Journal of Oral Biology and Craniofacial Research 16 (2026) 52–58

Contents lists available at ScienceDirect

Journal of Oral Biology and Craniofacial Research

journal homepage: www.elsevier.com/locate/jobcr

Lateral stress distribution analysis on hafnium metal bar for implant superstructure- A finite element analysis

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ARTICLE INFO

Keywords:
Finite element analysis
Hafnium
Implant-supported prosthesis
Bar framework
Stress distribution
Titanium
PEEK
Cobalt–chromium

ABSTRACT

Background: The mechanical behavior of implant-supported prostheses is strongly influenced by the material properties of the bar framework, particularly under lateral masticatory loading. While titanium and cobalt--chromium are established materials, alternatives such as polyetheretherketone (PEEK) and hafnium may offer distinct biomechanical advantages. The aim of this study was to compare the lateral stress distribution in implant-supported prostheses fabricated with four different bar materials using finite element analysis.

Method: ology: A three-dimensional finite element analysis (FEA) was conducted on a mandibular edentulous model with four endosseous implants arranged in an All-on-4 configuration. Four groups were evaluated based on bar material: titanium (Ti), cobalt–chromium (CoCr), polyetheretherketone (PEEK), and hafnium (Hf). A total of four simulation models were created, each subjected to a 100 N anterior and 300 N posterior lateral load. Von Mises stresses were analyzed in the bar, abutments, screws, and peri-implant bone.

Results: PEEK recorded the lowest stress in the bar (∼25 MPa) and peri-implant bone but induced elevated stresses in the abutment (348 MPa) and screw (288 MPa). CoCr showed the highest stress within the bar (∼114 MPa) with lower values in other components. Titanium and hafnium presented a balanced stress profile, with no region exceeding 300 MPa. Hafnium closely mirrored titanium's biomechanical response, demonstrating efficient load distribution without critical stress concentrations.

Conclusion: Bar material significantly affects lateral stress distribution in implant-supported prostheses. Hafnium displayed biomechanical behavior comparable to titanium, indicating its promise as a potential alternative framework material. Further in vitro and clinical validation is warranted.

1. Introduction

Bar-supported implant prostheses are a fundamental solution in the rehabilitation of edentulous mandibles, offering enhanced prosthesis stability, load distribution, and support for overdentures and fixed restorations.[1,2] The splinting effect of the bar framework helps distribute occlusal forces across multiple implants, reducing micromotion and peri-implant bone stress.[3,4] This contributes significantly to the preservation of marginal bone levels and the long-term success of implant treatments.[5,6]

The mechanical performance of these frameworks is highly dependent on the material properties of the bar.[7] Titanium (Ti) and cobalt–chromium (Co–Cr) alloys are conventionally used in clinical practice due to their high stiffness, favorable mechanical strength, and long-term biocompatibility.[8,9] Titanium remains a gold standard owing to its high corrosion resistance and excellent osseointegration profile,[10] while Co–Cr alloys are often selected when increased rigidity and wear resistance are desired.[11] Polyetheretherketone (PEEK), a high-performance thermoplastic polymer, has recently emerged as a viable alternative material for implant superstructures.[12] Owing to its elastic modulus (∼3–4 GPa) being closer to that of human cortical bone (∼13–20 GPa), PEEK may act as a mechanical buffer, potentially reducing stress transfer to peri-implant bone structures.[13,14] This shock-absorbing effect has been postulated to benefit bone preservation,

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https://doi.org/10.1016/j.jobcr.2025.11.003
Received 2 September 2025; Received in revised form 19 October 2025; Accepted 4 November 2025
Available online 11 November 2025
2212-4268/

especially under dynamic or oblique loading conditions.[15] However, its low stiffness also results in increased deformation under load, which could lead to higher stress concentrations in the abutment and implant screws.[16,17] The behavior of materials under load varies markedly. High-modulus materials like Ti and Co–Cr resist deformation and confine stresses within the bar, possibly sparing the surrounding bone from excessive load.[18,19] Conversely, lower modulus materials such as PEEK may deflect more, redistributing forces toward the supporting structures.[20] This balance between stiffness and flexibility creates a design challenge in selecting a bar material that protects both the framework and peri-implant tissues.[21] In recent years, PEEK has been increasingly used in digital prosthodontics for partial denture frameworks, interim restorations, and removable partial dentures due to its lightweight, resilient property, modulus of elasticity and digital milling capability.[22] These applications highlight its versatility and potential as a substitute for metallic frameworks in implant prosthodontics.

Hafnium (Hf), a transition metal with mechanical and chemical similarities to zirconium, has drawn interest for biomedical applications due to its high corrosion resistance, excellent biocompatibility, and favorable mechanical properties.[23,24] Hafnium is a Group IVB transition metal with an elastic modulus of approximately 140 GPa, placing it between titanium (110 GPa) and cobalt–chromium (200 GPa), thereby offering a balance between rigidity and flexibility. It exhibits excellent corrosion resistance due to the formation of a stable hafnium oxide (HfO_2) layer, and demonstrates high biocompatibility and low ion release, similar to titanium and zirconium.[25] These combined characteristics suggest potential for reduced galvanic corrosion and improved long-term stability in oral environments compared with traditional titanium alloys or Co–Cr frameworks. With a modulus of elasticity (~140 GPa) that lies between Ti and Co–Cr, hafnium may offer a unique biomechanical profile suitable for implant bar applications.[26] Despite this potential, its application in dental prosthodontics remains underexplored.

Finite element analysis (FEA) is a validated and widely used computational approach for predicting the mechanical response of implant-supported restorations.[27] FEA enables precise modeling of complex load conditions, material behaviors, and bone-implant interactions in a controlled virtual environment.[28,29] In this study, FEA is employed to simulate and compare the lateral stress distribution in mandibular implant-supported bars fabricated from hafnium, titanium, cobalt–chromium, and PEEK. This in vitro study aims to analyze the lateral stress distribution in mandibular implant-supported prostheses using finite element analysis, comparing hafnium bar frameworks with those made from titanium, cobalt–chromium, and PEEK to evaluate hafnium's mechanical suitability as a prosthetic bar material.

2. Materials and methods

2.1. Study design and grouping

This in vitro study was conducted following ethical approval obtained from the Institutional Review Board of the Dental College and Hospitals, Chennai, India (Approval Number: SRB/SDC/PROSTHO-SRB/SDC/PROSTHO-2206/25/071). The primary aim of the study was to evaluate and compare stress distribution within the prosthesis, implant components, and surrounding peri-implant bone under standardized lateral stress conditions.

To ensure consistency and isolate the effect of prosthetic framework material on stress distribution, all experimental groups were modeled using identical parameters: a uniform mandibular bone model, identical implant configuration and dimensions, consistent prosthetic design, fixed boundary conditions, and equivalent loading scenarios. The sole variable was the type of material used for the prosthetic framework.

The study was divided into four experimental groups based on the framework material utilized in the finite element models:

- **Group 1 (Ti):** Titanium framework, representing the current clinical gold standard due to its favorable mechanical properties and biocompatibility.
- **Group 2 (Hf):** Hafnium framework, a relatively novel material exhibiting mechanical characteristics similar to those of titanium and zirconium.
- **Group 3 (PEEK):** Polyetheretherketone framework, a high-performance polymer known for its elastic modulus comparable to that of cortical bone, promoting stress distribution akin to physiological conditions.
- **Group 4 (CoCr):** Cobalt-chromium alloy framework, characterized by its superior strength and rigidity, often used in high-load-bearing prosthetic applications.

By maintaining all other modeling parameters constant, this study aimed to isolate and assess the impact of different framework materials on the biomechanical behavior of the implant-supported prosthesis system.

2.2. Model preparation

3D digital model of edentulous mandible was developed using Computer-Aided Design (CAD) software (SolidWorks©; Dassault Systèmes SolidWorks© Corp., Concord, MA, USA), The model incorporated two distinct bone layers: a 2 mm uniformly thick cortical shell and a cancellous core, both designed as isotropic, homogeneous, and linearly elastic structures based on mand anatomy.

The implant geometry was based on the Nobel Biocare® Branemark-type design. 4 endosseous implants of dimension (4 × 10 mm, parallel-walled, internal connection). 2 in anterior and 2 posteriors representing all on 4 configurations on top of which screw retained full arch type framework was designed over multi-unit abutment, in all four groups the bar dimension were kept the same. To reproduce physiologic lateral masticatory loading, a 100 N load was applied to the anterior region and a 200 N load to the posterior region of the bar, both acting laterally along the bucco-lingual axis. These loading magnitudes correspond to the range of functional forces generated during lateral mandibular excursions and are consistent with previous finite-element analyses and in-vitro studies on implant-supported prostheses.[30,31]

2.3. Meshing

The study was executed through a structured workflow involving CAD modeling, meshing, analysis, and post-processing. Three primary software platforms were used: **SolidWorks 2021** for computer-aided design (CAD) of the mandibular model and prosthetic components, **HyperMesh 14** for mesh generation and refinement, and **Abaqus 6.14** for simulation and stress analysis. The FEM process was divided into three core stages: pre-processing, solving, and post-processing. Mesh convergence testing was performed until the difference in maximum von Mises stress between successive refinements was less than 5 %, confirming model stability.

For meshing, a 10-node tetrahedral element was selected. The node and element count for each model are provided in Table 1.

Table 1
Node and element details.

Name	No. of Nodes	No. of Elements
Cortical	35573	70921
Cancellous	69850	265263
Bar	7673	24973
Implant	20100	66680
Abutment	5788	17348
Screw	7724	25404

2.4. Preprocessing

All modeling parameters such as implant positioning, bone geometry, abutment design, and screw configuration were maintained consistently across groups to ensure standardization. The only variable introduced was the material assigned to the prosthetic bar framework. Material properties were sourced from reliable peer-reviewed literature and input into the Abaqus 6.14 simulation environment. The mechanical characteristics assigned to each framework material are presented in Table 2 below.

2.5. Solving phase

The prepared finite element models were solved using Abaqus 6.14, employing a static linear analysis to evaluate stress distribution under lateral loading conditions. Each model differing only in the material assigned to the prosthetic bar (Hafnium, Titanium, Cobalt–Chromium, or PEEK) was analyzed independently under identical boundary constraints. The applied loads consisted of a 100 N lateral force on the anterior region and a 300 N lateral force on the posterior region of the prosthetic bar, both directed buccally to simulate masticatory forces occurring during functional lateral excursions. The analysis aimed to assess how the stiffness of each material influenced the stress response within the implant-supported bar assembly.

2.6. Post-processing phase

Post-processing was conducted using the visualization module in Abaqus to evaluate the mechanical behavior of each material configuration. Von Mises stress was selected as the primary parameter for interpretation, providing a reliable indicator of stress concentration under complex loading. Stress distributions were examined in all critical regions, including the prosthetic bar, abutments, implants, screws, and both cortical and cancellous bone. For each material, maximum stress values were extracted and compared to determine how lateral loads were transmitted and dissipated throughout the system. This comparison helped establish differences in mechanical performance among the materials and offered insight into the suitability of hafnium as an implant bar framework material under lateral force conditions.

3. Results

The finite element analysis focused on evaluating the lateral von Mises stress distribution across key components of the implant-supported prosthesis system using four different bar materials: Titanium, Hafnium, PEEK, and Cobalt–Chromium. The results highlight how variations in material stiffness influence stress transmission under functional lateral loading conditions.

PEEK bar (Model 3) exhibited the lowest stress levels in the cortical and cancellous bone, as well as within the prosthetic bar itself, indicating its effective stress-absorbing properties. However, this came at the cost of significantly elevated stress concentrations in the abutment and screw, suggesting a transfer of load to the supporting components rather than within the framework. In contrast, the CoCr bar (Model 4) demonstrated the highest internal stress within the bar due to its high rigidity, yet it transmitted relatively less stress to the surrounding bone structures. Titanium and Hafnium showed intermediate behavior, with stress distributions that balanced between structural rigidity and biomechanical compatibility with bone.

Table 2
Mechanical characteristics assigned to each framework material.

Name	Young's Modulus (MPa)	Poisson's Ratio
Cortical	13,700	0.30
Cancellous	1370	0.30
Ti – Bar	114,000	0.33
Hafnium – Bar	78,000	0.37
PEEK – Bar	3600	0.36
Cobalt – Bar	210,000	0.30
Implant	114,000	0.33
Abutment	114,000	0.33

Under lateral loading, changing the bar material had minimal effect on cortical and cancellous bone stress distribution, as shown in Fig. 1, where all four materials exhibited relatively comparable color maps. However, the internal prosthetic components showed significant differences in stress behavior depending on bar material.

The PEEK bar recorded the lowest stress within the bar itself (∼25 MPa), as shown, yet this resulted in stress being redirected to the abutment and screw, where peak values rose sharply to approximately 348 MPa and 288 MPa, respectively (Fig. 2). This suggests a stress transfer mechanism from the compliant bar to the fixation components. This behavior arises from PEEK's low elastic modulus, which allows greater framework deflection and transfers load to the underlying connection components. While the flexible bar reduces stress within itself, it increases stress in critical interfaces, potentially predisposing to screw loosening or abutment fatigue.[32]

On the other hand, the cobalt–chromium bar absorbed the greatest amount of load internally (∼114 MPa), keeping stress in other components including bone, abutment, and screw within lower ranges. Titanium and hafnium behaved in a balanced manner; while not minimizing stress in any one component, they avoided any excessive concentration, with no single area exceeding ∼300 MPa.

The comparative stress analysis under lateral loading revealed distinct biomechanical behaviors among the four-framework materials titanium, hafnium, PEEK, and cobalt chromium as illustrated in Fig. 3. Stress distribution in cortical and cancellous bone was relatively consistent across all groups, with cortical bone stress ranging around 103 MPa and cancellous bone stress between 21.06 and 22.46 MPa. Notably, PEEK recorded the lowest bar stress (25.33 MPa) but the highest stress in abutment (347.7 MPa) and screw (288.3 MPa), indicating excessive load transfer to connecting components. In contrast, cobalt–chromium showed the highest internal bar stress (113.7 MPa) while maintaining lower stress values in the abutment and screw, suggesting its superior ability to shield supporting structures through internal stress localization. Titanium and hafnium exhibited intermediate behavior, with balanced stress profiles and no region exceeding 300 MPa, making them biomechanically favorable. These findings are quantitatively summarized in Table 3, which presents the maximum von Mises stress values (in MPa) across six key regions cortical bone, cancellous bone, prosthetic bar, implant, abutment, and screw. Collectively, the results highlight that material stiffness significantly influences stress distribution, and hafnium, with its intermediate modulus, offers a promising balance between structural integrity and stress mitigation.

4. Discussion

The present finite element analysis (FEA) evaluated lateral stress distribution in mandibular implant-supported prosthetic systems utilizing 4 bar materials hafnium (Hf), titanium (Ti), cobalt chromium (CoCr), and polyetheretherketone (PEEK). The results reveal that material stiffness significantly alters the stress distribution within the prosthesis and its supporting structures under lateral functional loads. Cobalt chromium, possessing the highest modulus of elasticity, absorbed the greatest internal stress within the bar (∼114 MPa), demonstrating minimal deformation but effectively shielding the surrounding peri-implant bone from stress transmission. In contrast, PEEK with an elastic modulus closer to that of cortical bone exhibited minimal bar stress (∼25 MPa), but caused marked increases in stress within abutments and prosthetic screws, exceeding 300 MPa. This suggests that PEEK's compliant nature allows energy dissipation away from the bar, but at the cost of overloading the connection hardware. Titanium and

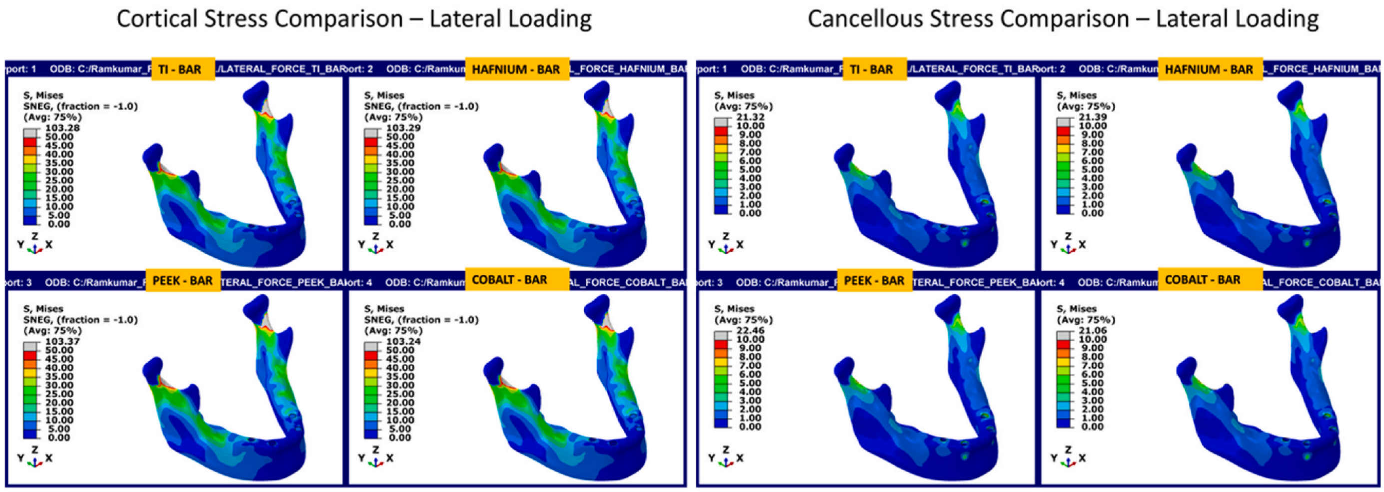

Fig. 1. Cortical and cancellous bone stress comparison under lateral loading.

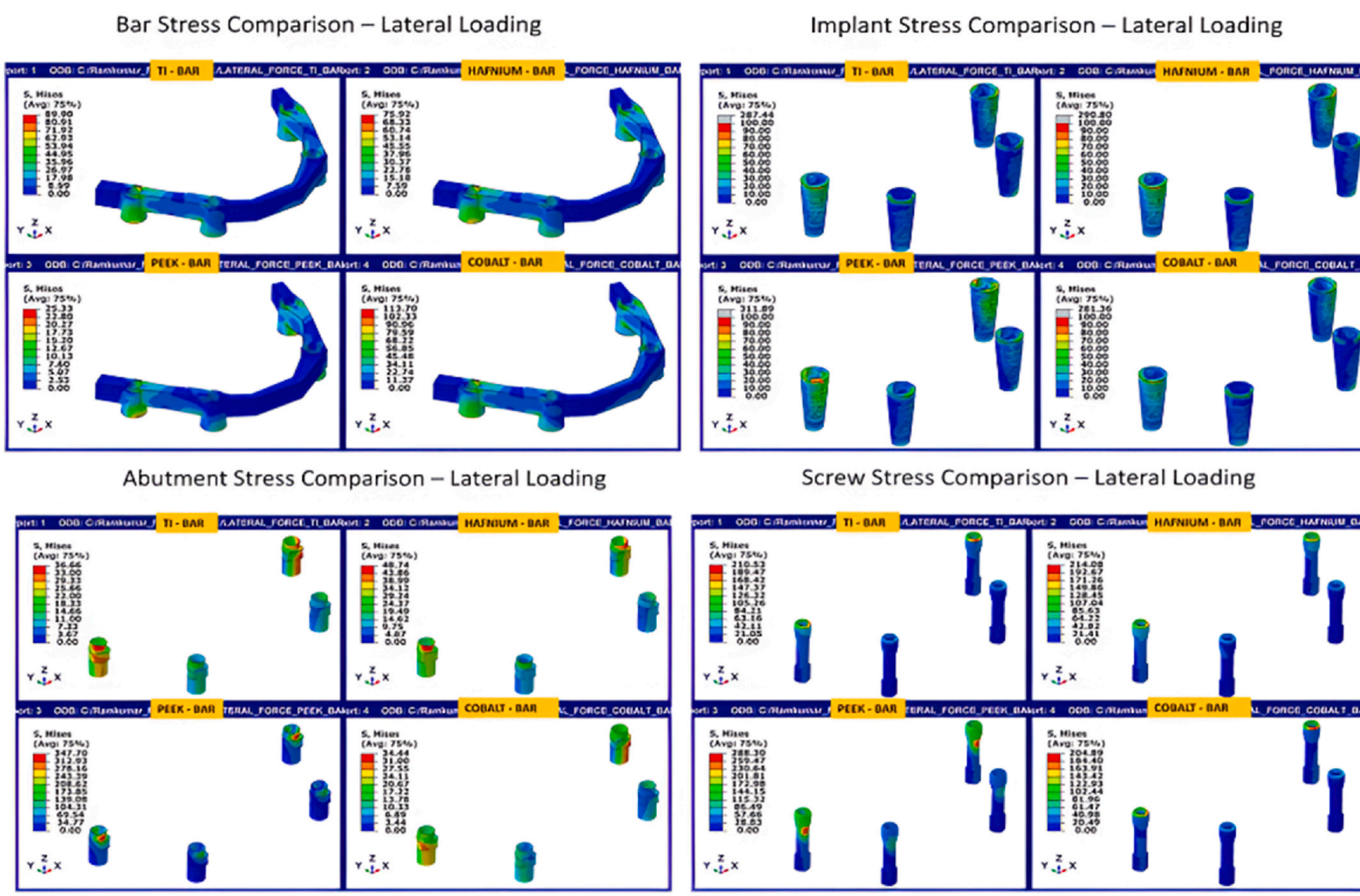

Fig. 2. Stress Comparison under Lateral Loading in bar, implant, abutment and screw.

Hafnium displayed balanced behavior between these two extremes, with neither bar nor abutment regions exceeding 300 MPa under the prescribed lateral loading scenario. Hafnium in particular, with its intermediate modulus (~120–140 GPa), demonstrated a stress distribution pattern nearly identical to titanium, with slightly improved bone load sharing. Based on these findings, the null hypothesis that lateral stress distribution does not significantly differ among materials is clearly rejected. The choice of bar material critically influences the magnitude and location of stress concentration within the implant-prosthesis complex under lateral functional forces.

These findings align with existing prosthodontic biomechanics literature, which have emphasized that matching the prosthesis material's stiffness to that of bone can modulate stress transfer. For example, Villefort et al. found that a PEEK framework (elastic modulus ~3–4 GPa) under vertical loading induced lower strain in peri-implant cortical bone compared to a metal framework, owing to PEEK's modulus being much closer to that of bone. However, subsequent studies have indicated that such low-modulus materials may increase stress concentrations in prosthetic components, highlighting a potential limitation in their mechanical performance despite favorable bone compatibility.[33] In a finite

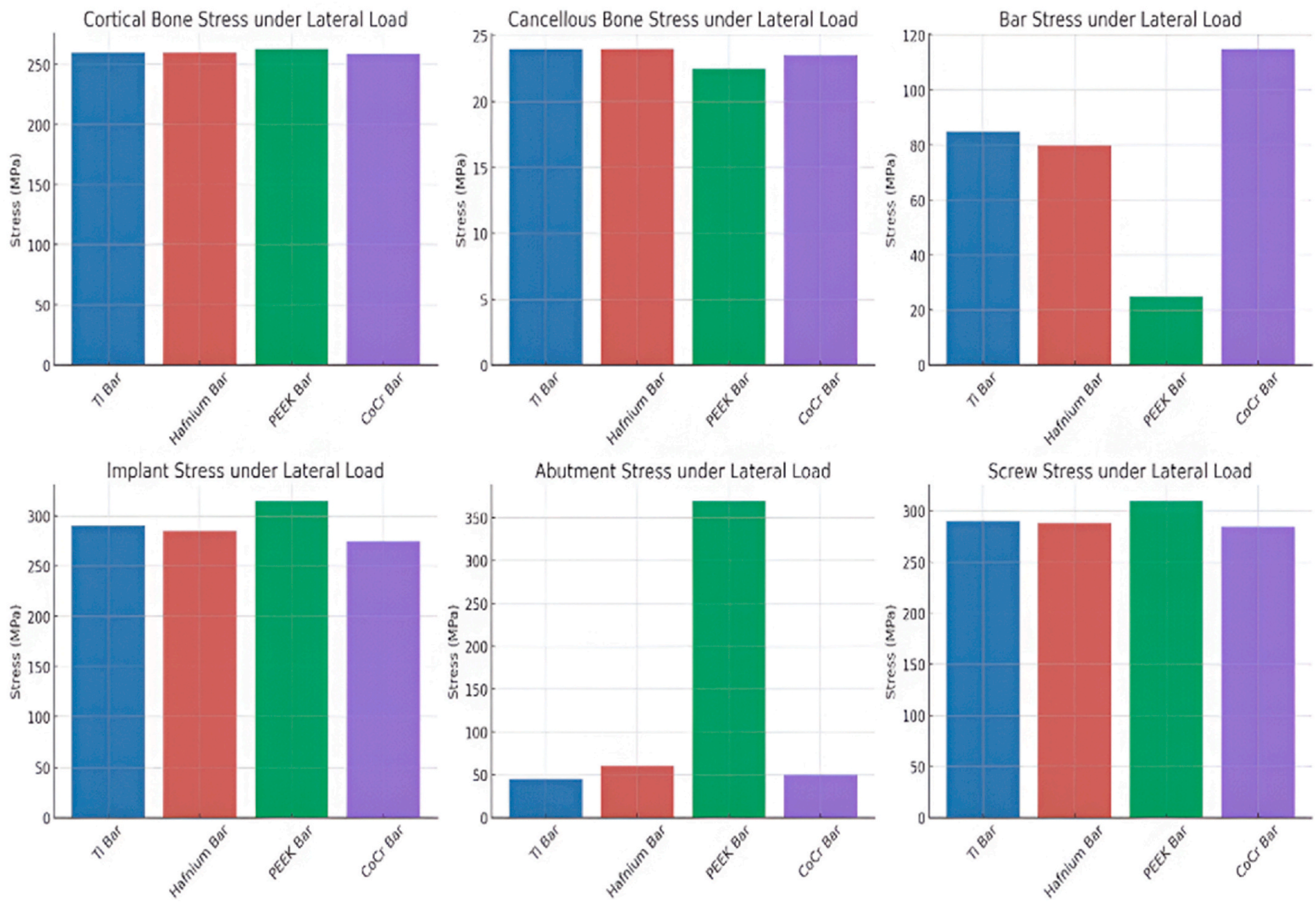

Fig. 3. Lateral von Mises Stress Distribution across Anatomical and Prosthetic Components.

Table 3
Stress result summary for lateral maximum load condition (MPa).

Name	Model 1 – Ti Bar	Model 2 – Hafnium Bar	Model 3 – PEEK Bar	Model 4 – Cobalt Bar
Cortical	103.28	103.29	103.37	103.24
Cancellous	21.32	21.39	22.46	21.06
Bar	89.90	75.92	25.33	113.70
Implant	287.44	290.80	311.89	281.36
Abutment	36.66	48.74	347.70	34.44
Screw	210.53	214.08	288.30	204.89

element analysis of mandibular full-arch prostheses, reported that low-modulus polymer bars (PEEK and PMMA) reduced von Mises stress within the framework and implants but induced critically high tensile stresses in trabecular bone. Only stiffer materials such as titanium, cobalt–chromium, and zirconia-maintained bone stress within physiological limits. Our findings are consistent with these results: while the PEEK bar slightly reduced bone stress under lateral loading, it markedly increased stress in the abutment screws, potentially contributing to mechanical complications. This effect appears more pronounced under oblique or lateral forces, corroborating Sirandoni et al.'s observations regarding resilient bar materials.[34] In contrast, rigid frameworks concentrate stress within the bar itself—a behavior consistent with the concept of stress shielding, wherein stiffer materials protect peri-implant bone by absorbing greater load. Hazır et al. (2025), through dynamic chewing simulations, confirmed that CoCr and Ti frameworks—due to their high elastic moduli—reduced stress transmission to bone and abutments while increasing internal framework stress. Conversely, PEEK frameworks distributed more stress to surrounding components. Their findings further demonstrated that higher framework stiffness significantly decreased peak stresses in supporting structures under lateral loading, despite elevating internal bar stress. These results highlight the biomechanical influence of material stiffness on load distribution within implant-supported prostheses.[35] The behavior of hafnium in our study, closely paralleling that of titanium, suggests that materials with intermediate stiffness may offer an optimal balance between load distribution and structural integrity. This aligns with findings in materials science, where titanium alloys with moderately reduced elastic moduli (e.g., Ti-Zr or β-titanium alloys) have demonstrated enhanced load-sharing capabilities without compromising mechanical stability.[25] Emerging clinical data support the findings of this finite element analysis. In a 26-month study, Nobre et al. reported comparable peri-implant bone preservation between full-arch prostheses supported by PEEK and titanium bars; however, mechanical complications were significantly more frequent with PEEK frameworks, including screw loosening and fractures. These results align with our simulation, suggesting that while PEEK may minimize bone stress, its lower stiffness increases mechanical load on prosthetic components, potentially compromising long-term reliability. Integration of computational and clinical outcomes is essential to optimize material selection for both biological compatibility and structural durability.[36]

In recent years, alternative biomaterials such as zirconia and PEKK (polyetherketoneketone) have gained attention for implant-supported prostheses owing to their favorable mechanical and esthetic properties. Multilayered zirconia systems now exhibit gradient translucency and improved flexural strength, offering better esthetics and higher structural stability compared to conventional monolithic zirconia.[37] However, the inherent brittleness of zirconia and its limited tolerance to cyclic fatigue remain key challenges. PEKK, a stiffer polymer than PEEK (elastic modulus ≈5–6 GPa), shows enhanced load-bearing capacity and energy absorption, which may provide improved stress distribution under functional loads.[11] These materials were not included in the present simulation set, but future analyses incorporating zirconia and PEKK could provide broader insight into the biomechanical performance of emerging framework materials.

From a clinical perspective, balanced stress distribution within the framework and abutment complex is crucial to minimize long-term complications such as screw loosening, bar fracture, or peri-implant bone resorption. Concentrated stresses approaching the fatigue threshold of abutment or screw materials could accelerate microgap formation and mechanical failure. The results highlight the importance of selecting materials that achieve optimal stiffness without excessive load transfer to the implant–bone interface.[38]

Despite the precision of finite element analysis, several methodological limitations restrict the generalizability of our findings. The use of static loading does not replicate the complex, cyclical, and multidirectional forces experienced during mastication, which can induce fatigue, micromovements, and time-dependent deformation. Dynamic or fatigue-loading simulations are needed to better assess the long-term performance of materials like PEEK and Hafnium. Furthermore, the bone was modeled as a homogeneous, isotropic structure with idealized osseointegration, overlooking the anisotropic and viscoelastic nature of actual bone and the variability in implant–bone interface conditions. The absence of soft tissues, such as mucosa or denture liners, and the exclusive use of a single bar configuration (straight, four-implant model) limit anatomical and prosthetic realism. The linear elastic material models also omit potential plastic deformation or failure, particularly relevant for polymers nearing their strength limits as in the case of the PEEK framework in this study, which approached 350 MPa. Sensitivity analysis of material property variation and loading direction was not conducted in this study and will be incorporated in future work to assess model robustness. Future research should incorporate nonlinear bone modeling, interfacial dynamics, and fatigue analysis, while exploring alternative materials such as PEKK, fiber-reinforced composites, and beta-titanium alloys. In vitro validation and clinical trials are essential to confirm these findings and support the use of novel materials like Hafnium in prosthetic frameworks.

5. Conclusion

This finite element analysis demonstrated that the mechanical properties of bar materials play a critical role in determining lateral stress distribution within mandibular implant-supported prostheses. Hafnium exhibited a stress distribution pattern similar to titanium, effectively balancing load transfer between the framework and supporting components. Cobalt–chromium localized stress within the bar, offering greater protection to peri-implant bone, while PEEK reduced bone stress but imposed higher loads on abutments and screws, indicating a higher risk of mechanical complications.

Owing to its favorable biomechanical characteristics, hafnium demonstrates potential as a viable alternative to conventional framework materials in implant-supported prostheses. Future experimental investigations and longitudinal clinical studies are essential to validate its long-term performance and clinical suitability in prosthodontic applications.

Patient's/Guardian's consent

No patients were involved in this study. Hence, patient's or guardian's consent was not required.

Ethical clearance

This study was conducted after obtaining ethical approval from the Institutional Research Board of the Dental College and Hospitals, Chennai, India. The approval number is included in the manuscript (SRB/SDC/PROSTHO- SRB/SDC/PROSTHO-2206/25/071).

Sources of funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors sincerely acknowledge the support of the Department of Prosthodontics and the institutional research committee for their guidance and facilities provided during the study.

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