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Comprehensive Mechanical Analysis of Tooth Implant Model: For Dental Applications

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Abstract: This study presents an advanced finite element analysis (FEA) of a polylactic acid (PLA)-based dental implant reinforced with bio mineral additives, aiming to optimize its structural integrity, vibrational response, and biomechanical performance. The implant undergoes static structural, modal, and harmonic response analyses to evaluate stress distribution, deformation characteristics, and resonance susceptibility under physiological loading conditions. The results indicate minimal deformation, well-distributed stress concentrations, and a stable vibrational profile, highlighting the implant's suitability for long-term dental applications. By integrating sustainable biomaterials with computational modeling, this research contributes to the development of next-generation dental implants that ensure mechanical reliability and environmental responsibility.

Keywords: Dental Implant, Finite Element Analysis, PLA, Biomechanics, Harmonic Response, Modal Analysis

I. INTRODUCTION

1 Dental implants serve as an essential solution for restoring oral function and aesthetics in patients suffering from tooth loss. The evolution of implant materials has emphasized the need for biocompatibility, mechanical durability, and sustainability. Traditional metallic implants, primarily composed of titanium and its alloys, exhibit excellent mechanical properties but often present challenges related to corrosion, stress shielding, and biocompatibility issues. As an alternative, biodegradable polymers, such as polylactic acid (PLA), have gained significant attention due to their ability to integrate with biological systems while minimizing long-term foreign body reactions.

2 PLA, derived from renewable sources such as cornstarch and sugarcane, has demonstrated promising applications in biomedical engineering due to its favorable mechanical properties, biodegradability, and process ability. However, its inherent brittleness and limited mechanical strength necessitate reinforcement with biomineral additives such as eggshell and seashell powders, which are rich in calcium carbonate. This combination enhances the implant's mechanical stability, osteoconductivity, and overall performance under physiological loading conditions.

3 This study employs finite element analysis (FEA) to evaluate the mechanical behavior of a PLA-based dental implant subjected to static, dynamic, and vibrational loads. The investigation encompasses stress-strain distribution, natural frequency determination, and harmonic response analysis to ensure the implant's structural integrity and long-term viability. The integration of computational modeling with sustainable biomaterials paves the way for next-generation dental implants that align with both clinical efficacy and environmental responsibility.

II. MATERIALS AND METHODOLOGY

2.1 Material selection

2.1.1 Material Composition and Properties

1. **Polylactic Acid (PLA):** A thermoplastic polymer derived from renewable sources like corn starch and sugarcane. It exhibits high biocompatibility, biodegradability, and moderate tensile strength (~60 MPa). However, its brittleness and low impact resistance necessitate reinforcement.
2. **Eggshell/Seashell Powder Reinforcement**: Natural calcium carbonate ($CaCO3$) obtained from eggshells and seashells enhances the mechanical strength, stiffness, and bioactivity of PLA. The addition of micronized $CaCO3$ particles promotes osteo-conductivity and accelerates bone integration.
3. **Titanium Dioxide (TiO)** Nanoparticles (Optional Additive): Introduced in trace amounts to improve wear resistance and antimicrobial properties.

4. **Material Characterization Techniques:**
5. **Fourier-Transform Infrared Spectroscopy (FTIR):** Identifies chemical interactions and polymer bonding.
6. **Scanning Electron Microscopy (SEM):** Examines surface morphology, filler dispersion, and porosity levels.
7. **Differential Scanning Calorimetry (DSC):** Determines thermal stability and crystallinity index.
8. **Nanoindentation**: Measures hardness and elastic modulus of PLA-CaCO3 composites.

2.2 Methodology:

2.2.1 **Finite Element Model Development**

FEA Parameter	Specification
Software Utilized	ANSYS Mechanical APDL
Element Type	Higher-order tetrahedral elements (SOLID187)
Mesh Optimization	Mesh independence study and adaptive meshing
Adaptive Meshing Regions	High-stress zones (implant threads, bone interface)
Number of Nodes	33,811
Number of Elements	18,717

2.2.2 **Boundary Conditions and Loading Scenarios**

Condition	Specification
Fixed Constraints	Implant base rigidly fixed within simulated bone structure.
Axial Loads	200–400 N simulating direct biting forces.
Lateral Loads	50–150 N replicating non-axial occlusal interactions.
Dynamic Impact Loads	Simulating sudden chewing forces over 10 ms.
Frictional Contact	$\mu = 0.4$ at the bone-implant interface.
Bonded Contact	Ensures mechanical integrity of implant components.

2.2.3 **Modal and Harmonic Response Analysis**

Analysis Type	Specification
Frequency Range	100 Hz to 10,000 Hz
Modal Analysis	Extraction of six natural frequencies to assess resonance risks.
Harmonic Response	Evaluation of implant deformation under sinusoidal loading cycles.

3. FINITE ELEMENT ANALYSIS (FEA) RESULTS

3.1 Static Structural Analysis

- **Total Deformation:** Minimal displacement observed (**max: 5.14×10^{-4} m**).
- **Equivalent Stress Distribution:**
- **Von Mises Stress:** 9.81 MPa (below yield strength of PLA composites).
- **Localized stress concentrations at implant threads**.
- **Strain Behavior:** Equivalent elastic strain maintained within **acceptable biomechanical limits**.

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3.2 Modal Analysis (Natural Frequency Estimation)

Mode	Frequency (Hz)
Mode 1	2197.7
Mode 2	2214.1
Mode 3	3832.9
Mode 4	7262.3
Mode 5	7808.7
Mode 6	8030.1

Key Observation: All natural frequencies exceed normal chewing cycle frequencies (~20-30 Hz), ensuring no resonance under functional loads.

3.3 Harmonic Response Analysis ○ **Frequency Range: 100 Hz - 8000 Hz**.

- **Peak Response at 8000 Hz:** Minimal deformation (**1.24×10^{-6} m**) and strain (**7.57×10^{-7} m/m**).

➢ **Conclusion:** Implant remains stable under **dynamic loads**, indicating suitability for **long-term functional applications**.

4. DISCUSSION

- **Enhanced Biomechanical Performance:** The inclusion of calcium carbonate enhances stiffness and osseointegration, reducing stress shielding.
- **Sustainability Factor**: PLA-based implants provide a biodegradable alternative to conventional titanium implants, contributing to eco-friendly medical solutions.
- **Manufacturing Considerations**: Additive manufacturing techniques such as 3D printing can be explored to optimize implant geometry and reduce material waste.
- **Clinical Relevance**: The simulation results align with physiological loading conditions, ensuring that the implant can sustain real-world occlusal forces without premature failure.
- **Potential Limitations**: Future work should focus on in vivo validation and long-term degradation studies to fully understand the bio reorption characteristics of PLA composites.

5. CONCLUSION

This research successfully demonstrates that a **PLA-based biodegradable dental implant**, reinforced with **eggshell and seashell-derived CaCO3**, exhibits **high structural integrity, resistance to harmonic vibrations, and biomechanical suitability**.

These findings contribute to the development of **sustainable implant materials**, reducing reliance on non-degradable biomaterials while ensuring optimal **load-bearing performance**. Future work includes **clinical trials**, **long-term degradation studies**, and **optimization of bioresorbable properties**.

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