

Project 1 (Dr. Ehsanul Hoque Apu)

Title: [Surrogate Modeling for Patient-Specific Craniofacial Reconstruction: Bridging the Gap Between High-Fidelity FEA and Real-Time Prediction](#)

Abstract

Patient-specific finite element analysis (FEA) has emerged as the gold standard for characterizing the heterogeneous and anisotropic mechanical response of craniofacial structures. However, the computational burden associated with high-fidelity simulations—derived from multi-scale imaging modalities such as Cone Beam CT (CBCT) and Micro-CT—remains a significant barrier to routine clinical integration. To resolve the latency between accurate biomechanical assessment and the real-time demands of surgical planning, the field is increasingly pivoting toward surrogate modeling. This review critically examines the state-of-the-art in surrogate modeling architectures applied to craniofacial biomechanics. We delineate the end-to-end computational pipeline, traversing from image segmentation and mesh generation (e.g., 3D Slicer) to high-fidelity physics-based solution schemes (e.g., MOOSE, Abaqus). The review categorizes current strategies into data-driven machine learning approaches (e.g., Deep Neural Networks, Gaussian Processes) and projection-based Reduced Order Models (e.g., POD-Galerkin), with specific focus on emerging hybrid paradigms like Physics-Informed Neural Networks (PINNs). We evaluate the fidelity-efficiency trade-off inherent in these models, particularly regarding their capacity to handle complex topology changes during osteotomy and reconstruction. Furthermore, we discuss the pivotal role of open-source frameworks in democratizing access to these technologies and facilitating reproducible workflows for generating predictive Digital Twins. We conclude that combining high-quality validation with reliable surrogate inference is essential for the development of the next generation of clinical decision support systems.

Keywords: Craniofacial Biomechanics, Surrogate Modeling, Finite Element Analysis (FEA), Machine Learning (ML), Reduced Order Modeling (ROM), Physics-Informed Neural Networks (PINNs), Digital Twins, Micro-CT / CBCT, Surgical Planning, Computational Medicine.

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The specific aims are to:

1. Synthesize existing literature on surrogate models for mimicking human craniofacial hard tissues.
2. Identify and categorize the models, based on their characteristics and supporting multi-scale imaging modalities such as Cone Beam CT (CBCT) and Micro-CT.
3. From literature, we will evaluate the models, particularly regarding their capacity to handle complex topology changes during osteotomy and reconstruction.
4. Draft a review manuscript and plan for an original study based on the findings.

What is the specific research question being addressed by the research project?

- What is the current evidence on variations of existing surrogate models for craniofacial hard tissue regeneration and reconstruction.