Project 2 (Dr. Ehsanul Hoque Apu)

Title: Toward the Dental Digital Twin: Integrating Image-Based Finite Element Modeling and Machine Learning for Predicting Peri-Implant Disease Progression.

Abstract:
Failure of dental implant failure is a complex process caused by the interplay of mechanical stresses and biological issues such as peri-implantitis. While conventional diagnostics mainly respond to problems, computer modeling provides a proactive way to predict failure mechanisms. Nonetheless, traditional Finite Element Analysis (FEA) has primarily been confined to static, linear-elastic models, which do not adequately capture the evolving, time-dependent nature of oral health conditions. This review explores the latest computational strategies for predicting implant failures, highlighting the evolution from basic models to sophisticated, dynamic simulations, with particular emphasis on the progression from medical imaging to predictive analytics. It details the utilization of Image-to-Mesh pipelines, multiphysics simulations, and surrogate modeling techniques. The review also explains how CBCT and Micro-CT scans—via tools such as 3D Slicer—are employed to develop patient-specific tissue models and describes the application of open-source platforms like MOOSE to integrate mechanical stress calculations with biological processes, thus simulating bone remodeling over time. Additionally, it underscores the role of Machine Learning in expediting complex FEA computations, thereby enabling near real-time predictive capabilities. The concept of “Virtual Laboratory" is introduced, wherein parameters are optimized and analyzed through computational simulations. Special attention is given to open-source workflows that link physical models to data-driven algorithms, using Python and MATLAB. The integration of high-quality imaging, multiphysics FEA, and artificial intelligence is propelling the development of the Dental Digital Twin—a comprehensive digital model of a patient’s oral health status. The authors believe that next-generation models will not only show current stress distributions but also forecast progressive bone loss, thereby enhancing surgical planning and proactive intervention.

Keywords: Dental Implants, Digital Twin, Finite Element Analysis (FEA), Multiphysics Simulation, Machine Learning, Bone Remodeling, Peri-implantitis, Patient-Specific Modeling.

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The specific aims are to:

1. Search and analyze existing literature.
2. Identify and categorize the computational models for Digital Twin, such as Finite Element Analysis (FEA), Multiphysics Simulation and Machine Learning.
3. From literature, we will evaluate the models, particularly regarding their capacity to predict the progression of Bone Remodeling and Peri-implantitis.
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 computational models for predicting the progression of Bone Remodeling and Peri-implantitis.