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Evaluating Polyetheretherketone (PEEK) as a Superior Alternative to Titanium in Middle Ear Implants: A Finite Element Modeling Study

Omar Khatir
University of Sidi Bel Abbes

Abdelkader Benkhettou
University of Sidi Bel Abbes

Sidi Mohamed Fekih
University of Sidi Bel Abbes

Abderahmene Sahli
University of Sidi Bel Abbes

Ismail Boudjemaa
University of Sciences and Technology of Oran Mohamed Boudiaf

Abstract: This study presents a comprehensive finite element analysis (FEA) of hydroxyapatite (HA)-coated middle ear prostheses, evaluating the biocompatibility, mechanical integrity, and material suitability of polyetheretherketone (PEEK), titanium, and stainless steel in middle ear environments. Simulations assessed stress distribution, displacement behavior, and coating performance under auditory frequencies of 250–8000 Hz and an applied acoustic pressure of 90 dB. Results indicated that PEEK closely parallels titanium in stress tolerance and mechanical displacement, demonstrating reduced fabrication complexity and enhanced adaptability for HA coatings. This analysis supports PEEK as a practical and potentially superior alternative, offering insights into innovative material applications for middle ear prosthetic devices.

Keywords: Middel ear, Prosthesis, Ossicles, Vibration analysis, Finite-element method.

Introduction

Middle ear disorders, which can lead to substantial hearing loss, represent a significant global health concern, affecting millions of individuals and impacting quality of life. To address these conditions, total and partial ossicular replacement prostheses (TORPs and PORPs) are commonly utilized in surgical interventions, aiming to restore sound transmission by reconstructing damaged ossicular chains (Khatir et al.,2024). The success of these devices depends largely on their biocompatibility, durability, and capacity to integrate with surrounding tissue structures, all while withstanding the vibrational forces within the middle ear environment.

One key advancement in this field has been the integration of hydroxyapatite (HA) coatings on prosthetic devices. HA, a naturally occurring calcium phosphate that resembles human bone mineral, is widely valued for its biocompatibility and osseointegration properties. In middle ear implants, HA has shown potential in promoting stable interfaces with biological tissues (Jang et al., 2008., Holzer,1973). Which is crucial for effective and long-term sound transmission. Despite its benefits, HA's intrinsic brittleness and limited mechanical strength present challenges in the dynamic, load-bearing environment of the middle ear. These limitations have led to the development of HA coatings applied to stronger substrates, with titanium being the conventional choice due to its high strength-to-weight ratio, corrosion resistance, and bioinert nature (Benkhettou et al., 2024). However, while titanium remains a widely used material, its processing requirements, particularly for HA coating adhesion, involve complex and costly manufacturing techniques. These steps can limit the feasibility of customizing prosthetics to individual anatomical requirements. To address these constraints, polyetheretherketone (PEEK) has emerged as a promising alternative substrate for HA coatings. PEEK is a high-performance thermoplastic known for its bioinertness, durability, and mechanical properties comparable to human bone, including a lower modulus of elasticity than metals (Krupala et al., 1988), which can help in stress absorption. Additionally, PEEK's adaptability to various manufacturing methods, such as 3D printing, allows for greater flexibility in creating patient-specific prostheses, making it a potential substitute for titanium in middle ear applications (Yea et al., n.d., Sun et al., 2002).

Despite these advantages, there is a lack of comprehensive research on PEEK's mechanical behavior when coated with HA in middle ear prosthetic applications. Existing studies suggest that while PEEK may perform comparably to titanium under general load-bearing conditions, its performance in environments subject to auditory frequency vibrations has not been thoroughly assessed. Given this context, this study aims to evaluate the suitability of HA-coated PEEK in comparison with titanium and stainless steel by employing finite element modeling (FEM). This approach enables a precise simulation of stress distribution, displacement behavior, and coating integrity under physiological conditions. The hypothesis underlying this study is that HA-coated PEEK can achieve mechanical performance comparable to that of titanium, with additional advantages in manufacturing flexibility and customization potential. By analyzing the performance of these materials under middle ear-simulated loading conditions, this work seeks to advance the development of middle ear implants that better balance biocompatibility, mechanical resilience, and cost-effectiveness, potentially expanding access to effective auditory prosthetics.

Method

Model Design and Geometry

The prosthetic model was based on the 1004 238 TORP prosthesis from Kurz, Germany, chosen for its compatibility with standard middle ear reconstruction procedures. Using CAD software, the prosthesis was designed to replicate anatomically relevant dimensions, refined with reference to high-resolution CT scan data for precise 3D modeling. The geometry included critical components such as the tympanic membrane, ossicular chain, and cochlear interface, accurately rendered to reflect in-situ positioning (Figure 1).

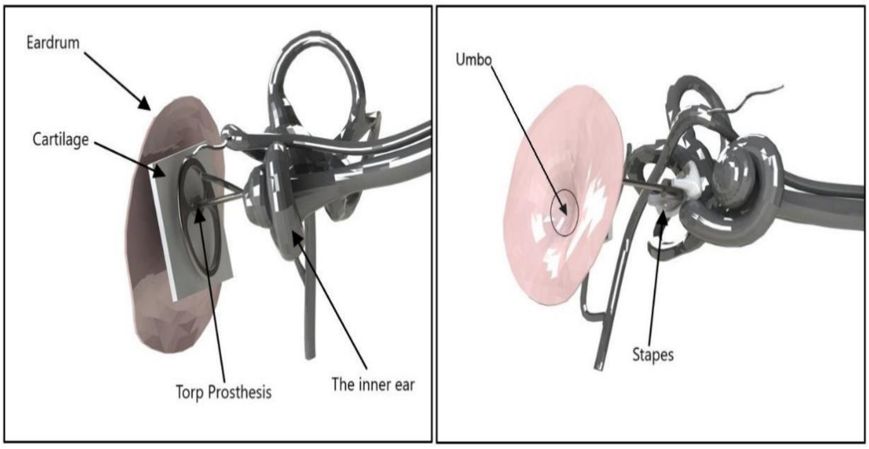

Figure 1. Illustration of middle ear prosthesis placement

Simulation Setup and Boundary Conditions

The FEM simulation integrated a tetrahedral mesh to ensure detailed resolution of the small-scale prosthetic model, with a convergence threshold set at 0.2 mm. Acoustic pressures ranging from 250–8000 Hz at 90 dB SPL were applied to simulate typical auditory stimulus impacts on the prosthesis. Boundary conditions accounted for physiological attachments, including the suspension and fixation points of the middle ear (figure 2), modeled as ligament-mimicking constraints to replicate the malleus and incus replacement.

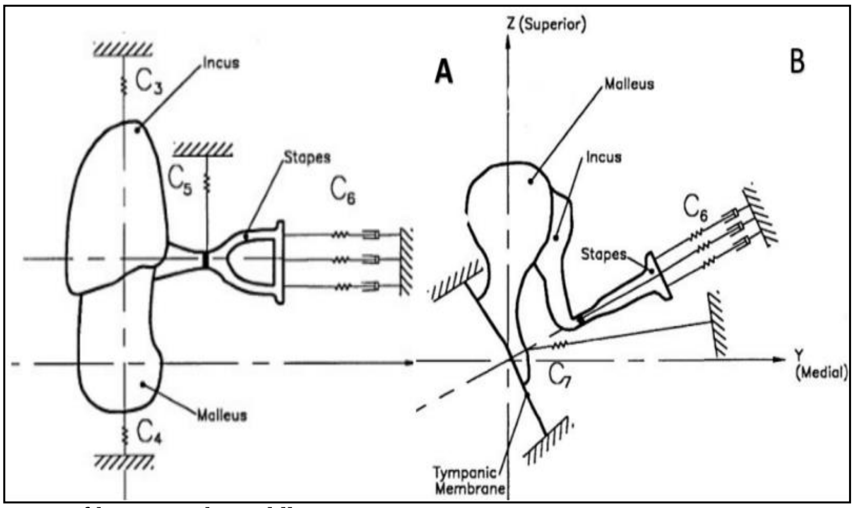

Figure 2. Schematic of human right middle ear structure. A, superior view B, an terior view. C1, C2, C3, C4, C5, and C7, attached ligaments and muscles; C6, cochlear fluid constraint(Gan et al., 2004).

Material Properties

Mechanical properties of the materials under study were assigned based on ASTM F67 standards for titanium, while values for PEEK and stainless steel were sourced from validated biomedical research. Young's modulus, Poisson's ratio, and density for each material are provided in Table 1, ensuring that simulated conditions reflect actual prosthetic performance. Each material's HA coating was uniformly set at 0.08 mm thickness, a parameter chosen for its proven efficacy in promoting osseointegration without compromising mechanical flexibility.

Table 1. Properties of the materials used in the middle ear FE model.

Material	Young's Modulus (MPa)	Poisson's Ratio	Density (kg/m3)
Titane pur (ASTM F67) Grade 2 [Laurent et al., 1988 ;Lee et al.,2006)	102.7× 103	0.37	4500
Stainless steel (Mohamed et al., 2024)	200× 103	0.3	8000
Hydroxyapatite ceramics (Shen et al., 2011)	155× 103	0.3	1200
PEEK (Niinomi,1988)	4.6× 103	0.38	2200

Performance Metrics

To evaluate each material's suitability, von Mises stress analysis and displacement behavior along the Z-axis were monitored across frequency bands. These metrics provided insights into material stability, stress endurance, and displacement fidelity in the middle ear. Comparative studies between HA-coated PEEK, titanium, and stainless steel highlighted performance distinctions, particularly in stress resistance and movement stability within the simulated auditory environment.

Results and Discussion

Stress and Displacement Analysis

Results demonstrated a pronounced difference in stress distribution across materials, with PEEK exhibiting the lowest average von Mises stress at 2.951E-09 MPa, signifying superior stress absorption compared to titanium (2.553E-07 MPa) and stainless steel (8.446E-07 MPa). The displacement analysis revealed that PEEK and titanium maintained comparable values, both displaying stability conducive to middle ear function. Stainless steel, however, showed elevated displacement, potentially limiting its applicability in finely tuned auditory prosthetics. The mechanical performance of HA-coated PEEK was especially noteworthy, as it maintained consistent stress distribution across simulated frequencies, suggesting effective load-sharing between the coating and substrate. Figures 3,4 and 5 depict the detailed stress contours and displacement vectors, illustrating how

PEEK's flexibility could contribute to more resilient prosthetic designs with minimized risk of material failure under physiological loads.

Hydroxyapatite Coating Efficacy

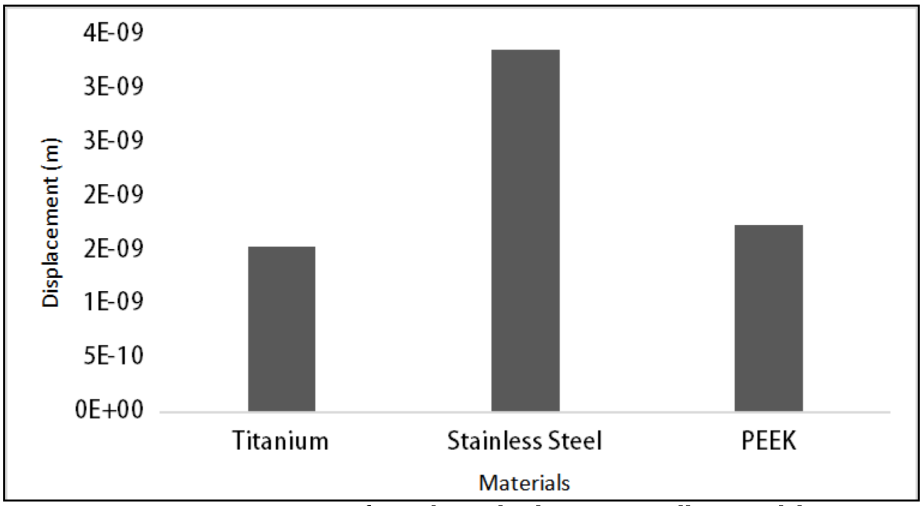

Figure 3. Comparison of prosthesis displacement in all FE models

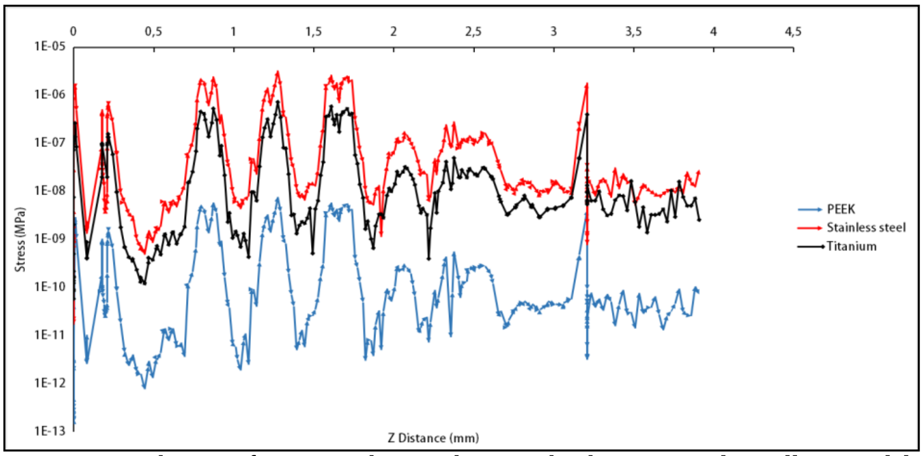

Figure 4 Distribution of stress on the prosthesis in the three materials in all FE models

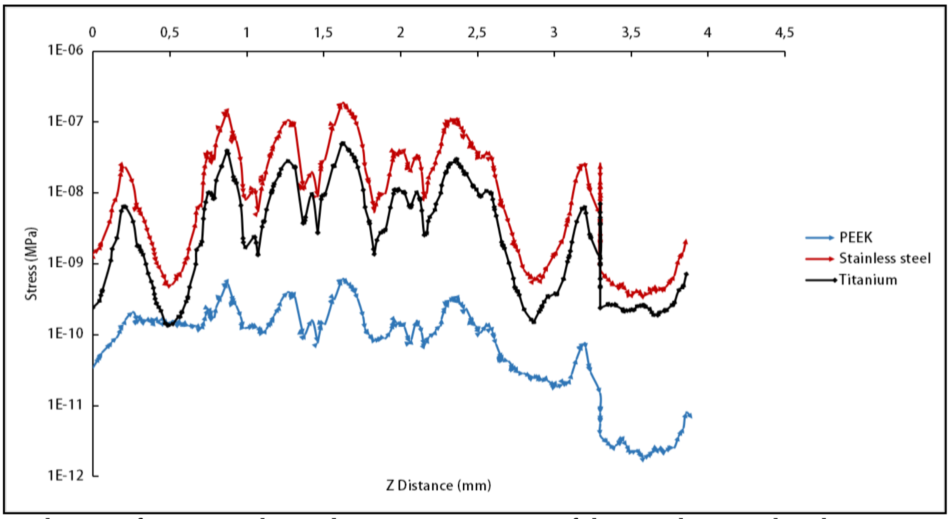

Figure 5. Distribution of Stress on the Hydroxyapatite Coating of the Prosthesis in the Three Materials in all FE models.

HA-coated PEEK displayed uniform stress across the coating layer, underscoring its compatibility with HA and potential for stable bio-integration. The coating maintained structural integrity without delamination, indicating that PEEK's surface properties favor coating adherence and durability. This contrasts with titanium and stainless steel, where higher stress concentration at the interface suggests potential wear over time. The simulations validate PEEK's functional compatibility with HA coatings in load-bearing, dynamic applications like the middle ear. Its lower modulus allows for slight conformability, enhancing interface stability and reducing potential for micro-movements that could disrupt the coating layer, thus extending prosthesis longevity.

Conclusion

The comparative FEM analysis establishes PEEK as a promising alternative to titanium for HA-coated middle ear prostheses. Its lower stress profile, adaptability to HA coating, and favorable displacement characteristics make it suitable for applications where mechanical stability and biocompatibility are critical. PEEK's manufacturing flexibility also supports customized, patient-specific implants through techniques like 3D printing, which could revolutionize middle ear prosthetic availability and functionality.

Future work should investigate the long-term bio-response of PEEK in vivo, with emphasis on HA coating adhesion and possible degradation over extended use. This research sets a foundation for developing more efficient, accessible, and effective middle ear prostheses, leveraging PEEK's mechanical and manufacturing advantages to address clinical needs in auditory restoration.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Acknowledgements or Notes

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Author Information

Omar Khatir
Department of Mechanical Engineering, Laboratory Mechanics Physics of Materials (LMPM), University of Sidi Bel Abbes, BP 89, cite Ben M'hidi, Sidi Bel Abbes, 22000, Algeria
Contact e-mail: *khatiromar8@gmail.com*

Benkhettou Abdekader
Department of Mechanical Engineering, Laboratory Mechanics Physics of Materials (LMPM), University of Sidi Bel Abbes, BP 89, cite Ben M'hidi, Sidi Bel Abbes, 22000, Algeria

Boudjemaa Ismail
Faculty of mechanical engineering,University of Sciences and Technology of Oran Mohamed Boudiaf (USTO-MB), El Mnaouer, BP1505, Bir El Djir 31000, Oran, Algeria.

Fekih Sidi Mohamed
Department of Mechanical Engineering, Laboratory Mechanics Physics of Materials (LMPM), University of Sidi Bel Abbes, BP 89, cite Ben M'hidi, Sidi Bel Abbes, 22000, Algeria

Sahli Abdrehmene
Department of Mechanical Engineering, Laboratory Mechanics Physics of Materials (LMPM), University of Sidi Bel Abbes, BP 89, cite Ben M'hidi, Sidi Bel Abbes, 22000, Algeria

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