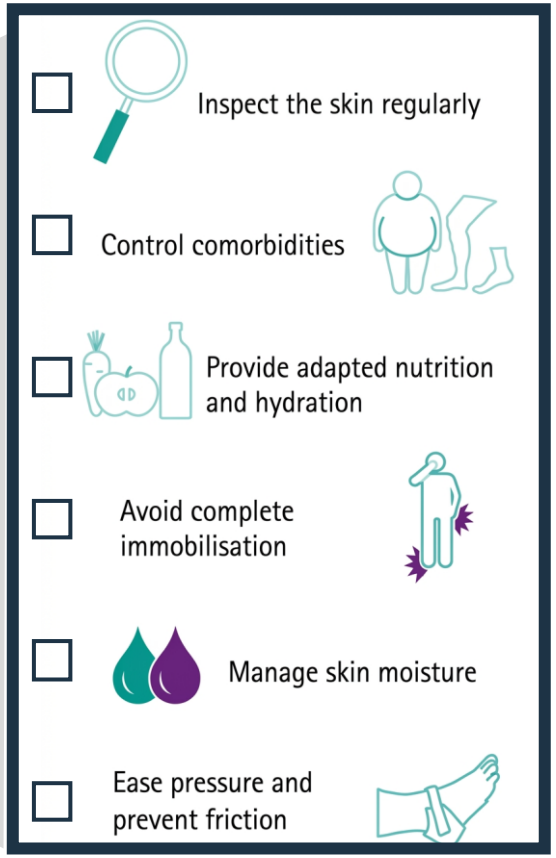
But the very first question you face is the hardest:

*How long will it take for **THIS specific patient** to get a PU?*

The Illusion of Control

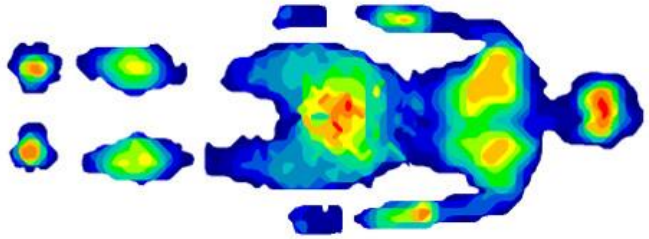
Clinical Scoring

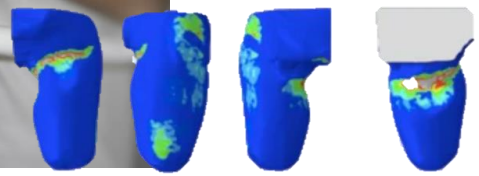


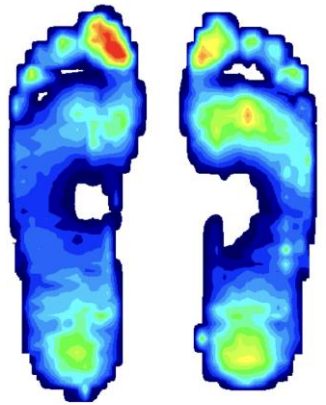
Norton score

The Illusion of Control

Pressure Maps







The Illusion of Control

Pressure Maps

Help for medical device **design**.

But completely **non-ecological** for permanent, real-time clinical monitoring.

The Diagnostic Dead End

Diagnostic Blind Spot

- External Sensors and Evaluation.
- No measurement of microcirculation.
- Imaging and Biopsies are limited to static monitoring.

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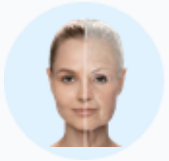

Extreme Patient Variability

- Ageing effect.
- Comorbidities.
- No universal clinical and mechanical evaluation.

The Material Twin Bridge

Real World

Analytics and Modelling

The Material Twin Bridge

Real World

Analytics and Modelling

Experiment

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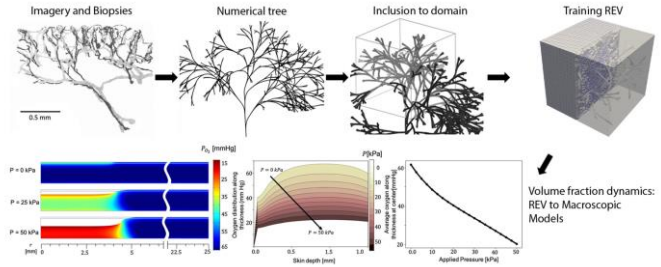
The Modelling Challenge

Limited access to data => Comprehensive modeling.

Over simplified models



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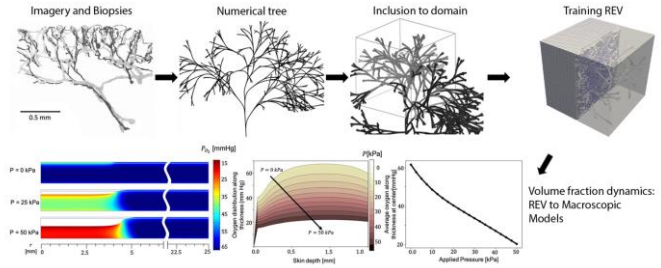

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vs

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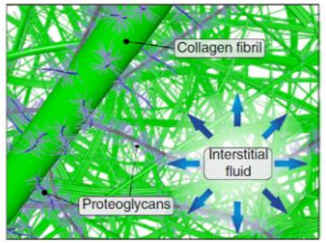

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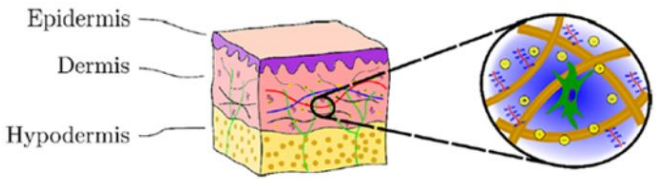

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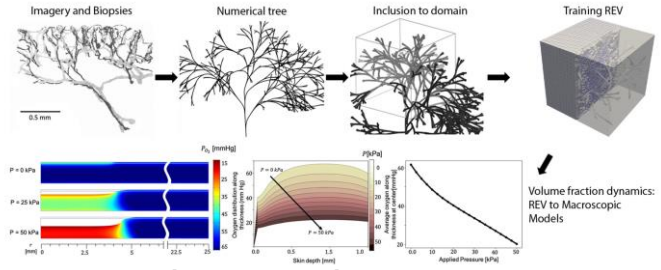

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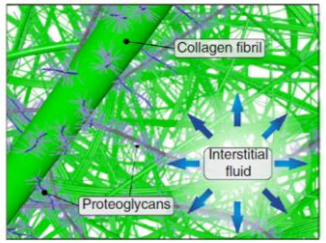

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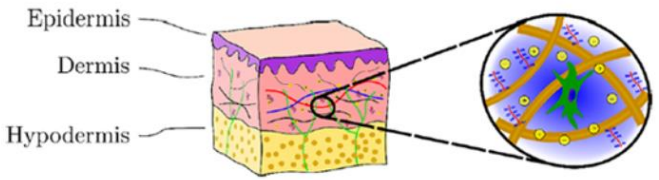

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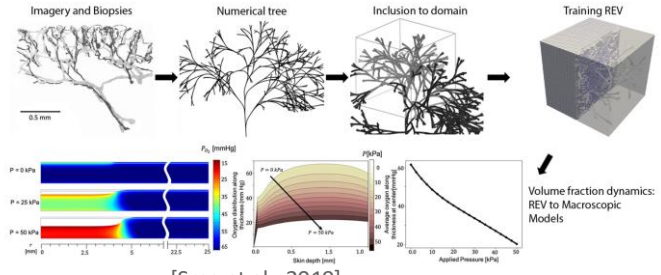

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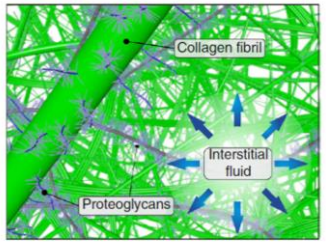

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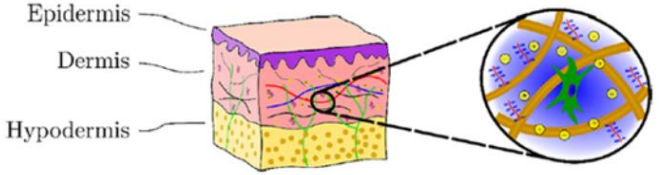

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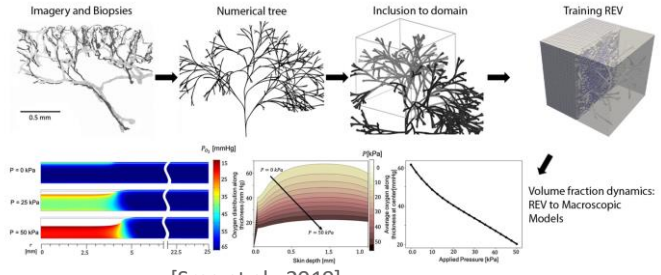

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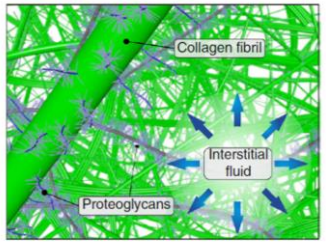

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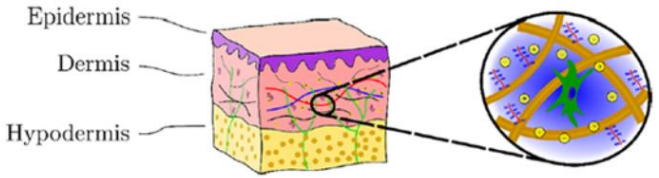

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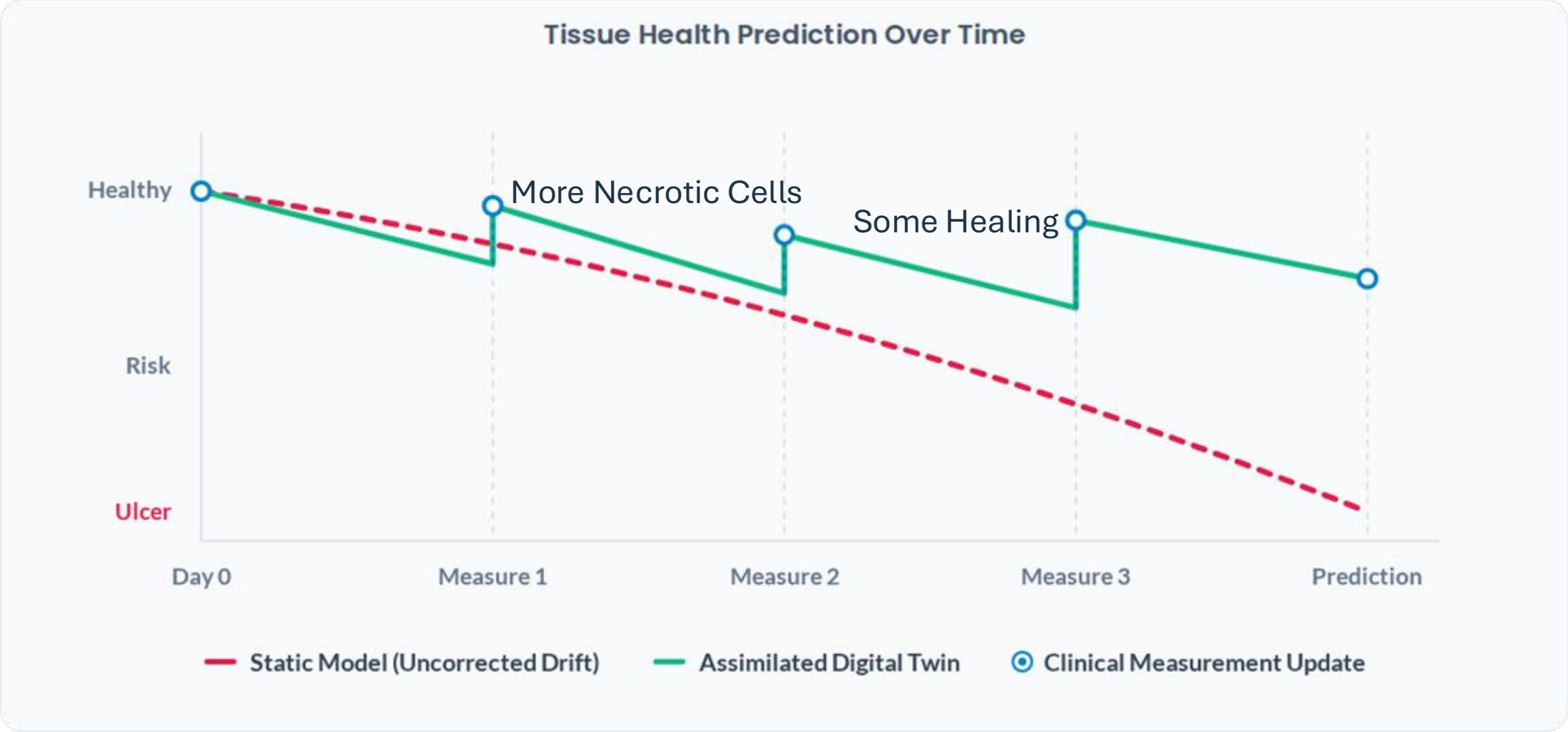
Few multi-physics *in vivo* studies have been **evaluated** for skin.

Access to **Inter-** and **Intra-** individual variations is crucial.

Allow for **dynamic** update (remodeling).

Data Assimilation: The Weather Forecast Analogy



The Solution: Dynamic Digital Physical Twins

Data Assimilation

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

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Biomechanical Simulation

- **Dynamics**: Simulates tissue response over hours/days.
- **Precision**: Pinpoints the exact location of ischemia.
- **Action**: Predicts collapse **before it happens**.

Back to Physics: Skin as a Sponge

THE 3 PHASES OF THE TISSUE

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

Back to Physics: Skin as a Sponge

Squeeze → Fluid forced out

Back to Physics: Skin as a Sponge

Squeeze → Fluid forced out

Hold → Fluid still moves

Back to Physics: Skin as a Sponge

Squeeze → Fluid forced out

Hold → Fluid still moves

Release → Fluid rushes back

Bridging the gap

Mechanical Models

✓ Captures stiffness, creep & relaxation.

✗ Ignores blood entirely.

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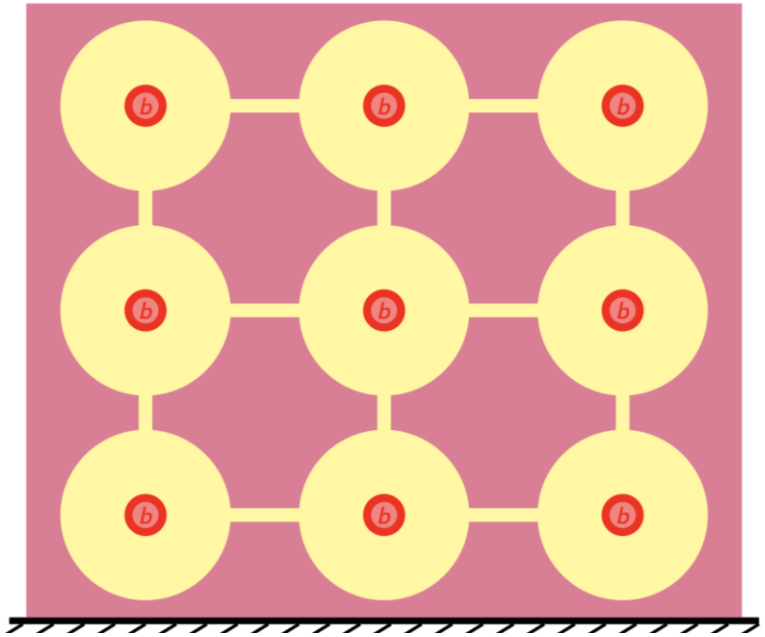
Poromechanics

- ✓ Analytical **coupling** of **mechanics** and **microcirculation**.
- ✓ Average theory at **organ scale**.

Bi-Compartment Porous Model



Adapted from the TCAT, [Gray and Miller, 2014]

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

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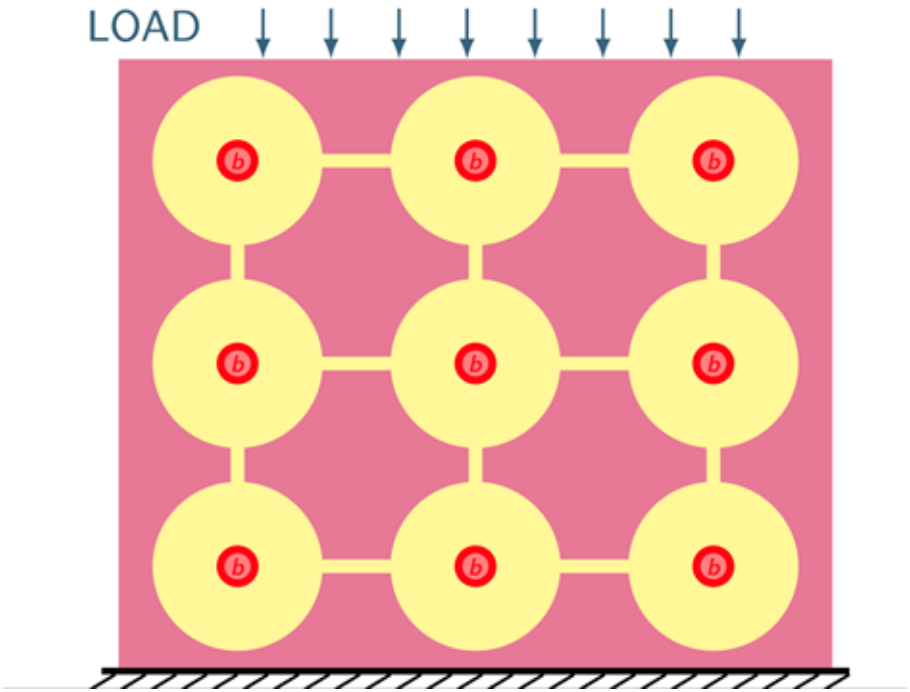

How does it work?

⇩

Increasing force on the **solid**

⇩

Increased pressure in the **pores**

⇩

Squeezed **blood vessels**

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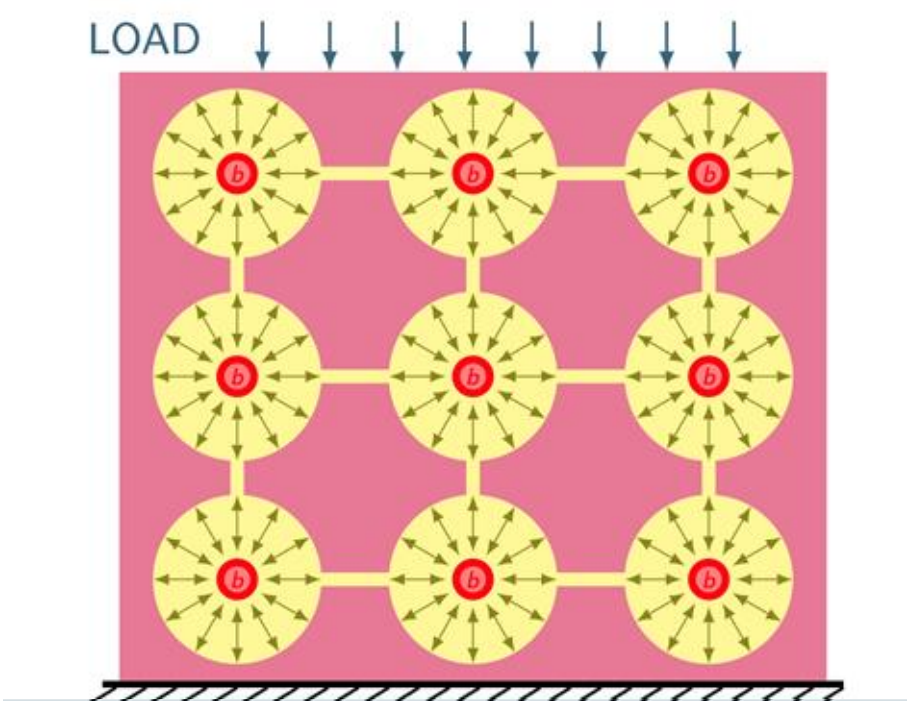

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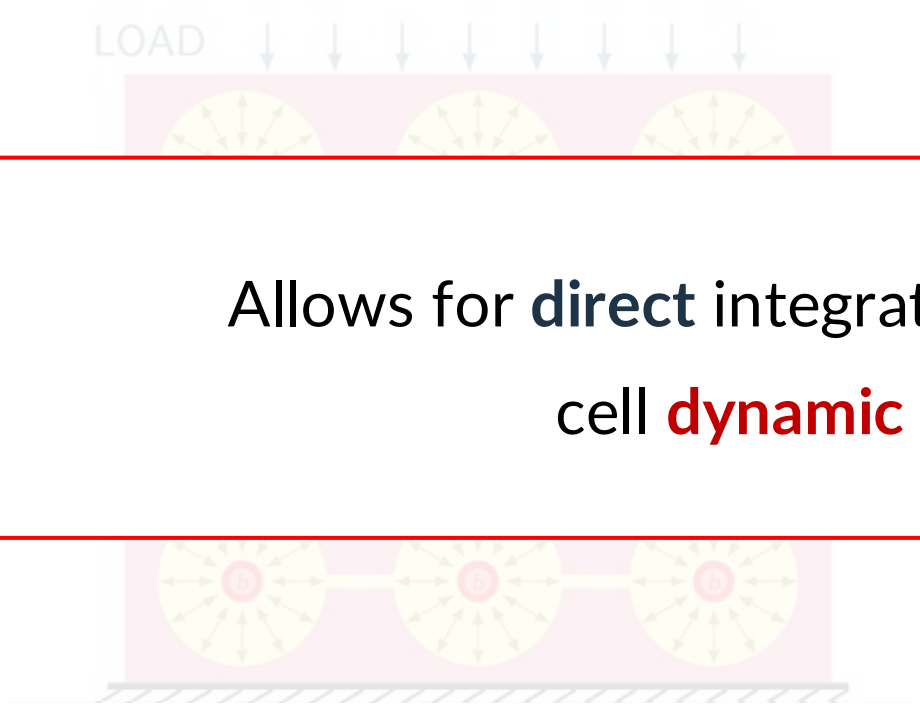

Allows for **direct** integration of **biological exchanges** and cell **dynamic death/healing** rates.

Squeezed blood vessels

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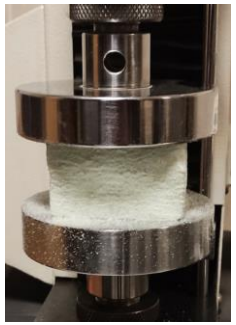
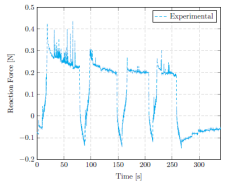
Challenging the Model

Real World



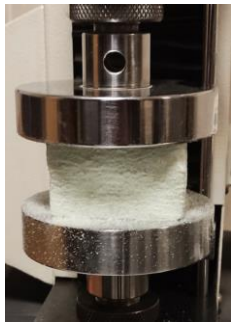


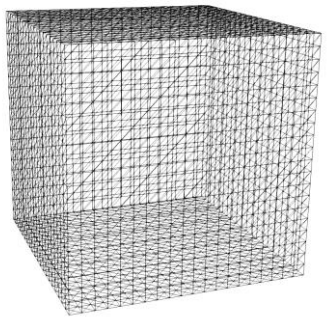
T. Lavigne et al., *JMBBM*, *IJNMBE*, 2023, 2024,2025

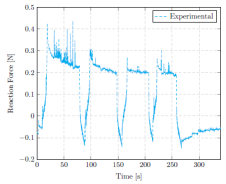
Challenging the Model

Real World

Discretized Domain







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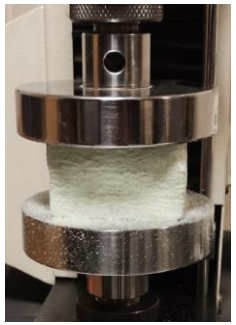

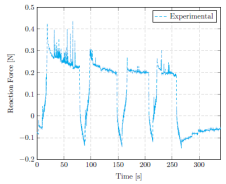

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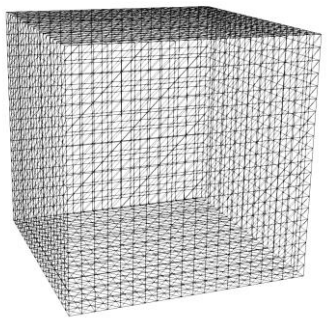


Model

Mass is conserved

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

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

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

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

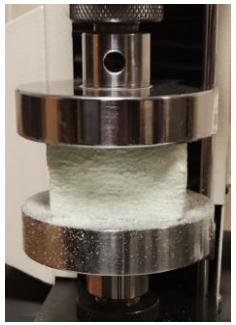
$$\int_\Omega C_{e,p}\frac{\mathrm{D}^s p^l}{\mathrm{D}t}q^b \mathrm{d}\Omega - \int_\Omega C_{e,p}C_{state}\frac{\mathrm{D}^s p^{lc}}{\mathrm{D}t}q^b \mathrm{d}\Omega - \int_\Omega C_{e,p}\frac{\mathrm{D}^s p^b}{\mathrm{D}t}q^b \mathrm{d}\Omega + \int_\Omega \frac{k^b}{\mu^b}\nabla p^b \nabla q^b \mathrm{d}\Omega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

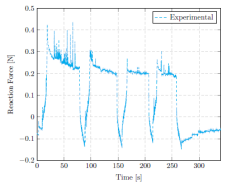
$$\int_\Omega \mathbf{t}^{\text{eff}}(\mathbf{u}^s):\nabla\mathbf{w}\mathrm{d}\Omega - \int_\Omega (1-\varepsilon^b)(p^l - S^c p^{lc})\nabla\cdot\mathbf{w}\mathrm{d}\Omega - \int_\Omega \varepsilon^b p^b \nabla\cdot\mathbf{w}\mathrm{d}\Omega - \int_{\Gamma_s} \mathbf{t}^{\text{imposed}}\cdot\mathbf{w}\mathrm{d}\Gamma_s = 0, \forall\mathbf{w}\in\left[H^1(\Omega)\right]^3$$

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

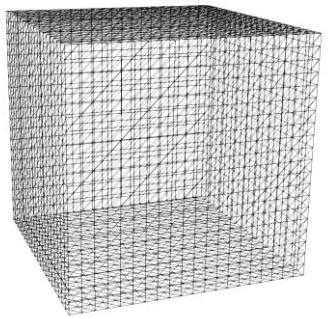
Challenging the Model

Real World





Discretized Domain



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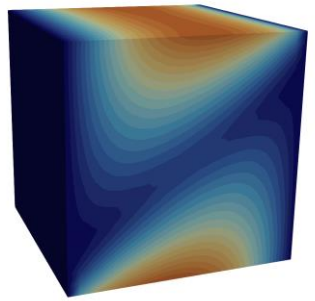
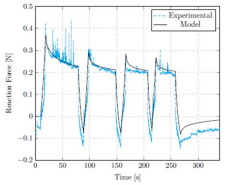
Computed Fields

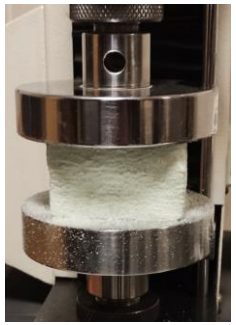


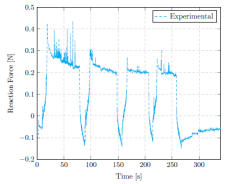


T. Lavigne et al., *JMBBM*, *IJNMBE*, 2023, 2024,2025

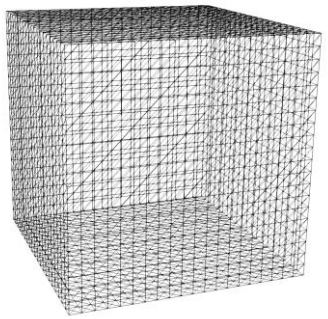
Challenging the Model

Real World





Discretized Domain



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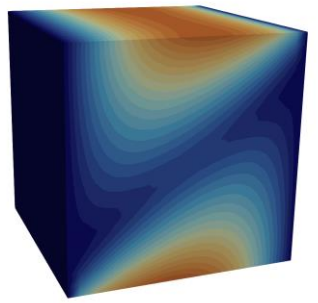
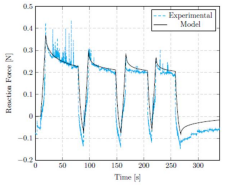
Computed Fields





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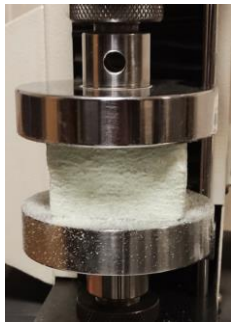
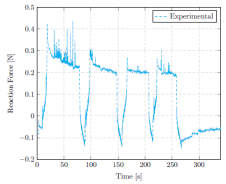
T. Lavigne et al., *JMBBM*, *IJNMBE*, 2023, 2024,2025

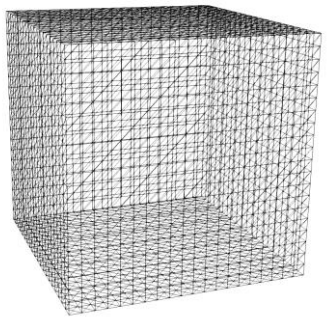
Challenging the Model

Real World





Discretized Domain



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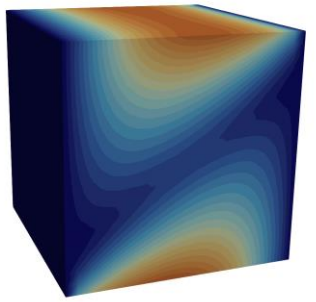
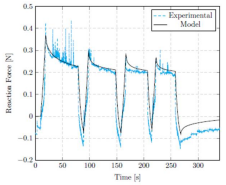
Computed Fields





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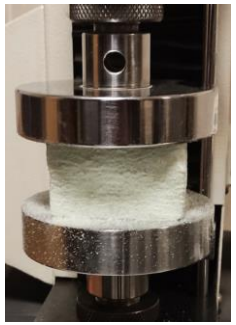
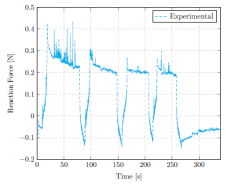
T. Lavigne et al., *JMBBM*, *IJNMBE*, 2023, 2024,2025

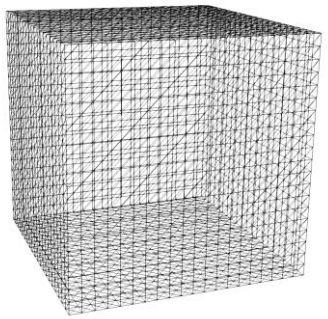
Challenging the Model

Real World





Discretized Domain



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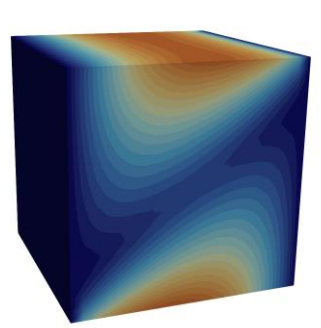

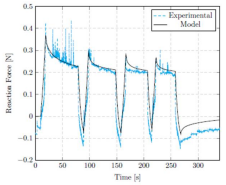

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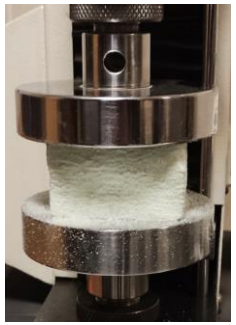
In silico Evaluation

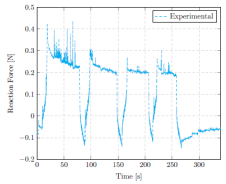
Refine the Permeability (fluid ability to move) parameter from porous imaging and numerical phantoms.
(T. Lavigne et al., *Arxiv*, 2025)

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

Challenging the Model

Real World





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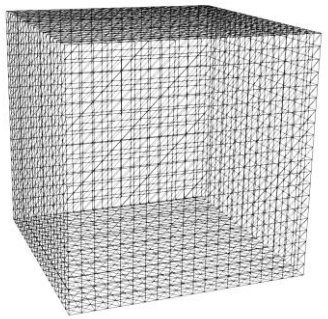

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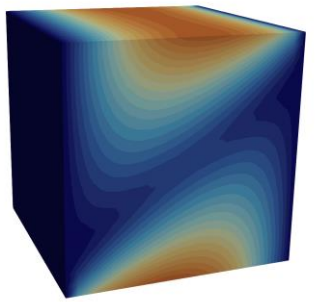
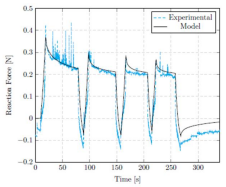
Computed Fields





Future outlook

Quantitative risk assessment.

Digital Twins inform on each specific risk scale.

Perspective of my work

New set of Parameters

Patient-Specific Calibration

Identification of parameters minimizing the error between Experimental and **Numerical** outputs (T. Lavigne et al., 2025a)

Sensitivity Analysis

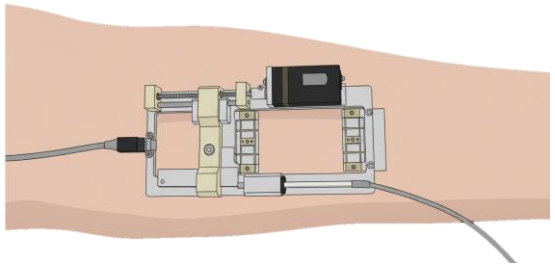
Random Variation of Parameters and impact assessment (T. Lavigne et al., 2025b)

In silico Evaluation

Refine the Permeability (fluid ability to move) parameter from porous imaging and numerical phantoms.
(T. Lavigne et al., *Arxiv*, 2025)

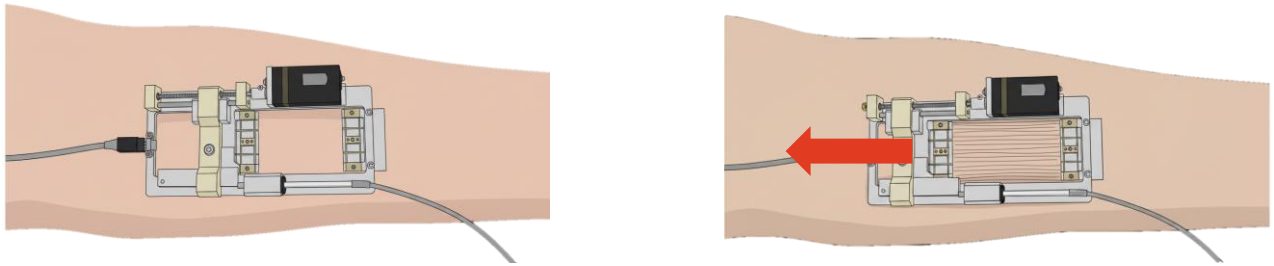
T. Lavigne et al., *JMBBM*, *IJNMBE*, 2023, 2024,2025

In Vivo Evaluation: Hold phase



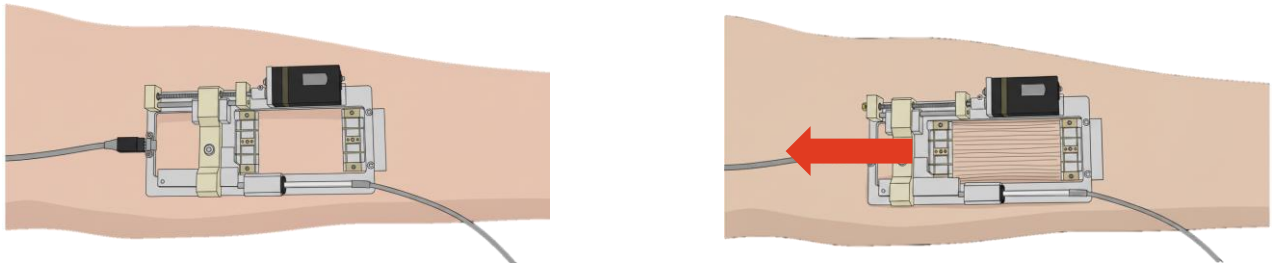
T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025a

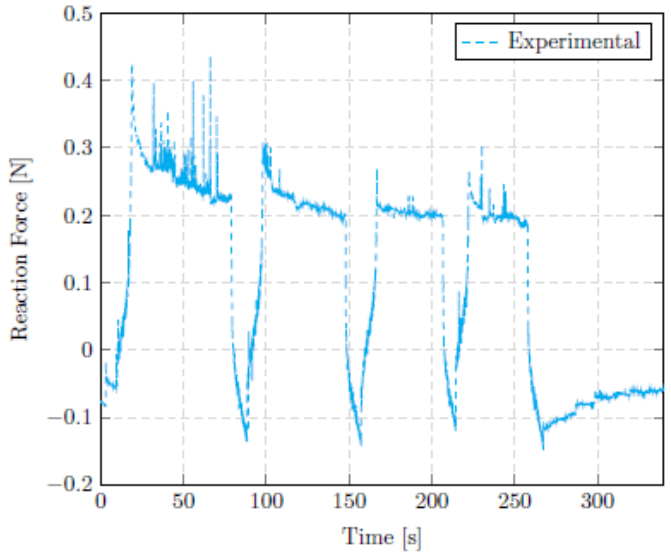
In Vivo Evaluation: Hold phase



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

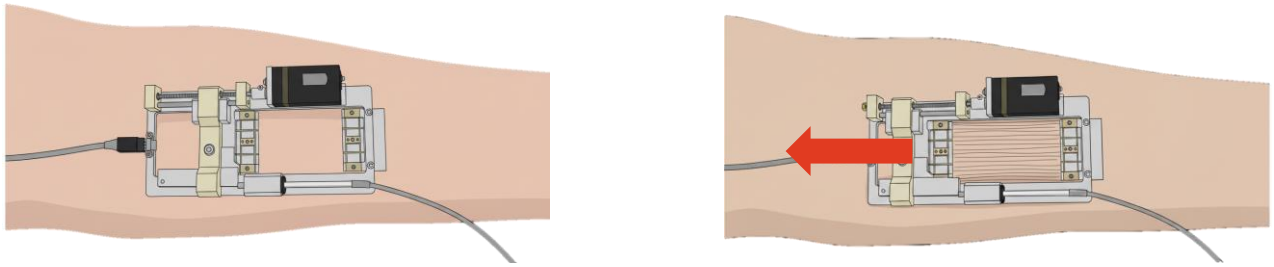
In Vivo Evaluation: Hold phase

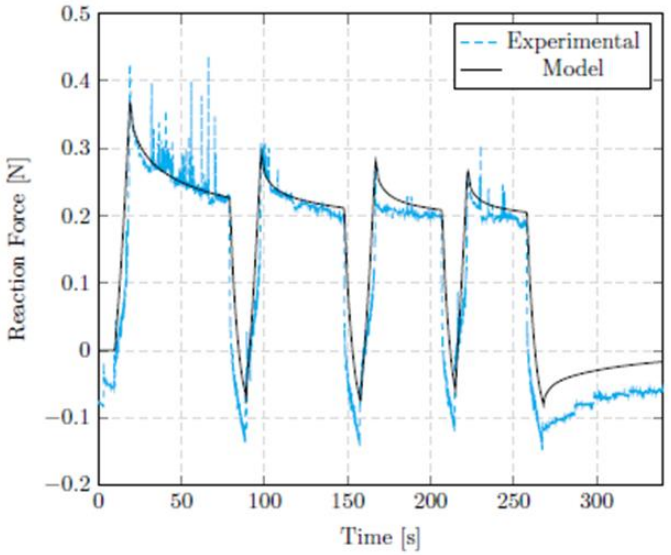




T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025a

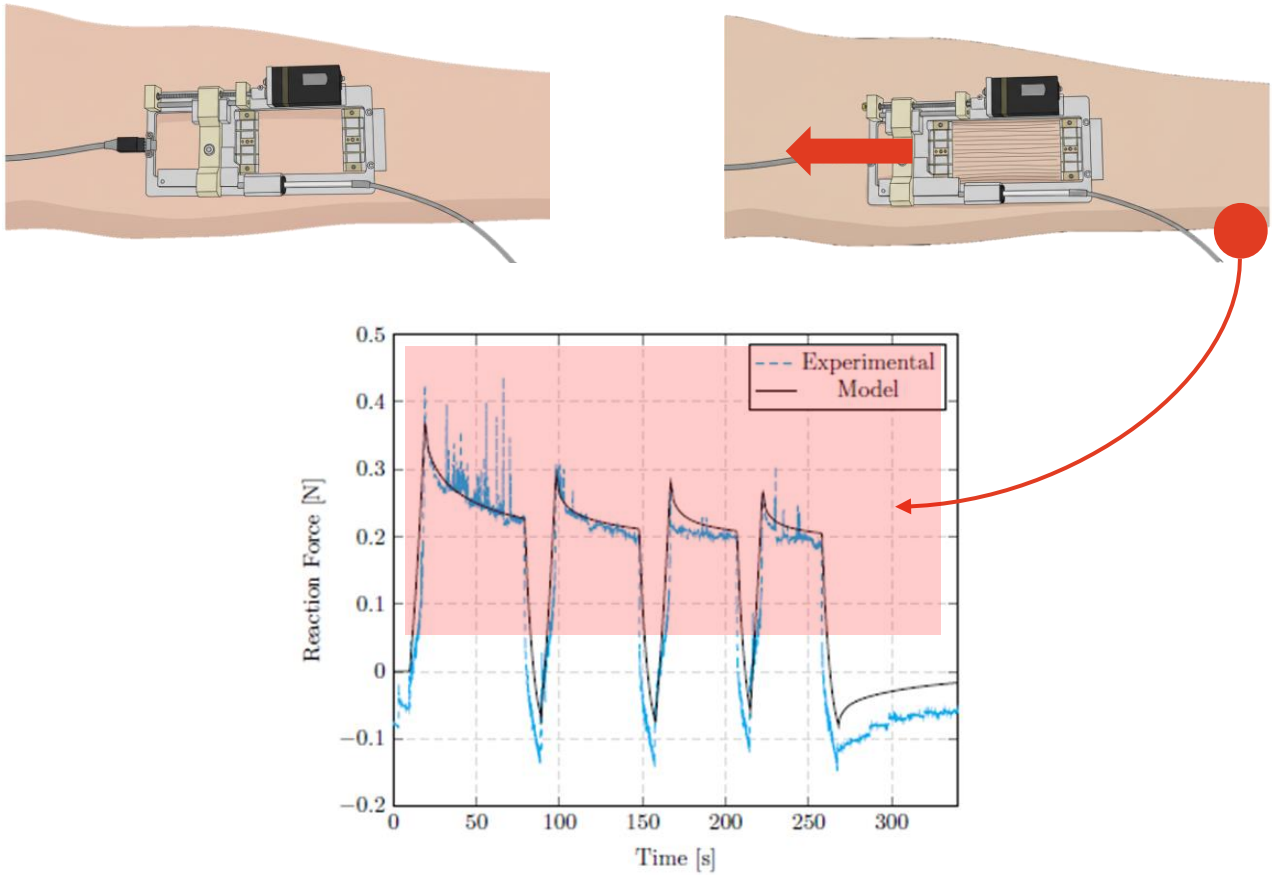
In Vivo Evaluation: Hold phase





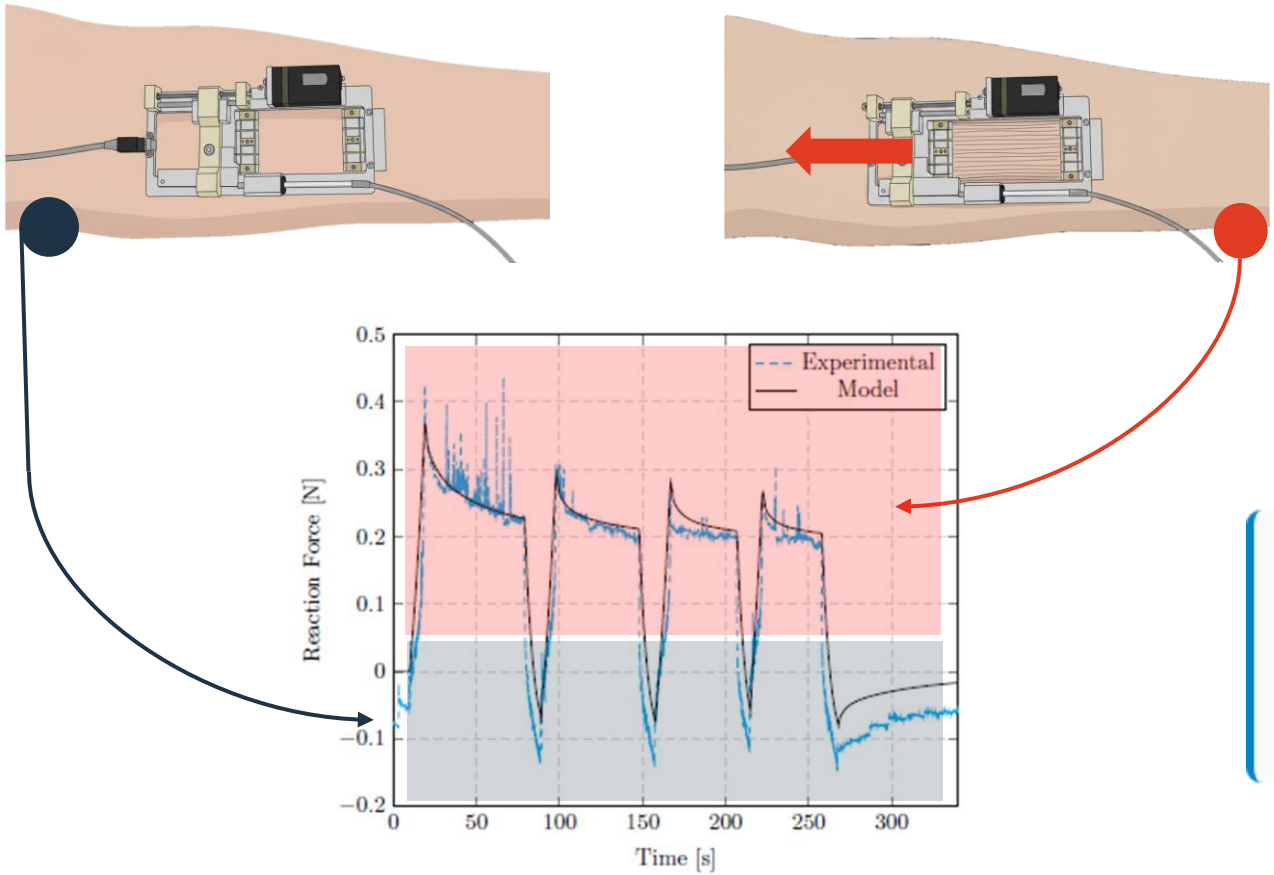
T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025a

In Vivo Evaluation: Hold phase



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

In Vivo Evaluation: Hold phase



Physics matches reality.

Patient Specific Mechanical Properties.

Poromechanics as an alternative to empirical viscoelasticity.

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

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

In Vivo Evaluation: Perfusion vs Mechanics

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

11 Human Volunteers

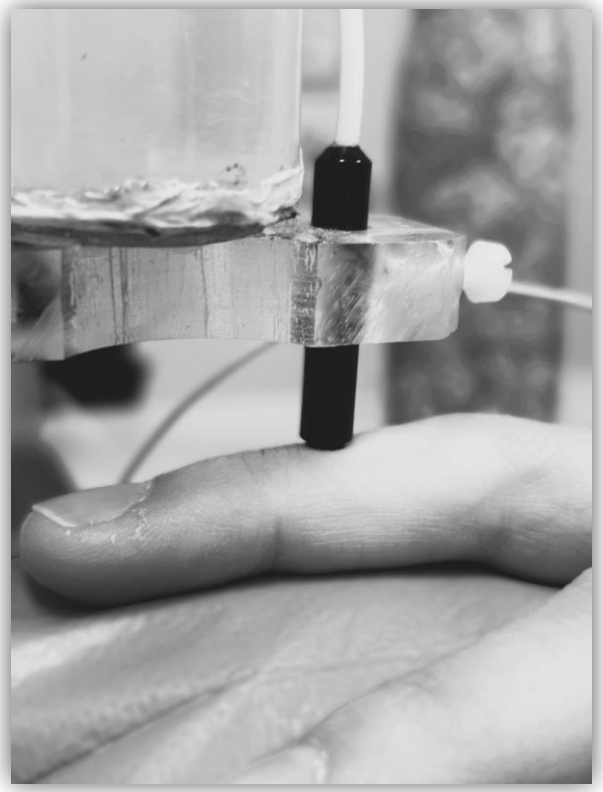
Gender-Inclusive Cohort

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

In Vivo Evaluation: Perfusion vs Mechanics

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

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

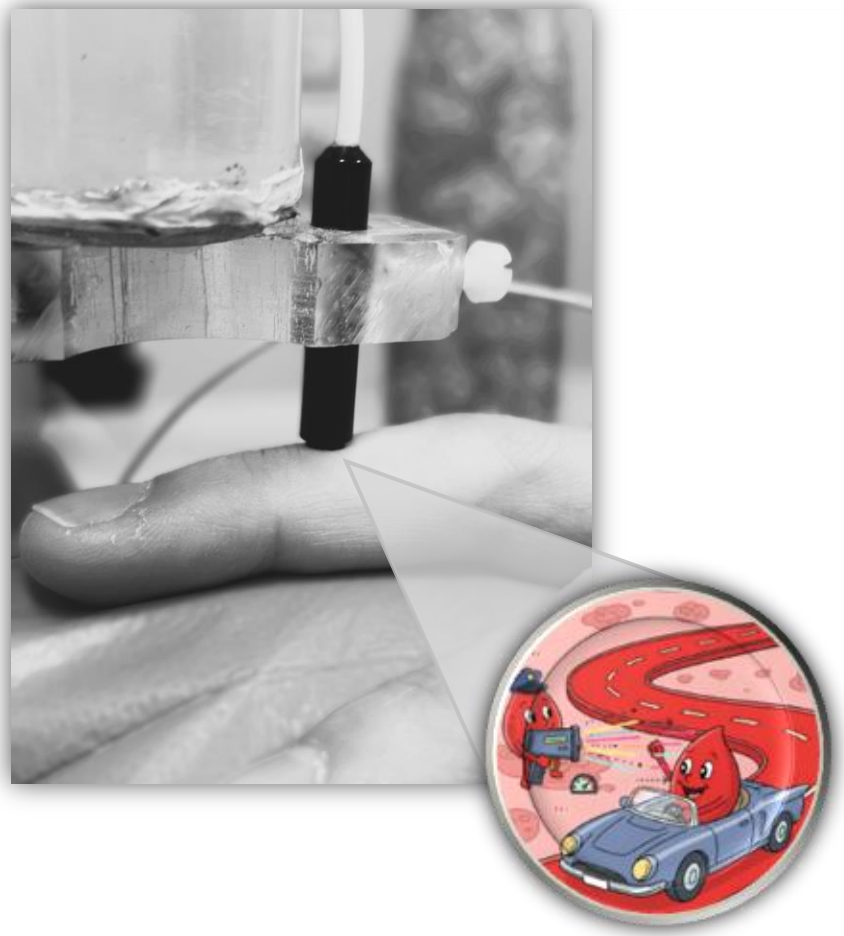


T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025b

In Vivo Evaluation: Perfusion vs Mechanics

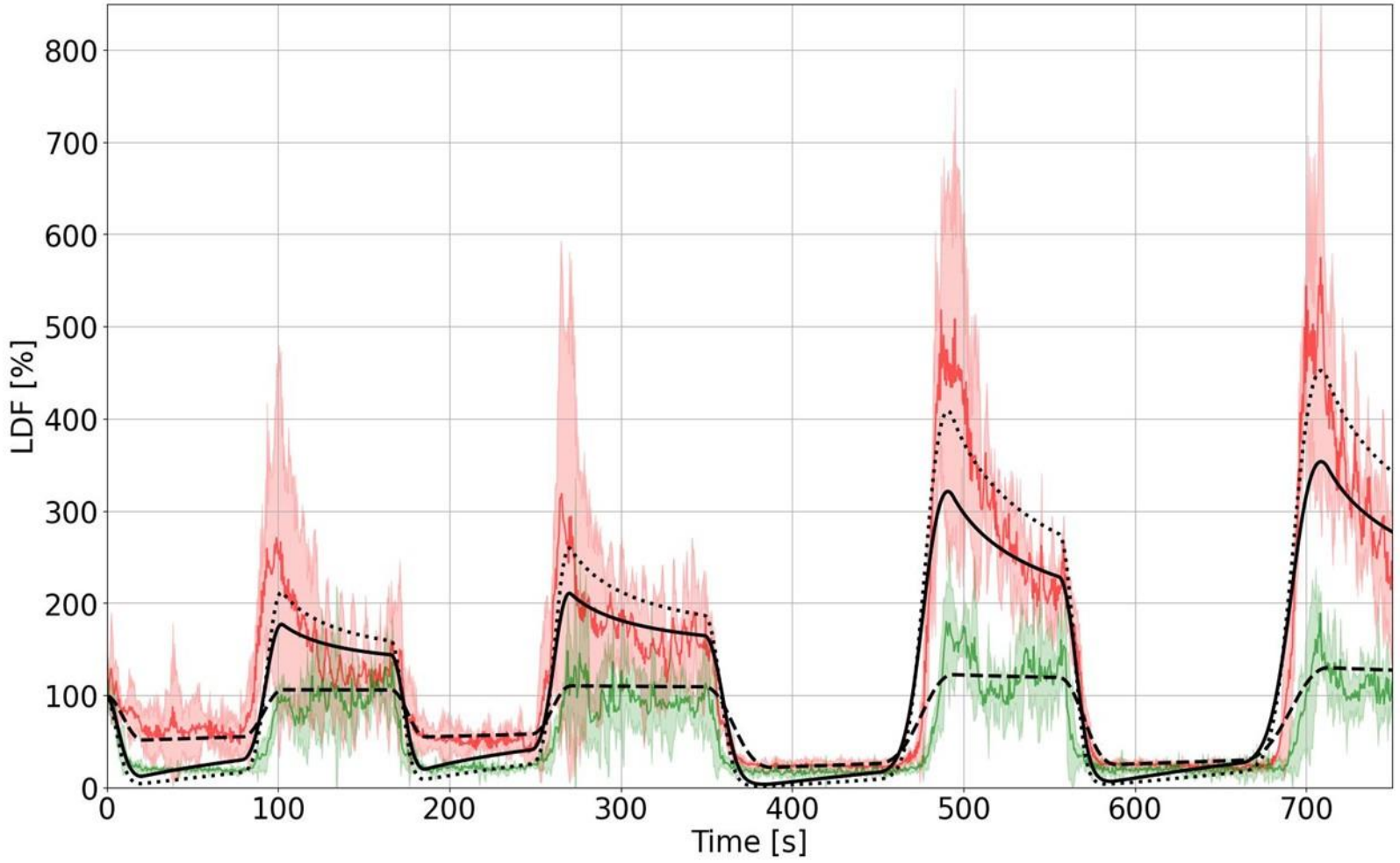
Ethical approval (national registration number RCB: 2023- A00418- 37)

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



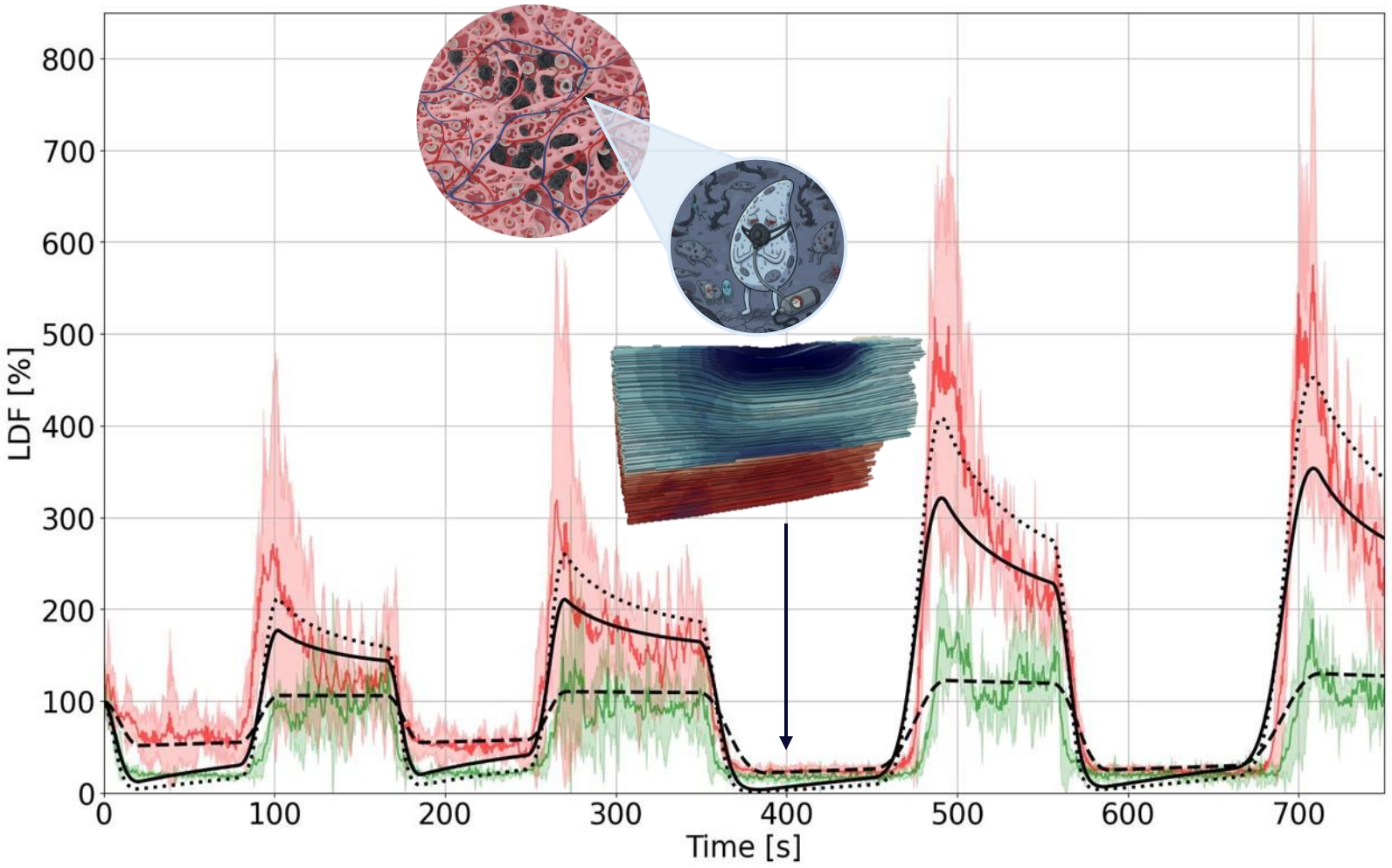
T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025b

In Vivo Evaluation: Perfusion vs Mechanics



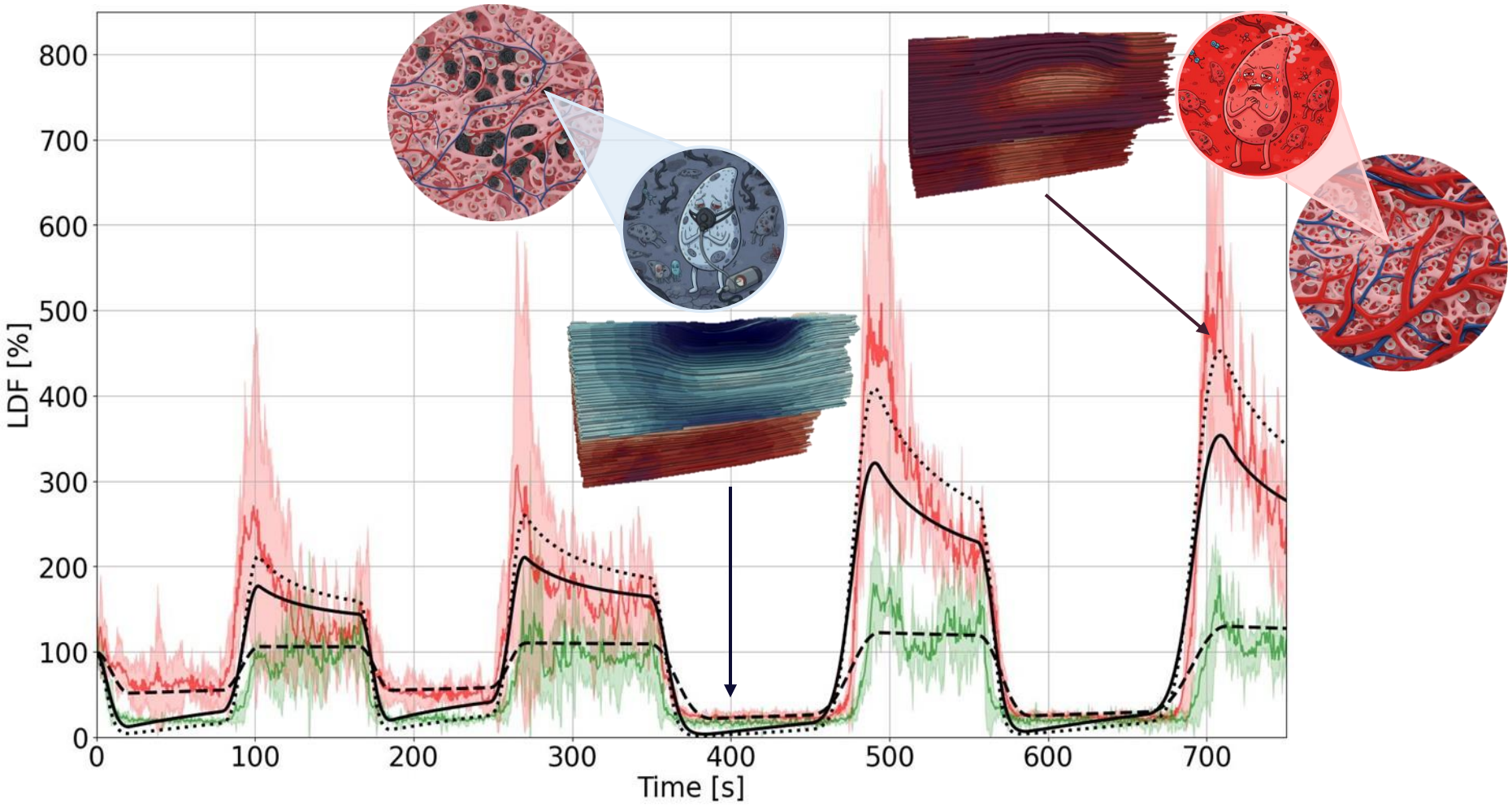
T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025b

In Vivo Evaluation: Perfusion vs Mechanics



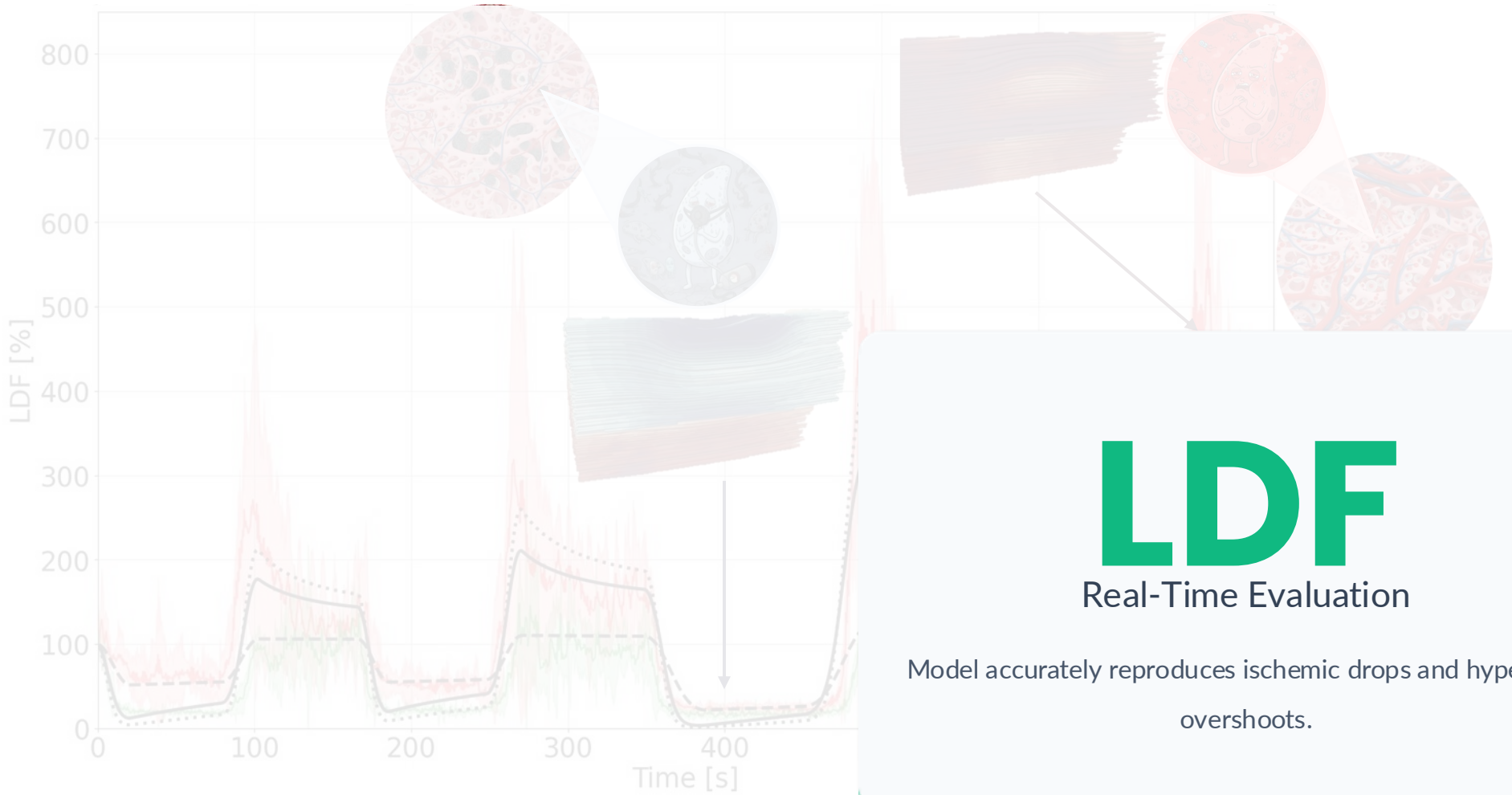
T. Lavigne et al., *Int. J. Numer. Method. Biomed. Eng.*, 2025b

In Vivo Evaluation: Perfusion vs Mechanics



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

In Vivo Evaluation: Perfusion vs Mechanics



LDF

Real-Time Evaluation

Model accurately reproduces ischemic drops and hyperemic overshoots.

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

Impact & Open Science

Output

6 Journal Articles

2025 Excellent Thesis Award
Best Poster (2nd), PhD Day '24

Open Source

FEniCSx & GitHub

Inria: "Reproducible Research"
Anonymised and available data

Impact & Open Science

Output

6 Journal Articles

2025 Excellent Thesis Award
Best Poster (2nd), PhD Day '24

Open Source

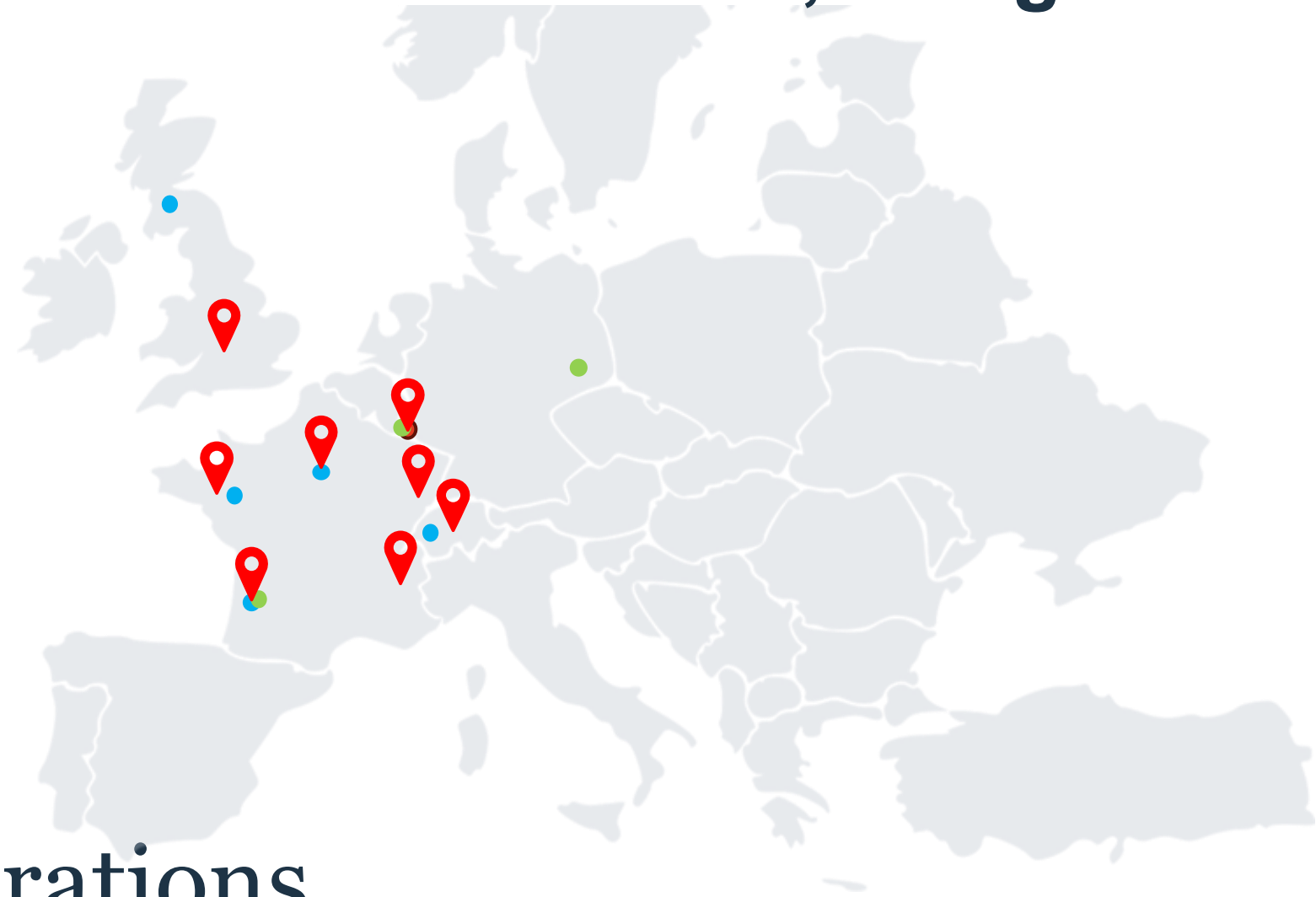
FEniCSx & GitHub

Inria: "Reproducible Research"
Anonymised and available data

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

Invited Talks and Conferences, and global Collabs.

Invited Talks and Conferences, and global Collabs.



Collaborations

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 / ENSAM / I2M · AFR-FNR

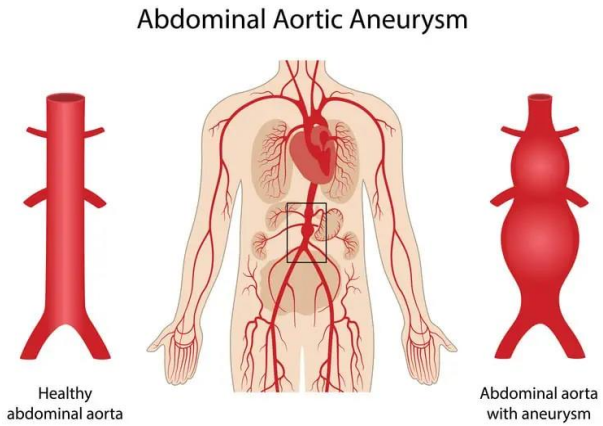
2025 – 2025 — **Post-Doctoral Researcher**
Univ. Bordeaux, I2M

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

From Foundation to Multi-Organ Application

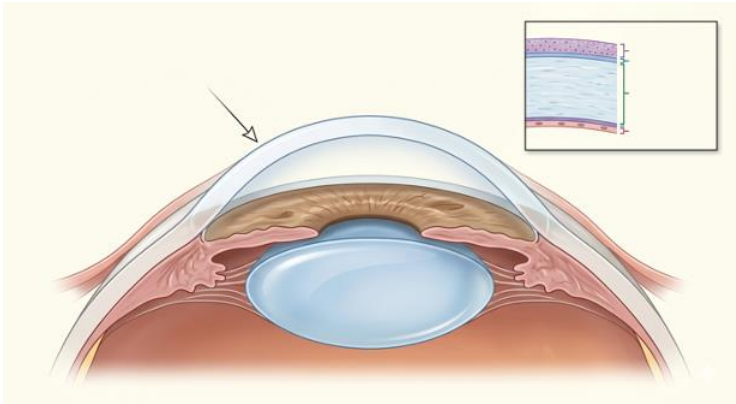
Brain Glioblastoma

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.

#uni.lu

Information: www.uni.lu
Virtual Tour: www.virtualtour.uni.lu

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socialmedia.uni.lu

Thank You!

"Predict ulcers before the tissue dies."

https://th0maslavigne.github.io

AFR-FNR Grant #17013812

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Lavigne T, Biomechanical Modeling of Human skin: a Hierarchical Porous Media Framework. PhD, Biomechanical Response of Human Skin : A Hierarchical Porous Media Framework. | Theses.fr

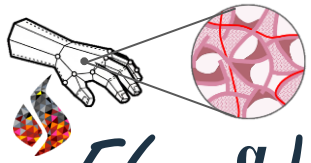
Fredriksson, I., M. Larsson, and T. Strömberg (2009). “Measurement depth and volume in laser Doppler flowmetry”. In: Microvascular Research 78.1, pp. 4–13.

Parvizi, A., S. Haddadi, A. Mollaei, P. Ghorbani Vajargah, P. Takasi, M. Firooz, S. J. Hosseini, R. Farzan, and S. Karkhah (2023). “A systematic review of nurses’ knowledge and related factors towards the prevention of medical device-related pressure ulcers”. In: International Wound Journal 20.7, pp. 2843–2854.

Vanderwee, K., M. Clark, C. Dealey, L. Gunningberg, and T. Defloor (2007). “Pressure ulcer prevalence in Europe: a pilot study”. In: Journal of Evaluation in Clinical Practice 13.2, pp. 227–235

Bi-Compartment Porous Model

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

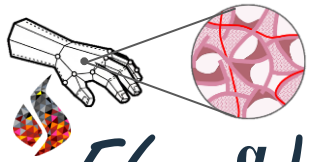
$$\nabla \cdot \sigma_{tot} = 0$$

Constitutive Laws

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

Bi-Compartment Porous Model

The Model: what is behind?



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

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

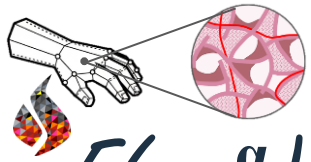
Solid

Stress-Strain law

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

Bi-Compartment Porous Model

The Model: what is behind?



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

Conservation Laws

Mass Conservation

Solid | Cells | IF

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

Force Equilibrium

Total stress

Darcy IF | Darcy Cells

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

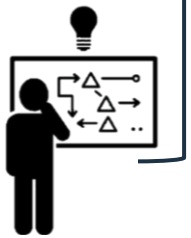
Constitutive Laws

Solid

Stress-Strain law

Pores

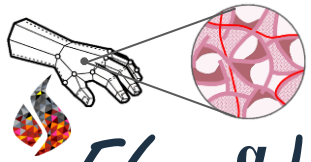
IF pressure / Cell Saturation



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

Bi-Compartment Porous Model

The Model: what is behind?



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

Conservation Laws

Mass Conservation

Solid | Cells | Oxygen

IF

Blood

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

Force Equilibrium

Total stress | Darcy Blood

Darcy IF | Darcy Cells

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

Constitutive Laws

Solid

Stress-Strain law

Pores

IF pressure / Cell Saturation

Vascular phase

Porosity | Permeability

Oxygen

Diff. Oxygen | Abs. Oxyge

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

Bi-Compartment Porous Model

The Analytical approach directly **links** macroscopic **mechanical loading** to microscopic **ischemia** through coupled physical laws, computed efficiently via the open-source FEniCSx.

T. Lavigne et al., *JMBBM*, 2023

Bi-Compartment Porous Model

The Analytical approach directly **links** macroscopic **mechanical loading** to microscopic **ischemia** through coupled physical laws, computed efficiently via the open-source FEniCSx.

Mass Conservation

$$\frac{\partial \varepsilon_\alpha}{\partial t} + \nabla \cdot (\varepsilon_\alpha v_\alpha) = 0$$

T. Lavigne et al., *JMBBM*, 2023

Bi-Compartment Porous Model

The Analytical approach directly **links** macroscopic **mechanical loading** to microscopic **ischemia** through coupled physical laws, computed efficiently via the open-source FEniCSx.

Force Equilibrium (Solid)

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

Mass Conservation

$$\frac{\partial \varepsilon_\alpha}{\partial t} + \nabla \cdot (\varepsilon_\alpha v_\alpha) = 0$$

T. Lavigne et al., *JMBBM*, 2023

Bi-Compartment Porous Model

The Analytical approach directly **links** macroscopic **mechanical loading** to microscopic **ischemia** through coupled physical laws, computed efficiently via the open-source FEniCSx.

Mass Conservation

$$\frac{\partial \varepsilon_\alpha}{\partial t} + \nabla \cdot (\varepsilon_\alpha v_\alpha) = 0$$

Force Equilibrium (Solid)

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

Darcy Flow (Fluid Velocity)

$$v_\alpha = -\frac{K_\alpha}{\mu_\alpha} \nabla P_\alpha$$

T. Lavigne et al., *JMBBM*, 2023

Who is at risk ?

You might know concerned people:

Diabetic Foot Ulcer

My uncle (>60y) developed an ulcer **despite wearing specialized medical shoes**.

Who is at risk ?

You might know concerned people:

Diabetic Foot Ulcer

My uncle (>60y) developed an ulcer **despite wearing specialized medical shoes**.

Wheelchair User

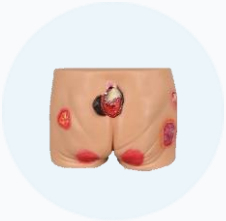
A 40y-o patient spent **1 year** in the hospital treating an ulcer... only for a new one to develop after **just 1 week** at home.

Who is at risk ?

You might know concerned people:

Diabetic Foot Ulcer

My uncle (>60y) developed an ulcer **despite wearing specialized medical shoes**.



Wheelchair User

A 40y-o patient spent **1 year** in the hospital treating an ulcer... only for a new one to develop after **just 1 week** at home.

Similar Disease

My own pilonidal cyst surgery resulted in **long-term healing** and **limited mobility**. (Common in teenagers).

Image Sources

https://www.researchgate.net/figure/MAP-OF-THE-PRESSURE-DISTRIBUTION-ON-THE-RESIDUAL-LIMB_fig4_322392490

Source: www.researchgate.net

https://static.vecteezy.com/system/resources/previews/072/510/390/non_2x/caring-doctor-attentively-discusses-patient-care-with-elderly-woman-resting-in-bright-hospital-room-fostering-trust-and-hope-photo.jpeg

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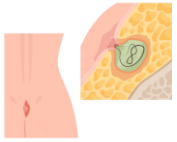

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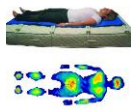
Image Sources



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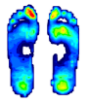
https://www.mescan.com/positionnement-confort

Source: www.mescan.com



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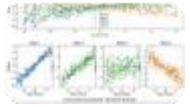
Source: www.ultrassist.com



https://www.mdpi.com/algorithms/algorithms-18-00443/article_deploy/html/images/algorithms-18-00443-g005-550.jpg

Source: www.mdpi.com

https://organicmerchant.com.au/wp-content/uploads/2024/07/sea-sponge-squeezed-in-hand.webp

Source: organicmerchant.com.au

Skin as a Sponge

How pressure kills blood flow — and how patient-specific modeling can stop it.

Thomas Lavigne[1,2,3], PhD

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

1: University of Luxembourg, Doctoral School in Science and Engineering (DSSE)

2: Ecole Nationale Supérieure d'Arts et Métiers, Ecole Doctorale Sciences et Métiers de l'ingénieur (ED SMI)

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