Probabilistic insights into human shoulder biomechanics

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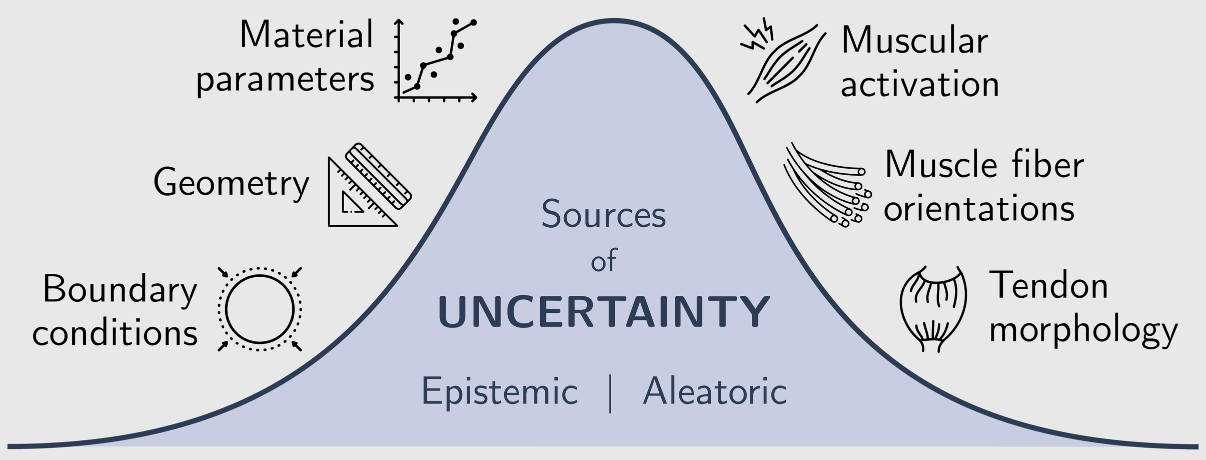
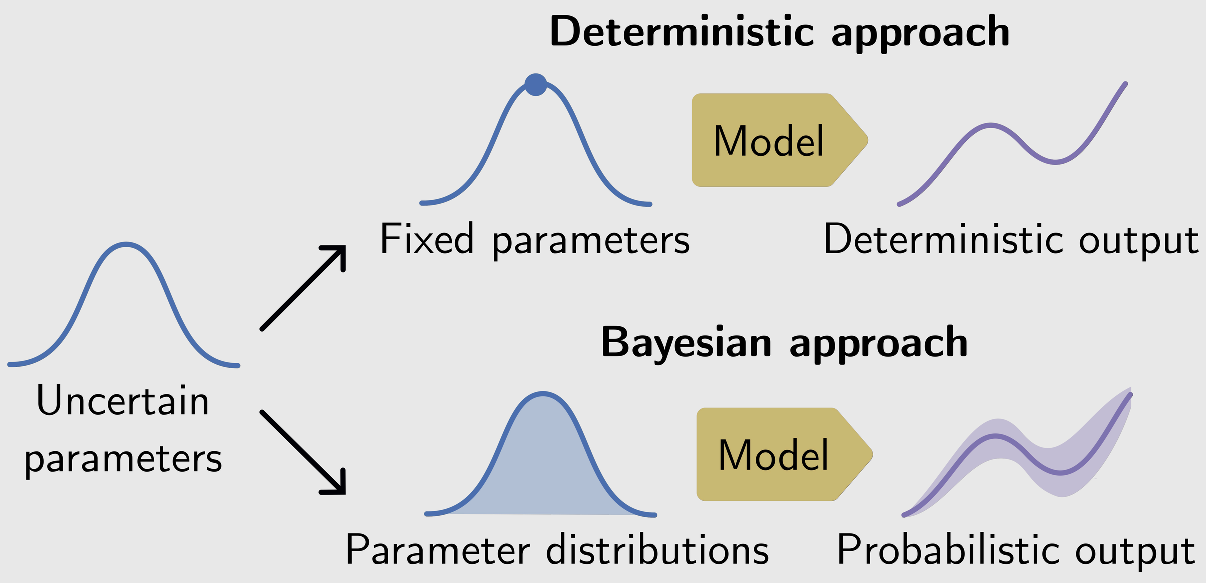
1 Introduction

- Continuum mechanical models of the shoulder enable in-depth analysis of biomechanics, pathological conditions, personalized treatments, and medical device design.
- Model predictions are inherently uncertain due to incomplete data, measurement errors, biological variability, and model assumptions, simplifications and errors.

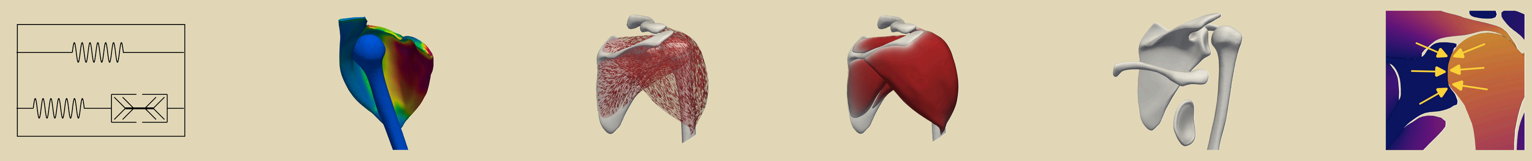


- By propagating input uncertainty through the model, probabilistic approaches capture the full range of possible outputs, enhancing prediction robustness and reliability. Since clinical decisions are based on probabilistic data, probabilistic model predictions are indispensable for informed, evidence-based decision-making.



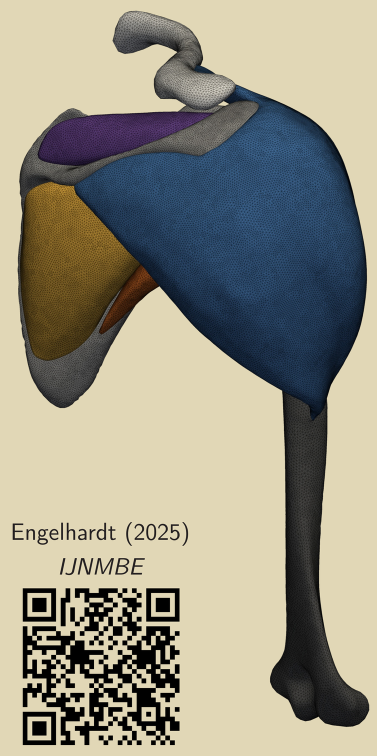
2 Continuum mechanical human shoulder model

Finite-element model of the human shoulder including key physiological features



Active, passive muscle tissue	Activation pattern	Muscle fiber architecture	Tendon morphology	Bone, cartilage, ligament	Component interactions
Generalized active strain material model	Spatiotemporally heterogeneous activation level	Fiber tensor embedded in material model	Homogenized constraint mixture model	Tissue-specific hyperelastic material models	Contact and meshtying constraints
$\alpha, \beta, \gamma, \kappa, \omega_0$ $\lambda_{\min}, \lambda_{\text{opt}}, P_{\text{opt}}$	$\{a_e^t\}_{e \in E, t \in T}$	$\{\mathbf{m}_e\}_{e \in E}$	$\{\xi_e^m, \xi_e^t\}_{e \in E}$ ρ_{mt}	E_b, ρ_b, E_c, ρ_c $K, \mu, \rho_l, \ldots$	S_I, S_O, S_C $\varepsilon_p, \ldots$

Uncertain input parameters



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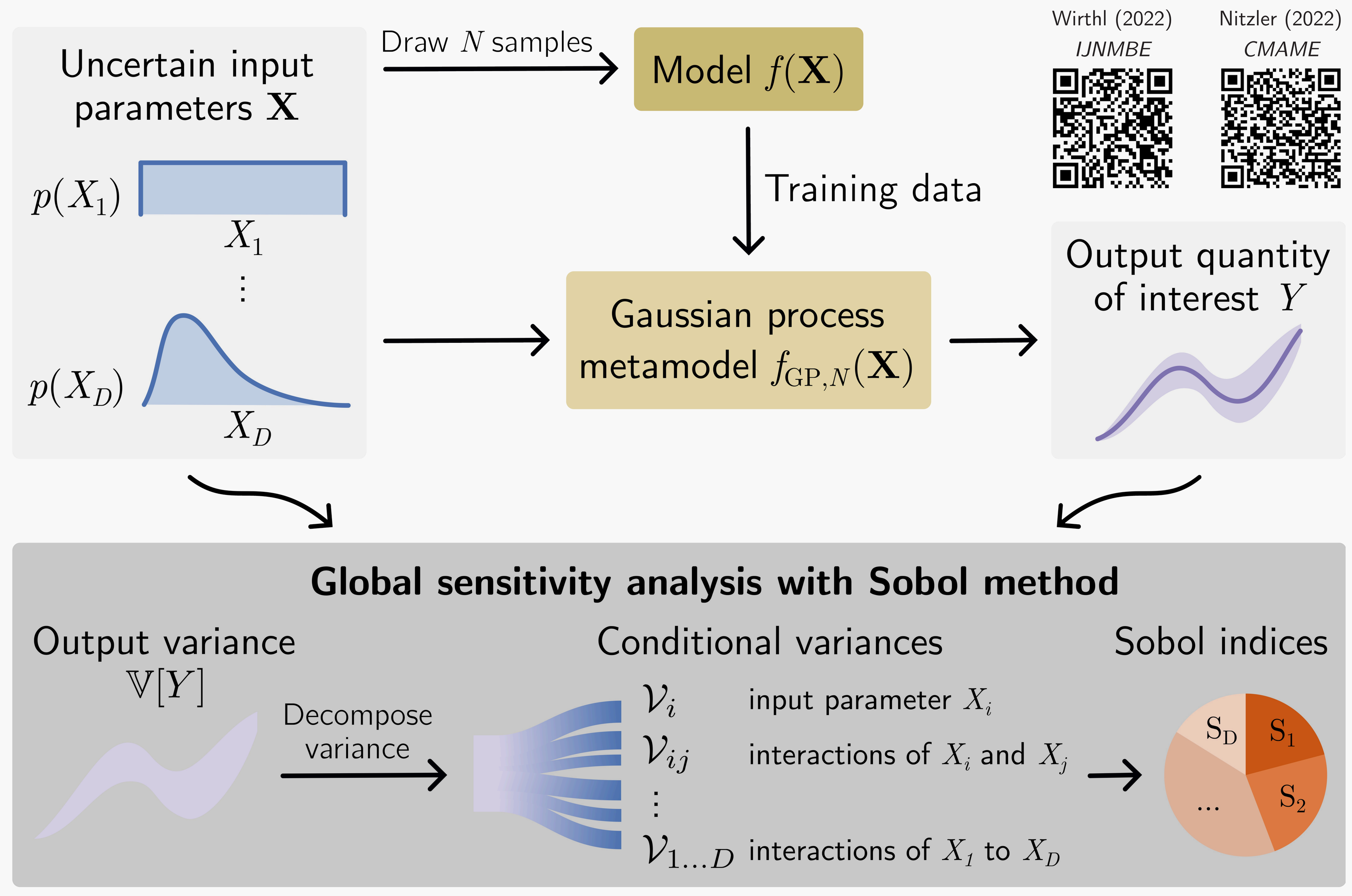
3 Uncertainty quantification and global sensitivity analysis

Prior Define input ranges and distributions based on domain knowledge.

Uncertainty quantification Quantify model output uncertainty due to variations in input space.

Sensitivity analysis Attribute output uncertainty to input parameters.

Gaussian process Approximate model output with trained metamodel when evaluations are costly.

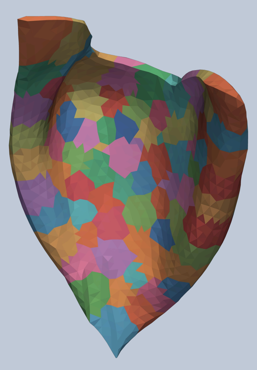


4 Application examples

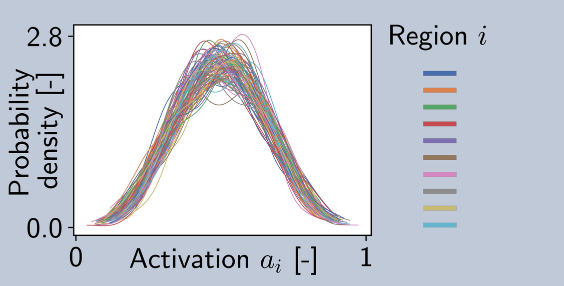
Uncertainty of muscular activation patterns

Uncertainty in muscular activation arises from neural noise, physiological variability, and measurement inaccuracies and incompleteness due to indirect or imprecise measurement methods.

Example: Probabilistic modeling of deltoid muscle contraction under uncertain activation



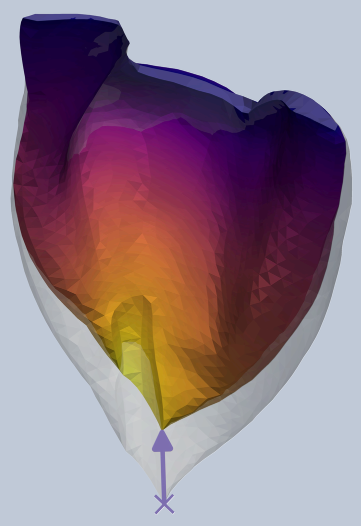
Model: Free contraction simulation of the deltoid muscle partitioned into 100 regions i with activations a_i.

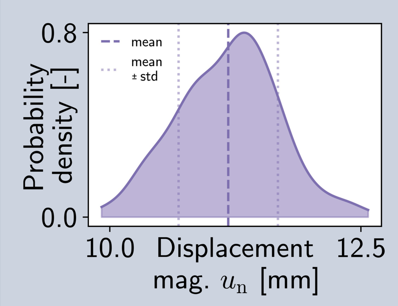


Activations $a_i \sim \text{Beta}(\alpha = 5, \beta = 5)$ with mean $\mu = \frac{\alpha}{\alpha+\beta} = 0.5 \; \forall \, i$

Input $\mathbf{X}$: Activation uncertainty modeled with Beta distributions with a coefficient of variation (CV) of 30%, consistent with upper bounds of intra-subject and inter-session normalized EMG (%MVC) variability reported in the literature.

Output Y: Displacement magnitude of the free end node u_n as a measure for the global contraction.





Variability of output u_n is low (CV = 4%) despite high input variability (CV = 30%). Higher variability seen in displacement magnitudes of other nodes (CVs ≤ 27%).

- Variability of the output deltoid contraction deformations remains lower than the assumed variability in input activations.

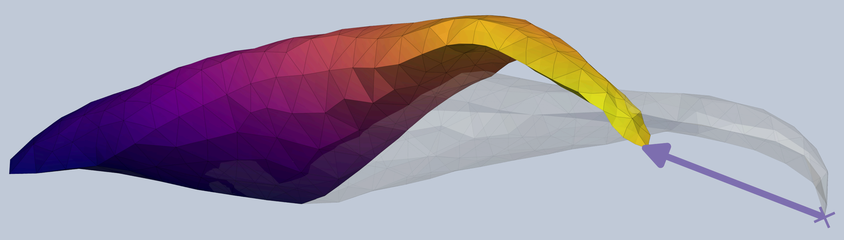
Uncertainty of muscle material model parameters

Motivation: Experimental stress-strain data on active and passive muscle tissue shows large variability. Material model parameters calibrated based on this data are thus uncertain.

Prior: Input parameter ranges determined based on 84 stress-strain curves from the literature (18 publications, eight load cases), with uniform distributions assumed.

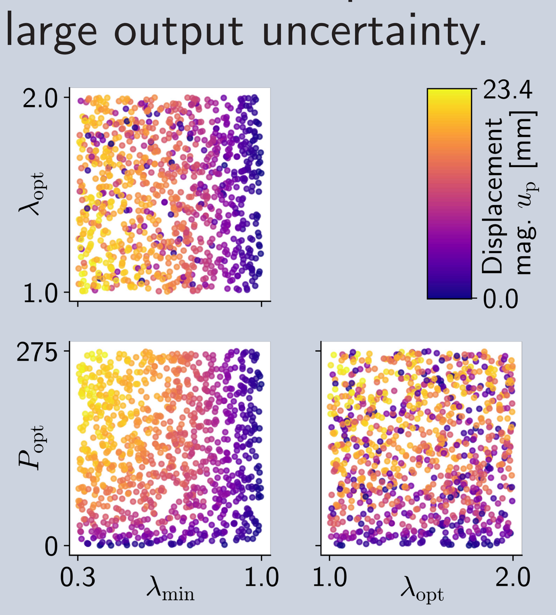
Example: Influence of active muscle material parameters on subscapularis contraction

Input $\mathbf{X}$
Min. fiber stretch $\lambda_{\min} \sim \mathcal{U}(0.3, 1.0)$
Opt. fiber stretch $\lambda_{\text{opt}} \sim \mathcal{U}(1.0, 2.0)$
Max. act. stress $P_{\text{opt}} \sim \mathcal{U}(0, 275)$

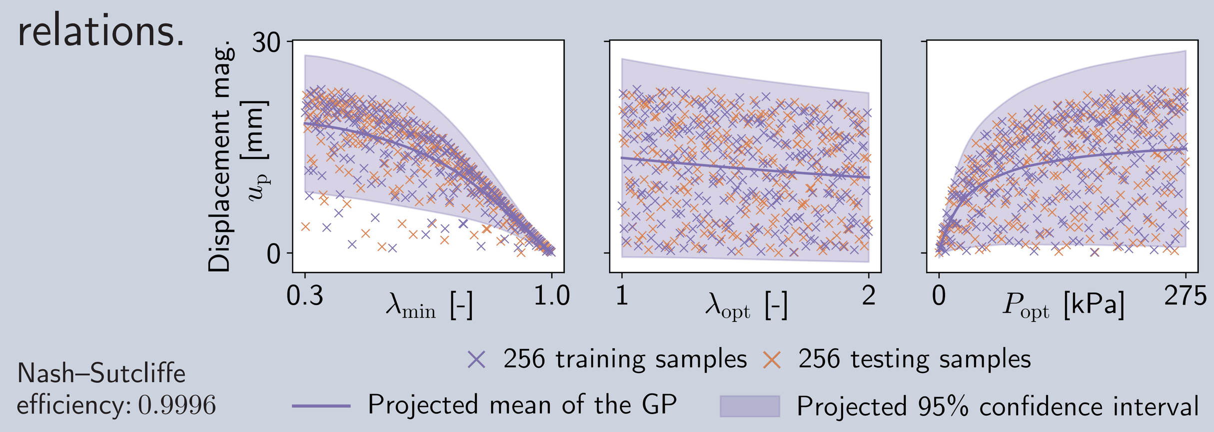


Output Y
Displacement magnitude of free end node u_p

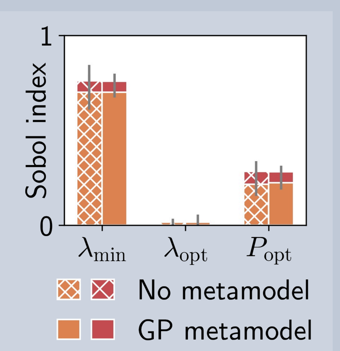
Monte Carlo samples reveal large output uncertainty.



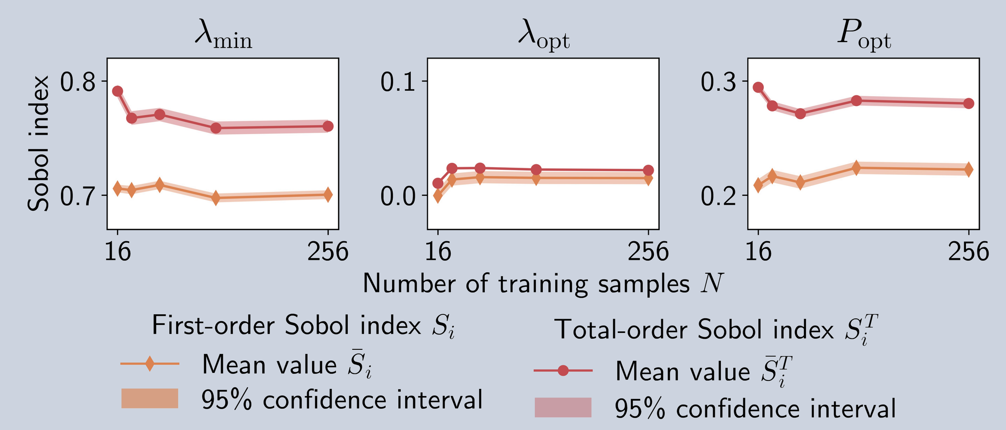
Gaussian process projections uncover (non)linear input-output relations.



Sobol indices predicted with and without Gaussian process metamodel are consistent.



Sobol indices converge with more training samples.



- Subscapularis muscle contraction (quantified by the free end displacement magnitude) is dominated by the minimal fiber stretch $\lambda_{\min}$. The optimal fiber stretch λ_{opt} has no influence.

5 Conclusion

- Uncertainty quantification improves result interpretability and reliability. Sensitivity analysis helps target experimental and computational efforts.
- A metamodel-based approach enables efficient global variance-based sensitivity analysis for computationally expensive models.
- As musculoskeletal models face high input uncertainty, probabilistic approaches are particularly relevant for reliable predictions, both clinically and scientifically.