A Physiologically Inspired Computationally Efficient Compartmental Model for the Gastrointestinal System

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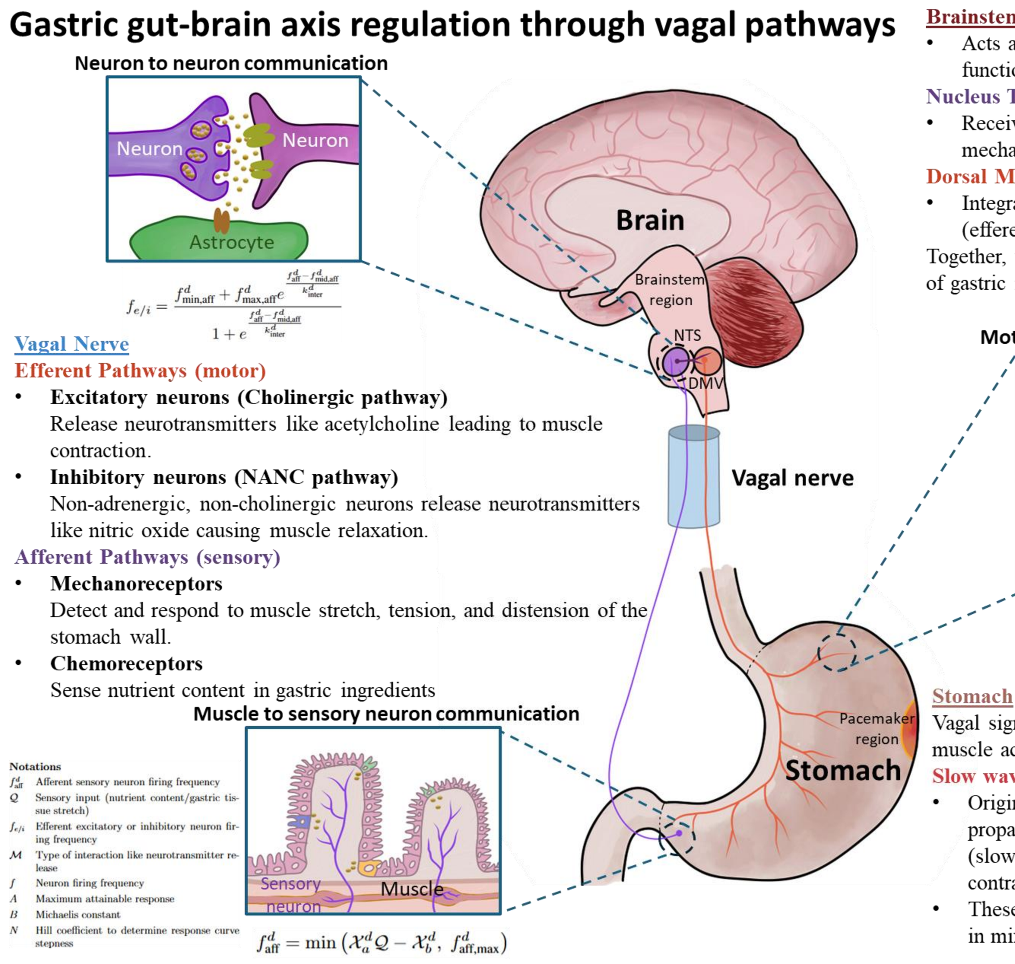
Introduction

- My research focuses on developing physiologically inspired, computationally efficient models of the gastrointestinal (GI) system.
- I integrate principles from systems biology, biomechanics, and control theory to understand and modulate GI motility and function.
- Using a computationally cheap compartmental modeling framework, I simulate coupled electrical, mechanical, and fluid processes that drive gastric motility and emptying by using just ordinary differential equations (ODEs) and algebraic equations.
- I have employed finite element (FEM) and finite volume (FVM) methods to verify and validate the derived reduced-order equations, ensuring physical accuracy and consistency with detailed biomechanical models.
- Since this framework is grounded by biophysics, it eliminates the need for large datasets—making it particularly valuable when human data are limited, unlike data-hungry AI approaches.
- The universal nature of the governing equations allows the model to be readily extended, with minor modifications, to simulate other organs such as the intestine, esophagus, or even cardiac tissue.
- My current work explores closed-loop vagal nerve stimulation (VNS) for personalized modulation of GI activity.
- I aim to extend this framework to build digital twins of the GI tract for improving experimental efficiency and patient-specific modeling.
- Through this research, I seek to bridge computational modeling, neural control, and precision medicine, advancing next-generation therapies for GI disorders.

Vagal Pathways Modeling

Gastric gut-brain axis regulation through vagal pathways



$$f_{e/i} = \frac{f^d_{\mathrm{min,aff}} + f^d_{\mathrm{max,aff}} e^{\frac{f^d_{\mathrm{aff}} - f^d_{\mathrm{mid,aff}}}{k^d_{\mathrm{inter}}}}}{1 + e^{\frac{f^d_{\mathrm{aff}} - f^d_{\mathrm{mid,aff}}}{k^d_{\mathrm{inter}}}}}$$

Vagal Nerve

Efferent Pathways (motor)

- **Excitatory neurons (Cholinergic pathway)**
  Release neurotransmitters like acetylcholine leading to muscle contraction.
- **Inhibitory neurons (NANC pathway)**
  Non-adrenergic, non-cholinergic neurons release neurotransmitters like nitric oxide causing muscle relaxation.

Afferent Pathways (sensory)

- **Mechanoreceptors**
  Detect and respond to muscle stretch, tension, and distension of the stomach wall.
- **Chemoreceptors**
  Sense nutrient content in gastric ingredients

Notations

- f^d_{aff} Afferent sensory neuron firing frequency
- Q Sensory input (nutrient content/gastric tissue stretch)
- $f_{e/i}$ Efferent excitatory or inhibitory neuron firing frequency
- $\mathcal{M}$ Type of interaction like neurotransmitter release
- f Neuron firing frequency
- A Maximum attainable response
- B Michaelis constant
- N Hill coefficient to determine response curve steepness

$$f^d_{\mathrm{aff}} = \min\left(\lambda^d_{\mathcal{M}} Q - \lambda^d_b, f^d_{\mathrm{aff,max}}\right)$$

Brainstem

- Acts as the central hub for vagal control of gastric function.

Nucleus Tractus Solitarius (NTS)

- Receives sensory (afferent) inputs from vagal mechanoreceptors and chemoreceptors.

Dorsal Motor Nucleus of the Vagus (DMV)

- Integrates signals from the NTS and sends motor (efferent) commands to the stomach.

Together, the NTS–DMV circuit mediates reflex control of gastric motility through **interneuron** processing.

$$\mathcal{P}_{\mathcal{M}} = \frac{A_{\mathcal{M}} f_{\mathcal{O}}^{N_{\mathcal{M}}}}{B_{\mathcal{M}}^{N_{\mathcal{M}}} + f_{\mathcal{O}}^{N_{\mathcal{M}}}}$$

Stomach

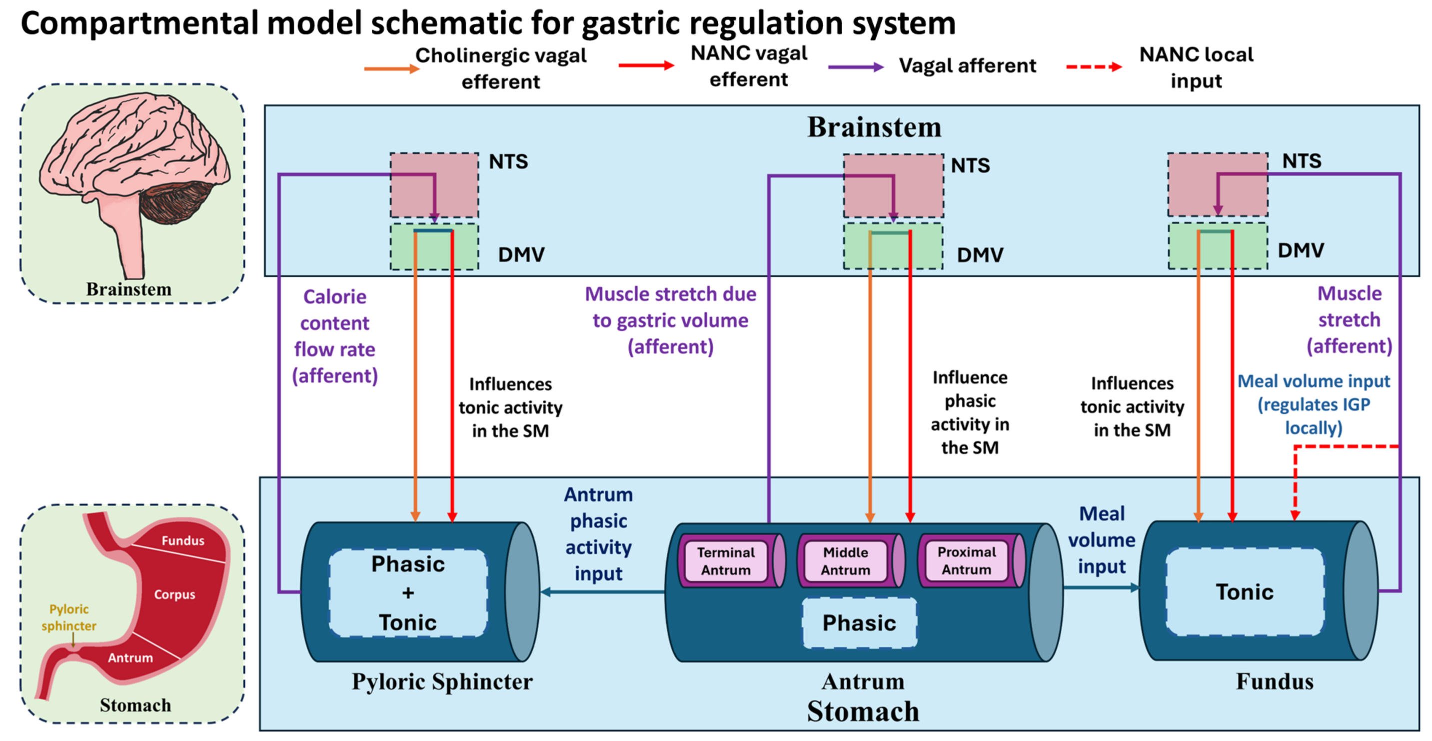
Vagal signals reach the stomach, modulating smooth muscle activity.

Slow waves

- Originate from the gastric pacemaker region and propagate toward the pylorus where action potentials (slow waves) produce coordinated muscle contractions.
- These contractions generate gastric motility, aiding in mixing and propulsion of gastric contents.

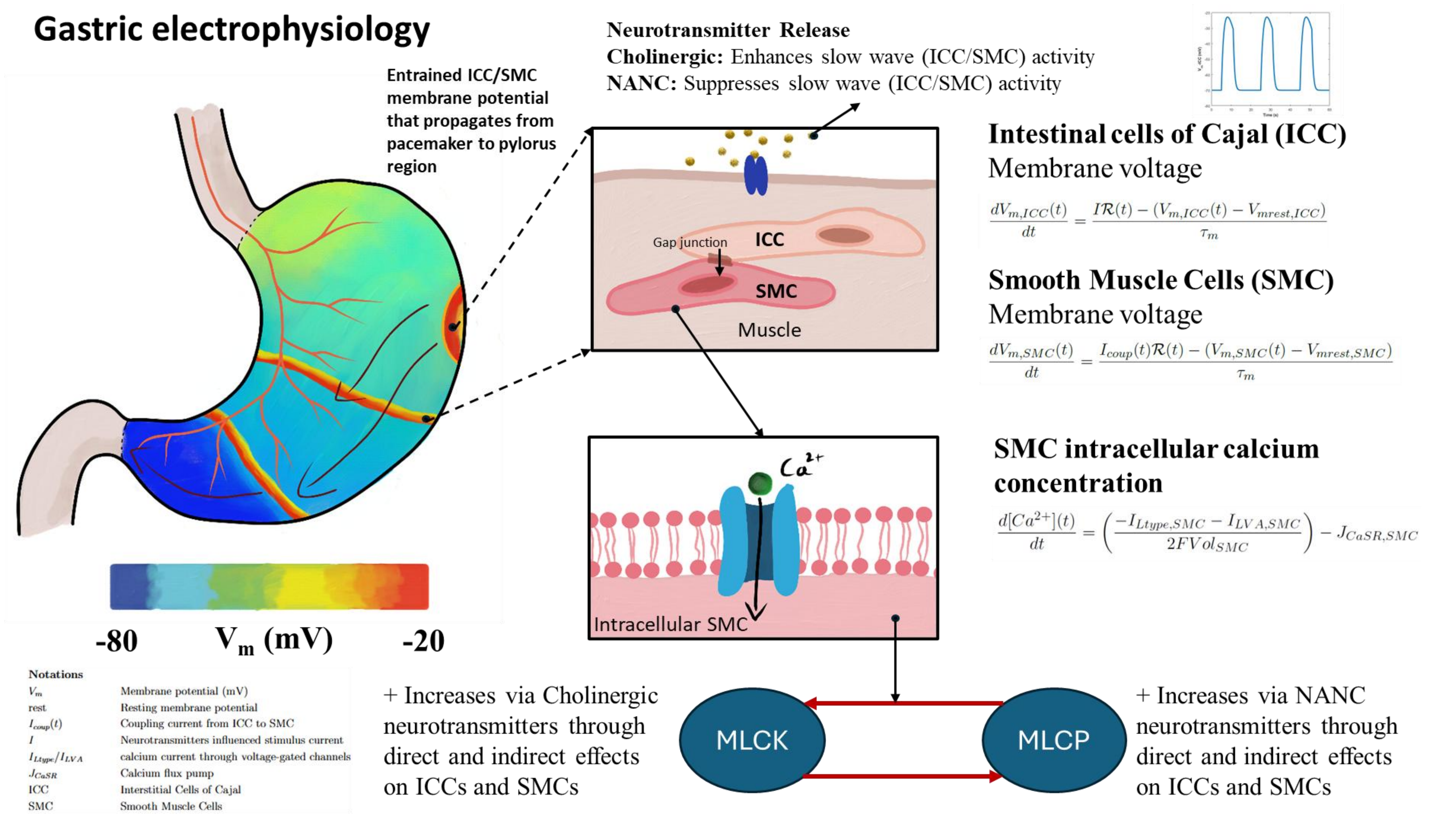
Developed Compartmental Model Framework

Compartmental model schematic for gastric regulation system

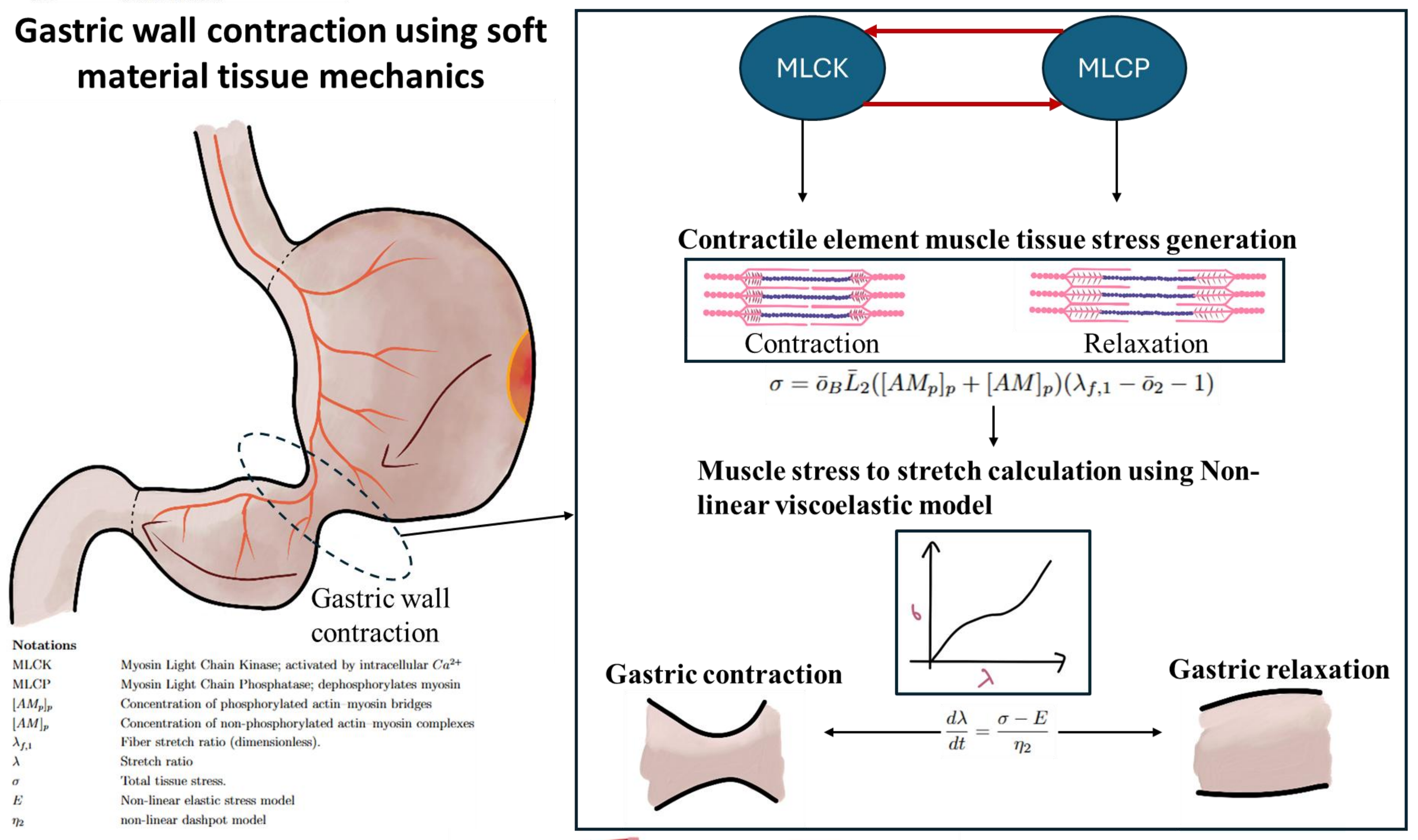


Organ Modeling

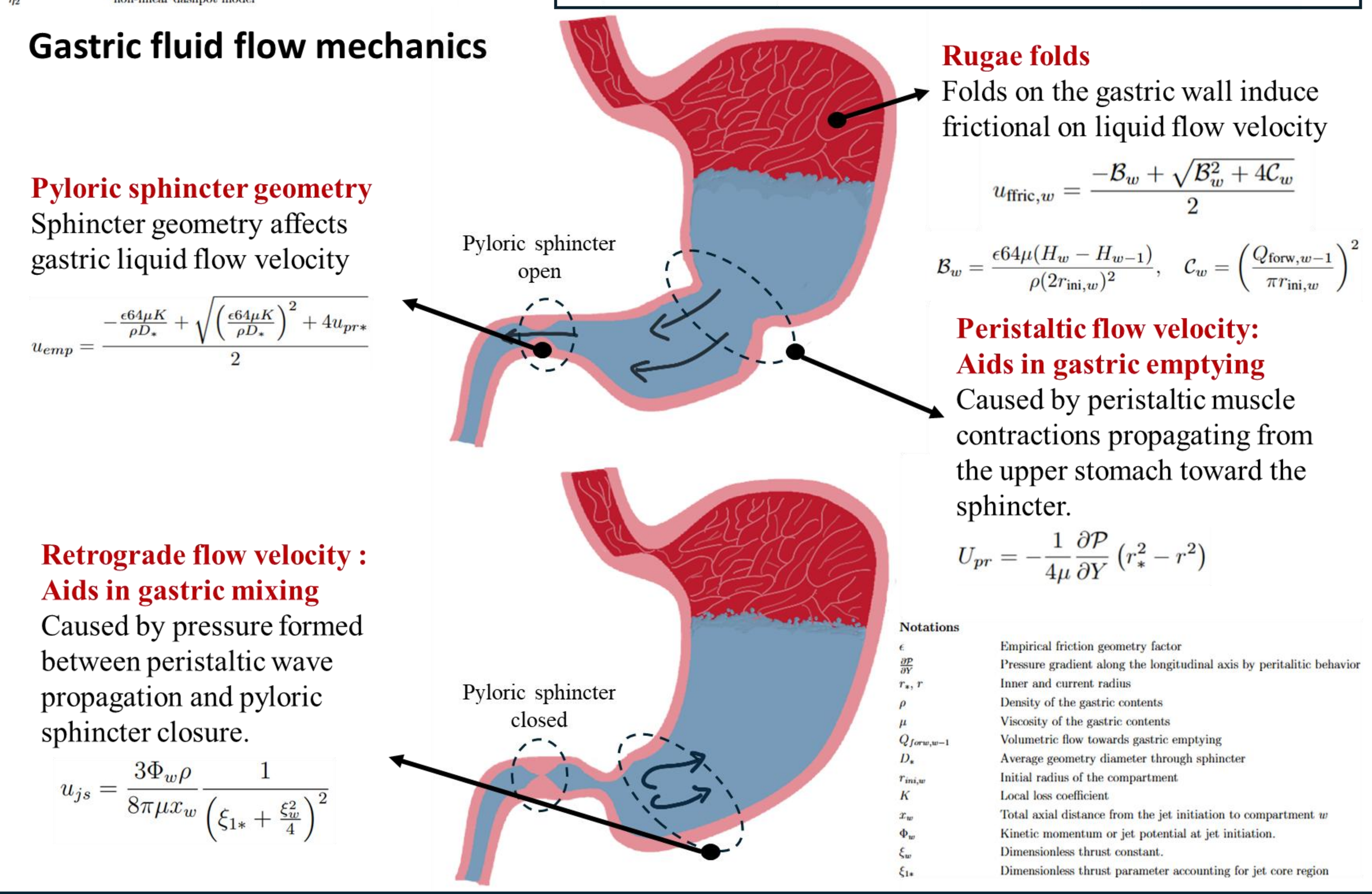
Gastric electrophysiology



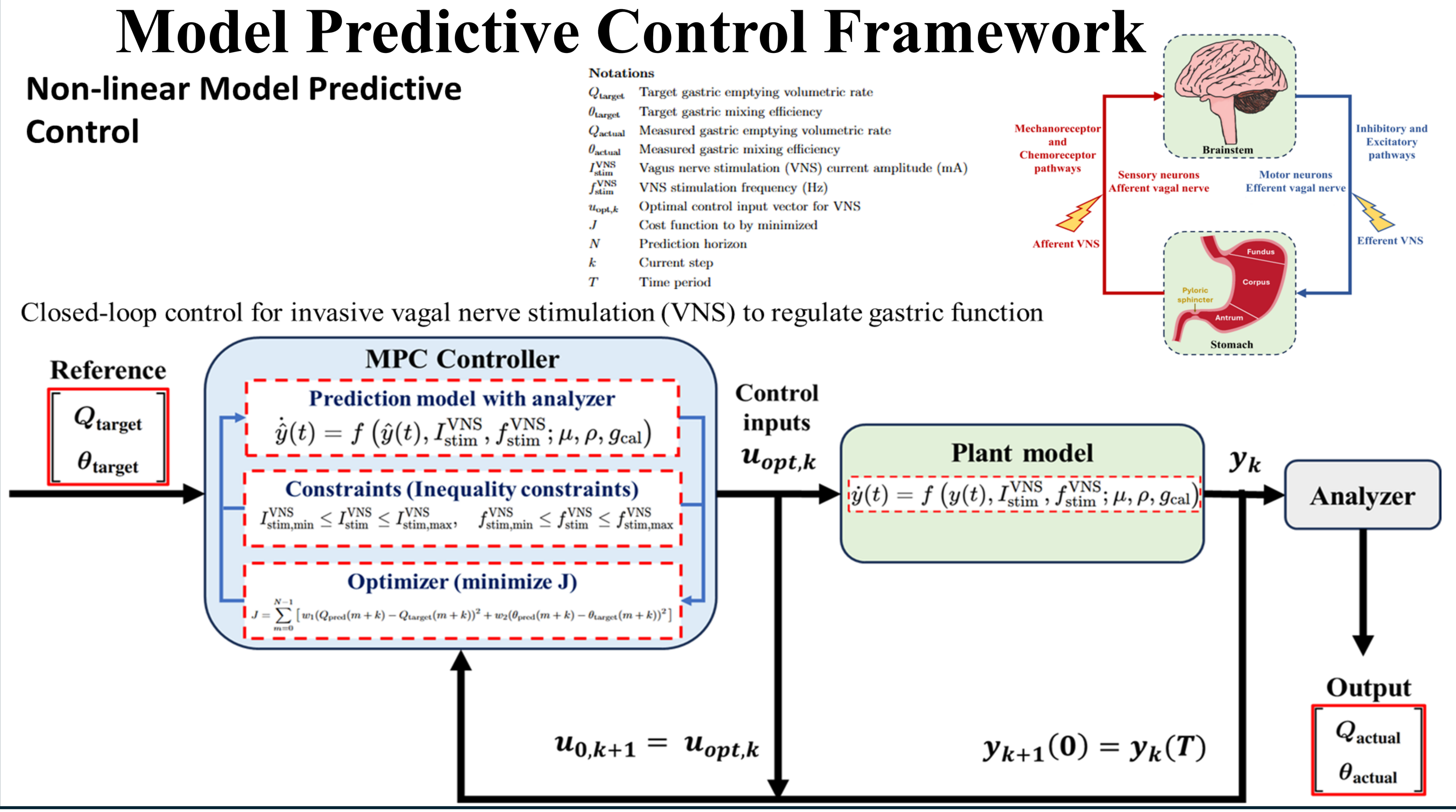
Gastric wall contraction using soft material tissue mechanics



Gastric fluid flow mechanics

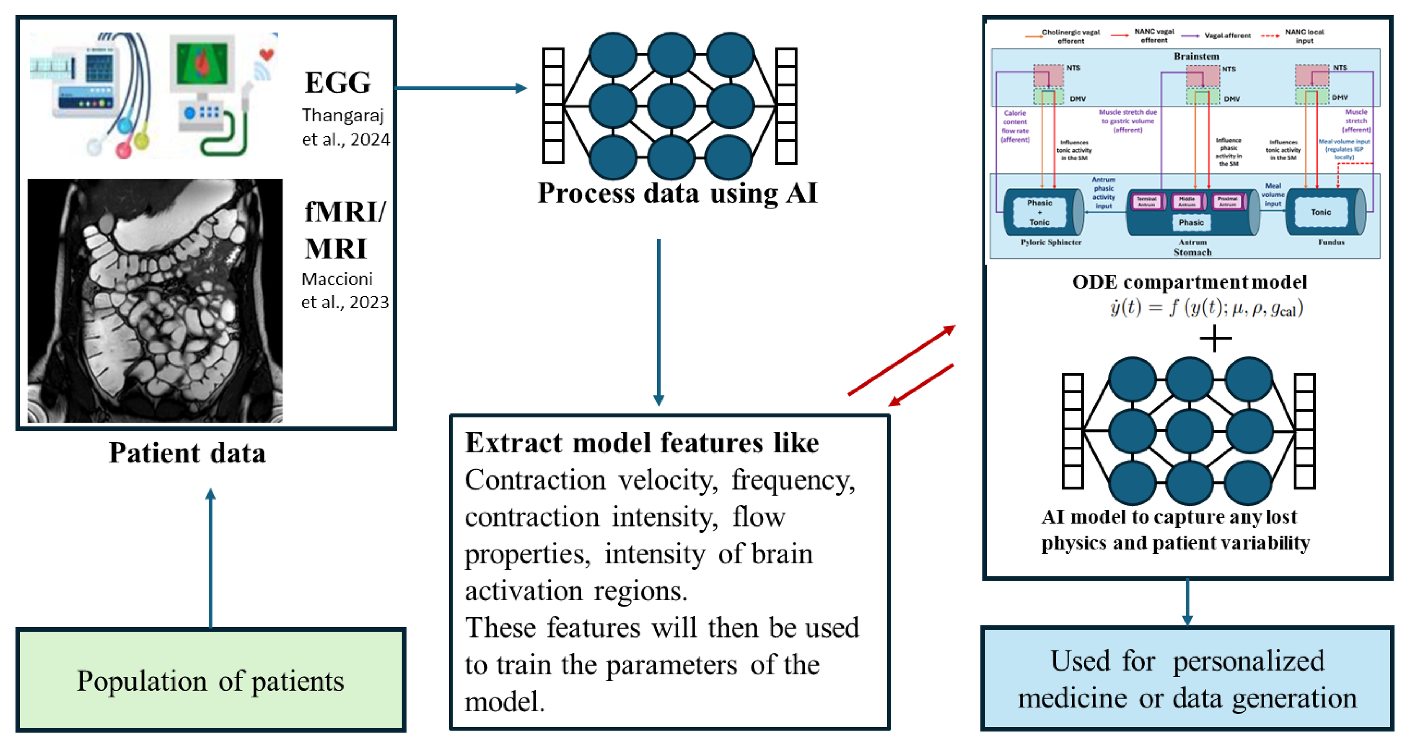


Model Predictive Control Framework

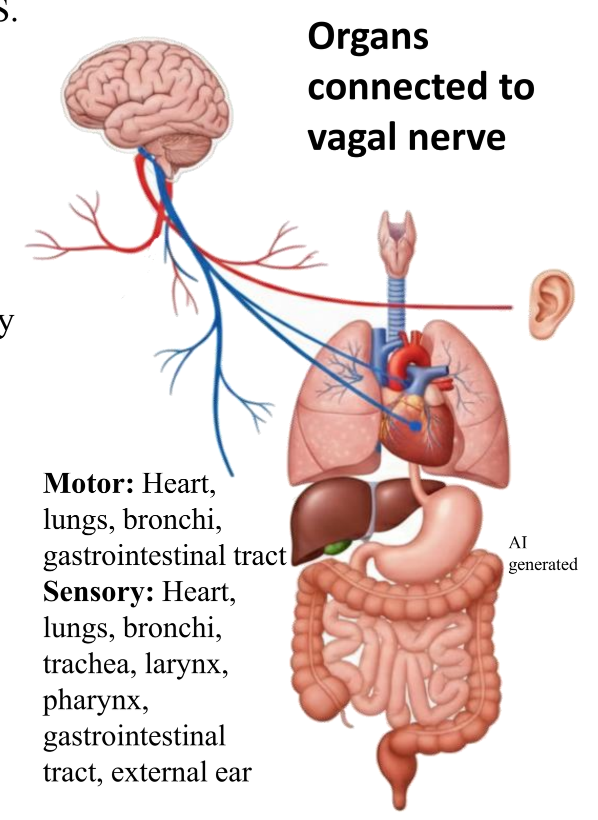


Integrating Current Modeling Approaches into Future Research Interests

Building digital-twins for therapy

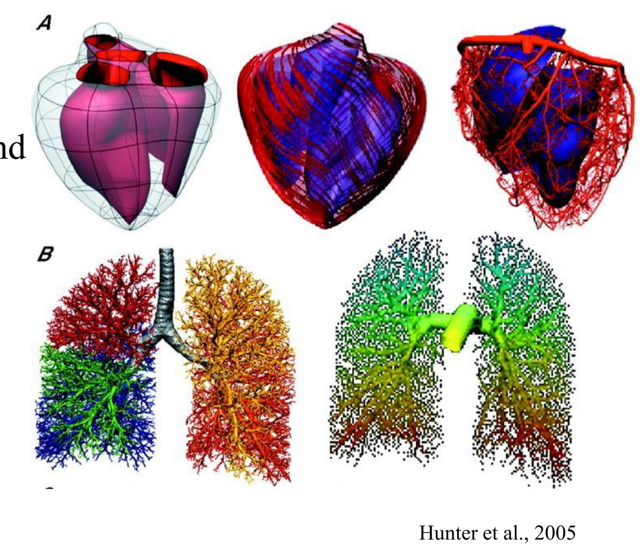


- **Feature extraction:**
  AI models (e.g., convolutional or transformer-based) can process physiological data such as EGG, fMRI, MRI, and CT scans to extract features (e.g., gastric contraction intensity or motility patterns) compatible with the compartmental model.
- **Parameter optimization:**
  Extracted features are used to train and refine parameters in the ODE-based gastric model, improving simulation accuracy.
- **Framework extension:**
  Embedding AI modules enables the model to capture missing physical mechanisms and incorporate patient-specific variability and stochasticity.
- **Digital twin for precision medicine:**
  The hybrid AI–physics model serves as a personalized digital twin for individualized diagnosis and therapy design.
- **Efficiency and data generalization:**
  The model can generate synthetic data for device design and analysis, reducing dependence on resource-intensive experiments.
- **Advantages over pure AI models:**
  Unlike data-hungry AI approaches, the physics-informed framework requires less data and maintains physiological interpretability.
- **Applications to stimulation therapies:**
  Supports model-based optimization of stimulation strategies, including direct organ stimulation and non-invasive methods such as taVNS.
- **Multi-organ simulation and therapeutic insight:**
  The framework can be extended to simulate other organs innervated by the vagus nerve, since stimulation may produce direct or indirect effects (e.g., changes in heart rate with altered gastric activity). Modeling these interactions enables evaluation of whether VNS effects are therapeutically beneficial or adverse.
- **Unified compartmental modeling approach:**
  Because the compartmental equations are generalizable, they can be adapted for other organ systems such as the heart or integrated with existing models (e.g., from [6]) to study system-level responses to vagal stimulation.
- **Long-term objective:**
  A long-term goal is to develop a comprehensive systems-level digital twin of the vagus nerve network, capturing detailed electrophysiology, soft tissue mechanics, and fluid dynamics across all connected organs.



Teaching Interests

- Develop interdisciplinary curricula that connect **biomedical engineering**, **applied mathematics**, and **computational modeling**.
- Emphasize **computational organ modeling**, including:
  - Electrophysiology (e.g., variations in action potentials across cortical neurons and visceral organs)
  - Soft tissue mechanics at the system level
  - Numerical methods for physiological systems
  - Fluid dynamics in biological contexts



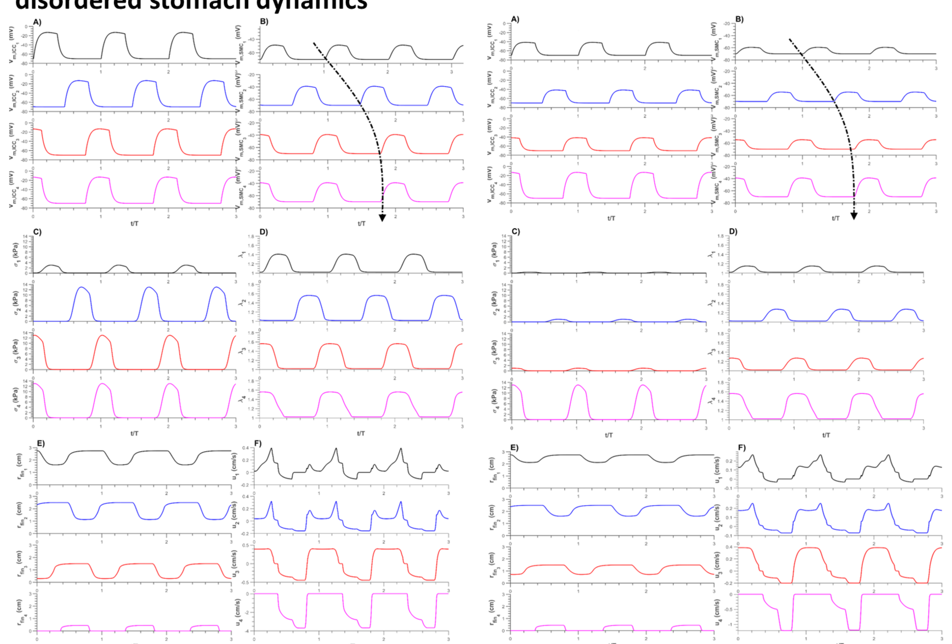
Hunter et al., 2005

- **Core teaching areas:**
  Enthusiastic about teaching foundational courses such as: Fluid Mechanics, Process Control, Principles of Chemical Engineering, Introduction to Computational Neuroscience

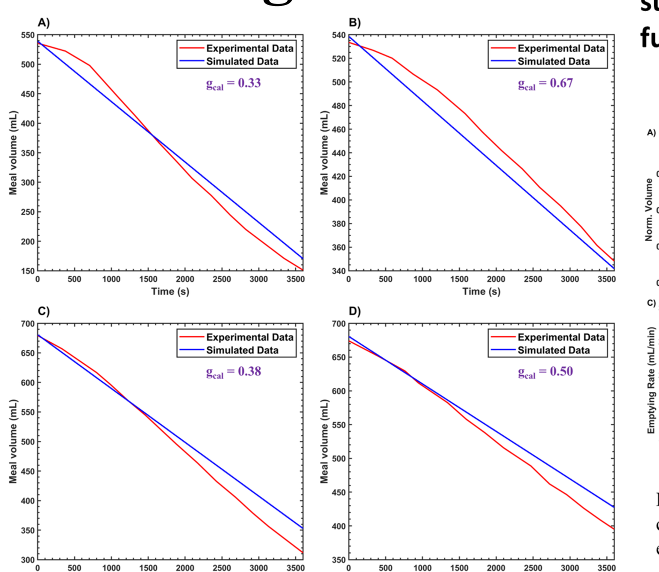
Modeling Results

Simulation results: Healthy vs disordered stomach dynamics

Four compartment model: A) Membrane potential of ICC B) SMC C) Stress D) Stretch in muscle tissue E) Compartmental radius and F) Gastric liquid velocity

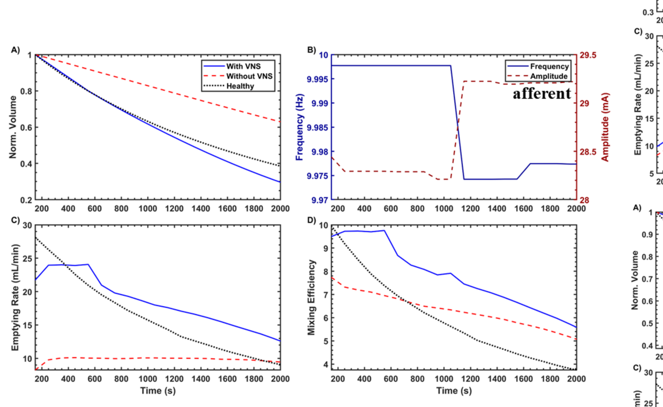


Simulation results: Gastric meal emptying plotted

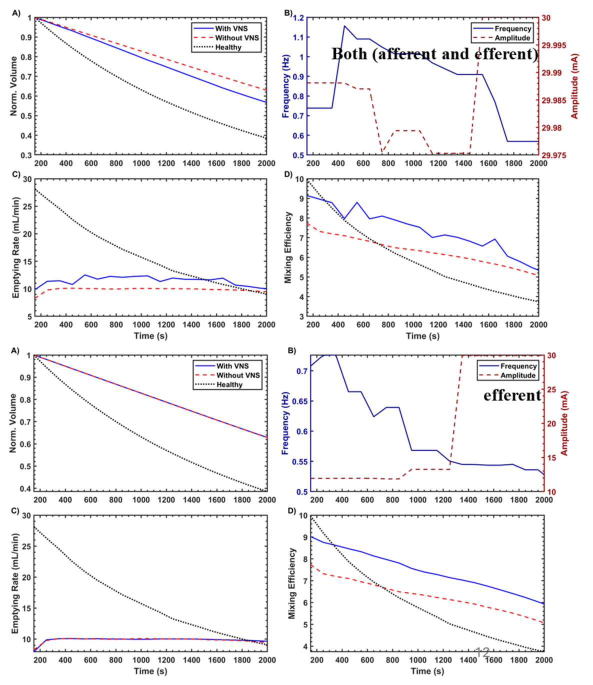


Gastric meal emptying plotted against time for gastric meals with different calorie content meal for experimental and simulated data, corresponding to g_{cal} values

Simulation results: Invasive vagal nerve stimulation (VNS) for disordered stomach: functional dyspepsia



Disordered stomach VNS A) Normalized gastric meal volume B) controlled VNS parameters C) Gastric emptying rate D) Gastric mixing efficiency



References and Acknowledgements

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