

Review Article

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Exploring polyetheretherketone in dental implants and abutments: A focus on biomechanics and finite element methods

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Abstract: This review article investigates the properties and applications of polyetheretherketone (PEEK) in the field of dental implantology. PEEK has emerged as a significant material of interest due to its mechanical strength, biocompatibility, and radiolucency. The article provides a detailed examination of PEEK's biocompatibility and the various reinforcements that enhance its performance, including PEEK/HA, PEEK/ β -TCP-TiO₂, and CFR-PEEK. Focusing on dental applications, we discuss PEEK's use in implant abutments, fixed dental prostheses, implants, and its commercial forms available for dental use. Further, the mechanical behavior of PEEK and its composites is analyzed, including its elastic behavior under various stress conditions and wear resistance. Moreover, the article conducts an integrative systematic review on the stress distribution in dental implants or abutments made from reinforced PEEK composites, assessed through finite element analysis. The aim of this review is to provide insights into the current state of research, the benefits, challenges, and future prospects of PEEK in implantology, and the biomechanical evaluation methods that underpin the development of this promising material.

Keywords: polyetheretherketone, biomaterials, dental implants, abutments, finite element, stress

1 Introduction

Advancements in dentistry involve the evolution of materials. Biocompatibility, aesthetics, low plaque affinity, and

characteristics similar to dental structure are among the essential criteria of modern materials used in dentistry [1,2]. Polymers are materials that have allowed significant technological progress in the second half of the twentieth century, although they are now controversial from an environmental standpoint [3–7]. Polyetheretherketone (PEEK) is among the most innovative polymers, described as “high performance.” It was first used in the 1980s in the aerospace and automotive industries [8,9]. Then, due to its remarkable mechanical properties, biocompatibility, and modulus of elasticity similar to human bone, PEEK began to be studied in the field of orthopedic prostheses in the 1990s [6,10–12]. Today, it is expanding in most clinical disciplines of dentistry. Often shaped conventionally, meaning through extrusion, compression, injection, or machining, manufacturers are now turning to 3D printing of PEEK, or additive manufacturing [13–16].

The advancement of dental implant, abutment, and associated materials necessitates adherence to established *in vitro* and *in vivo* tests before they are fit for commercial use. Conducting *in vivo* tests on a substantial number of samples can be lengthy and may pose challenges to animals or patients involved. Moreover, potential inaccuracies in these assessments could lead to misleading outcomes, impacting both the materials and the results of the experiment. Therefore, the finite element method (FEM) emerges as a valuable tool for predicting potential mechanical complications using theoretical models coupled with *in vitro* tests [17–20]. The finite element analysis (FEA) is frequently used to assess the biomechanical behavior of implantable biomaterials *in vitro*, whether in orthopedics, traumatology, or oral implantology, a trend is reflected by the increasing number of publications on the subject (Figure 1). This method allows for the evaluation of stress distribution during the load transfer of an implant to the underlying bone structures and typically follows a consistent procedure.

This article delves into the latest advancements in PEEK-based biomaterials for dental applications, highlighting recent improvements in properties and mechanical testing. We will conduct an integrative systematic review focused on analyzing

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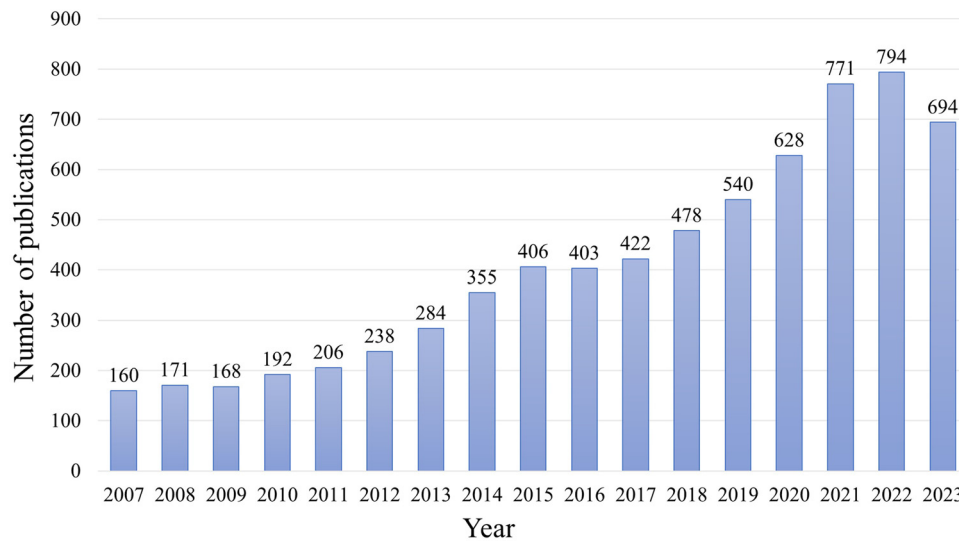


Figure 1: The number of PubMed indexed publications on finite elements used in dental specialties since 2007. Search query: (peek) AND (dental implants) AND (FEA) OR (FEM).

stress distribution across dental implants and abutments made from carbon fiber-reinforced PEEK composites, utilizing FEM studies as a core analytical tool (Figure 1). The investigation is structured around key research questions, aiming to uncover through a systematic approach:

- 1) How are PEEK and its composites applied in the dental field, especially as materials for implant abutments and the core of dental implants?
- 2) What do mechanical tests, including those for tensile, compression, bending stress, wear resistance, and particularly fatigue tests, reveal about the suitability of PEEK and its composites for dental implant applications?
- 3) How does FEA enhance our understanding of stress distribution in dental implants and abutments made from carbon fiber-reinforced PEEK composites?

The electronic searches described previously contributed to initial grouping:

- On PubMed: 181 articles
- On ScienceDirect: 275 articles

After eliminating duplicates, the titles, and abstracts of the articles resulting from the searches, only 45 publications were retained.

A complete reading of the text and an analysis of the relevance of the articles finally led to a final result grouping 25 articles (Table 2). The publication dates of the articles range between 2010 and 2023, except for 1 article.

A selection tree of articles (as depicted in Figure 2) was therefore made from the 25 articles, including 6 literature reviews (21–24–27–28–41–43), 12 studies for FEA (22–23–29–30–32–33–34–35–37–39–44–45), and 9 *in vitro* experimental studies (25–26–31–36–38–40–42).

2 Information sources and search strategy

A literature search on PubMed (via National Library of Medicine) and ScienceDirect (Elsevier BV) was conducted using the following search terms (Table 1):

- **Term 1:** (peek) AND (stress analysis, mechanical) AND (dental)
- **Term 2:** (peek) AND (dental) AND (mechanical phenomena) AND (stress, mechanical) AND (material testing)
- **Term 3:** (peek) AND (dental) AND (finite element) AND (FEA)

Table 1: Electronic search results from PubMed and ScienceDirect databases

Database	Results For			Total results
	Term 1	Term 2	Term 3	
PubMed	79	24	78	181
PubMed without duplication	40	13	55	108
ScienceDirect	137	69	69	275
ScienceDirect without duplication	74	45	54	173

Table 2: Aim, materials, methods, and key findings derived from the chosen research papers

Articles	Type of literature and study design	Objectives	Methods	Types of biomaterials studied and their composition	Results
2023 Title: Biomaterials and clinical application of dental implants in relation to bone density – A narrative review Author: Khaohoen <i>et al.</i> Keywords: biomaterial, bone density, dental implants, ... Reference: [21]	Type: Dental/ review	To assess how implant materials, designs, and surgical techniques impact bone density, focusing on titanium, zirconia, and PEEK implants, and to determine the optimal choices for varying bone densities	Analysis of literature on the biomechanical and biological effects of dental implant materials and designs on bone density	1. PEEK 2. Zirconia 3. Titanium	Titanium is preferred for its reliability, though it presents visibility issues in thin gums and allergy concerns Zirconia is chosen for aesthetics and metal sensitivity but may fracture more easily PEEK is promising for its bone-like properties, yet requires further research Implant geometry is critical, especially in low-density bone, to enhance stability
2023 Title: Evaluation of stresses on mandible bone and prosthetic parts in fixed prosthesis by utilizing CFR-PEEK, PEKK, and PEEK frameworks Author: Shash <i>et al.</i> Reference: [22]	Type: Dental/FEA	The article aims to assess the impact of using polymeric frameworks instead of titanium on stress distribution within the components of fixed prostheses and surrounding bone tissue, considering the influence of spongy bone density on the success of fixed prosthesis in edentulous patients	A FEA assessed stress distribution in an edentulous mandible with fixed prostheses using polymeric materials (CFR-PEEK 60%, CFR-PEEK 30%, PEKK, PEEK) vs titanium, simulating unilateral and bilateral 300 N forces on prostheses in spongy bones of varying densities (normal, low, high)	1. CFR-PEEK 60% 2. CFR-PEEK 30% 3. PEKK 4. PEEK	The study showed that the PEEK framework minimized stress on bone tissues and increased mucosa stress, thus reducing bone resorption risk Frameworks tested (CFR-PEEK 60%, CFR-PEEK 30%, PEKK, PEEK) worked well in normal and high spongy bone densities
2023 Title: Evaluation of stress and strain on mandible caused by changing the bar material in hybrid prosthesis utilizing “All-on-Four” technique Author: Shash <i>et al.</i> Reference: [23]	Type: Dental/FEA	The research aimed to explore the viability of using ceramics, polymers, and composites as alternative materials for the bar component in hybrid prostheses, traditionally made of titanium or gold, to address full edentulism and restore the mastication mechanism	A 3D mandible model with a hybrid prosthesis was analyzed using various bar materials. The study measured von Mises stress on the prosthesis and mandible, including maximum and minimum principal stresses and strains on the bone. The simulation tested unilateral and bilateral forces to evaluate their impact on cortical and cancellous bones and mucosa stress	1. Porcelain 2. Zirconia 3. Alumina 4. ZTA 5. ATZ 6. PEKK 7. PEEK 8. CFR-PEEK 9. GFR-PEEK 10. FRR 11. HA-PEEK	A PEEK bar reduced von Mises stresses on cortical and cancellous bones significantly under unilateral and bilateral forces, while slightly increasing mucosa stress, remaining below pain thresholds. Despite these variations, all materials, including ceramics, polymers, and composites, kept bone stresses within safe limits,

(Continued)

Table 2: *Continued*

Articles	Type of literature and study design	Objectives	Methods	Types of biomaterials studied and their composition	Results
2022 Title: Properties of polyetheretherketone (PEEK) implant abutments: A systematic review Author: Ghazal-Maghras <i>et al.</i> Keywords: Abutment, polyetheretherketone, titanium, dynamic fatigue, ... Reference: [24]	Type: Dental/ review	To know the mechanical and functional properties of PEEK abutment and to find out if it is a potential substitute for titanium abutments	The search focused on studies from 2018 to 2020 in English, documented in PROSPERO with ID 274834. Data extraction and quality evaluation adhered to revised CONSORT standards	12. BIOHPP 1. Titanium (Ti) 2. PEEK	suggesting they are viable alternatives to titanium for hybrid prosthesis bars The existing data indicate that PEEK implant abutments lack the necessary biomechanical properties to serve as a permanent replacement for titanium abutments. Nonetheless, they are regarded as a suitable temporary option, particularly if placed in the anterior region
2022 Title: Influence of different combinations of CAD-CAM crown and customized abutment materials on the force absorption capacity in implant supported restorations – <i>In vitro</i> study Author: Taha <i>et al.</i> Keywords: customized abutments, force, force absorption, implant prosthetics, ... Reference: [25]	Type: Dental/ experimental study	To assess the capability of implant-supported restorations to absorb force, employing various CAD-CAM materials in the creation of crowns and customized abutments	Utilized 12 3D finite element models, 6 implant designs, applied axial loads, and analyzed displacements, stress, and strain in bone tissue	1. Titanium (Ti) alloy 2. PEEK 3. Ti-PEEK composite	Force curve progression varied by material. Zirconia abutments had highest slopes in ZZ, then EZ, VZ, PZ. PEEK abutments showed least slopes in ZP, EP. PEEK abutments increased slope loss in Zirconia, e.max crowns but not in PEEK, Vita Enamic crowns
2022 Title: <i>In vitro</i> assessment of PEEK and titanium implant abutments: Screw loosening and microleakage evaluations under dynamic mechanical testing Author: Ortega-Martínez <i>et al.</i> Reference: [26]	Type: Dental/ experimental study	This <i>in vitro</i> study aimed to evaluate the mechanical and functional properties of PEEK implant abutments as an aesthetic, non-metallic alternative to traditional titanium abutments, which have aesthetic limitations and are more challenging to customize in clinical settings	In this study, 24 PEEK and 24 titanium grade 5 implant abutments fixed to MIS Implants type M4 were tested for screw loosening and microleakage in a 2% methylene blue solution, under static and dynamic conditions following ISO 14801:2016 standards. Observations at 8× magnification and statistical analysis (2-factor ANOVA, chi-square) compared the PEEK and titanium groups	1. PEEK for manufacturing half of the implant abutments. 2. Titanium grade 5 for the other half of the implant abutments. 3. MIS Implants type M4 (3.75 × 16 mm)	The study showed that titanium implant abutments performed better mechanically than PEEK abutments, with titanium experiencing around 10% torque loss compared to PEEK's, which is up to 50%. Additionally, 91.6% of titanium abutments had no microleakage, whereas all PEEK abutments did under dynamic loading

(Continued)

Table 2: Continued

Articles	Type of literature and study design	Objectives	Methods	Types of biomaterials studied and their composition	Results
2022 Title: Biomaterials and clinical applications of customized healing abutment – A narrative review Author: Chokaree <i>et al.</i> Keywords: PEEK, PMMA, customized healing abutment, ... Reference: [27]	Type: Dental/ review	The article aims to assess materials for customized healing abutments used in implant surgery to enhance tissue appearance and reduce treatment and prosthesis fabrication time	A literature review was conducted, searching English-language articles on customized healing abutments in Google Scholar, PubMed/MEDLINE, ScienceDirect, and Scopus databases up to August 2022	1. PEEK 2. PMMA 3. Zirconia 4. Resin composite 5. Titanium	All materials—PEEK, PMMA, zirconia, resin composite, and titanium—showed promising results for customized healing abutments. However, more research is needed to compare their effects on peri-implant tissues conclusively
2022 Title: PEEK biomaterial in long-term provisional implant restorations: A review Author: Suphangul <i>et al.</i> Keywords: PEEK, carbon fiber, implant abutment, ... Reference: [28]	Type: Dental/ review	The review article examines PEEK as a material for long-term provisional implant restorations in dental implantology, highlighting its growing use in various dental procedures	A comprehensive search across Google Scholar, ScienceDirect, PubMed/MEDLINE, and Scopus identified English-language articles on PEEK as a biomaterial for long-term provisional implant restorations, selecting relevant ones for literature review	1. PEEK 2. CFR-PEEK	PEEK, especially when enhanced with 30–50% carbon fibers, is recognized for its broad applicability in implant dentistry, including dental implants, temporary abutments, and various prostheses, indicating its promise for both temporary and long-term provisional restorations. This suggests potential for wider clinical use
2021 Title: Stress distribution around different abutments on titanium and CFR-PEEK implant with different prosthetic crowns under parafunctional loading: A 3D FEA study Author: Mourya <i>et al.</i> Reference: [29]	Type: Dental/FEA	Clinical studies linked implant failure to bruxism, while 3D FEA evaluated stress distribution in straight and angled abutments with titanium and CFR-PEEK implants and two crown types under parafunctional loading	Twelve 3D bone block models of the maxillary right premolar with osseointegrated implants were divided into CFR-PEEK and titanium groups, each featuring three abutment angles and two crown types. Stresses from 1,000 N vertical and 500 N oblique loads were analyzed using ANSYS software	1. CFR-PEEK 2. Titanium 3. Prosthetic crowns: PFM, and PEEK	Both CFR-PEEK and titanium implants yielded similar bone stress under vertical and oblique loads, with straight abutments outperforming angled ones, and PEEK crowns inducing less stress than (PFM)
2021 Title: Biomechanical performance of Ti-PEEK dental implants in bone: An in-silico analysis Author: Ouldryerou <i>et al.</i>	Type: Dental/ experimental study and FEA	To compare Ti-PEEK composite dental implants with conventional titanium implants, assessing host bone behavior,	Utilized 12 3D FEMs, six implant designs, applied axial loads, and analyzed displacements, stress, and strain in bone tissue	1. Titanium (Ti) alloy 2. PEEK 3. Ti-PEEK composite (with the outer layer made of PEEK and	Ti-PEEK implants outperformed conventional dense titanium implants (Implant A) in non-bone loss conditions. However, in bone loss scenarios, both

(Continued)

Table 2: *Continued*

Articles	Type of literature and study design	Objectives	Methods	Types of biomaterials studied and their composition	Results
Keywords: Bone, Composite, Implant, Mechanostat, Ti-PEEK Reference: [30]		especially under conditions of marginal bone loss		inner structures made of Ti)	Implant A (made entirely of dense titanium) and Implant E (designed with titanium in the upper half and PEEK in the lower half) showed equal effectiveness
2020					
Title: Comparative evaluation of the wear resistance of two different implant abutment materials after cyclic loading Author: Ragupathi <i>et al.</i> Keywords: Abutment, Polyether ether ketone, implant-abutment interface, ... Reference: [31]	Type: Dental/experimental study	The paper aims to compare the wear resistance of titanium and PEEK abutment materials when paired with titanium implants after cyclic loading, assessing significant differences in wear resistance under repeated mechanical stress	The study involved 20 titanium implants in resin blocks, divided into groups with titanium and PEEK abutments, each undergoing 550,000 cycles of cyclic loading. Surface roughness was measured by profilometry, abutment surfaces imaged by SEM, and elemental analysis conducted using EDS, to evaluate changes at the implant-abutment interface before and after loading	1. Titanium (Ti): Group I 2. PEEK: Group II	The study compared wear resistance of titanium and PEEK abutment materials connected to titanium implants after cyclic loading, finding no significant difference in wear patterns or surface roughness changes between the two, as confirmed by SEM and EDS analyses. Both materials are comparably effective for dental implant abutments, with PEEK offering an aesthetic alternative
2019					
Title: Effect of different biocompatible implant materials on the mechanical stability of dental implants under excessive oblique load Author: Bataineh <i>et al.</i> Keywords: CFR-PEEK, biocompatible, biomaterials, deformation, dental implant, ... Reference: [32]	Type: Dental/FEA	The study evaluates the impact of replacing traditional titanium with carbon reinforced polyether ether ketone (CFR-PEEK) composites on stress distribution in peri-implant bone under excessive oblique loading, examining if CFR-PEEK's bone-like mechanical properties can enhance stress distribution and decrease implant failure risks	The methodology includes constructing 3D models of a dental implant in the first mandibular molar from CT scans and creating five models using titanium, CFR-PEEK, and lithium disilicate. It employs 3D FEA to assess stress distribution at the implant-bone interface under excessive oblique loads and examines physical interactions, including friction effects between contacting surfaces	1. Titanium (Ti) 2. CRF-PEEK 3. Lithium disilicate	The study compared wear resistance between titanium and PEEK abutment materials connected to titanium implants post-cyclic loading, revealing only slight and statistically insignificant differences in surface roughness and wear patterns as confirmed by SEM and EDS analyses. Both materials proved comparably effective for dental implant abutments, with PEEK also offering aesthetic benefits

(Continued)

Table 2: Continued

Articles	Type of literature and study design	Objectives	Methods	Types of biomaterials studied and their composition	Results
2018 Title: 3D FEA study on implant threading role on selection of implant and crown materials Author: Wazeh <i>et al.</i> Keywords: Dental implant, FEA, PEEK, PEKK, Titanium Reference: [33]	Type: Dental/FEA	Examination of the impact of thread design in dental implants and the choice of material on mandibular bone response, considering two distinct crown materials: Translucent zirconia and PFM	Two single-piece dental implant designs with a proxy crown were modeled on simplified bone structures in FEA. CAD/CAM software crafted the components, which were assembled and analyzed in ANSYS, applying 100 N compressive and 50 N oblique loads	1. Reinforced PEKK 2. PEKK 3. Titanium 4. Zirconia 5. PFM	In 24 cases, micro-threading slashed the dental implant's peak Von Mises stress by 50–70% compared to conventional threading. A 50 N oblique force generated 4–5 times the stress on the implant as a 100 N vertical load. Crown material swaps had minimal impact on cortical bone stress, while titanium implants cut stress by 50–100% vs reinforced PEKK or PEEK
2018 Title: Computational modelling: damage mechanics; laminated orthopaedic devices; mechanical testing; medical grade carbon fiber reinforced PEEK Author: Gallagher <i>et al.</i> Keywords: computational modelling, damage mechanics, ... Reference: [34]	Type: Dental/FEA	The study focuses on the mechanical behavior and failure mechanisms of PEEK-OPTIMA™ Ultra-Reinforced, a unidirectional CFR-PEEK, to develop laminated orthopedic devices and predictive computational models	A series of multi-axial experimental tests were conducted, including tension, compression, in-plane shear, and fracture toughness tests, along with the development of a computational failure model that incorporates observed damage mechanisms	PEEK-OPTIMA™ Ultra-Reinforced laminates	The study identifies three key damage mechanisms: inter-laminar delamination, intra-laminar cracking, and anisotropic plasticity. The computational model effectively predicts these complex failure mechanisms, supporting the design of safe, fiber-reinforced laminated orthopaedic devices
2018 Title: Effect of different restorative crown and customized abutment materials on stress distribution in single implants and peripheral bone: A three-dimensional FEA study Author: Kaleli <i>et al.</i>	Type: Dental/FEA	To evaluate the stress distribution effects of resin-matrix ceramic and PEEK customized abutments on dental implants and adjacent bone using FEA	The study used 3D modeling with STL data to create implant systems and abutments, and developed six models combining different restoration materials (TZI, IPS, VTE) and abutments (PEEK, zirconia). These models were	1. Bone-level implant system 2. Titanium base abutment 3. Translucent zirconia (TZI) for restoration	Oblique loading induced elevated stress in implants, crowns, and cortical bone, with VTE crowns showing lower stress. Zirconia abutments faced greater stress than PEEK

(Continued)

Table 2: Continued

Articles	Type of literature and study design	Objectives	Methods	Types of biomaterials studied and their composition	Results
Reference: [35]					
			subjected to vertical (200 N) and oblique (100 N) loads, analyzing stress distribution <i>via</i> von Mises and principal stress methods	- Lithium disilicate glass ceramic (IPS) for restoration - Polymer-infiltrated hybrid ceramic (VTE) for restoration - PEEK for customized abutments	ones. Stress patterns in implants and surrounding bone remained consistent across all models
2016					
Title: Comparison between PEEK and Ti6Al4V concerning micro-scale abrasion wear on dental applications Author: Sampaio <i>et al.</i> Keywords: Bio-tribology, micro-scale abrasion, PEEK, Ti6Al4V, wear Reference: [36]	Type: Dental/experimental study	The study compared the abrasive wear resistance of PEEK and titanium alloy (Ti6Al4V) under simulated three-body abrasion conditions to mimic wear from food and toothpaste during mastication and tooth brushing	The study conducted micro-scale abrasion tests on PEEK and Ti6Al4V cylinders, using varied loads and hydrated silica suspensions, measuring wear volumes and analyzing wear scars with SEM to determine wear mechanisms	- PEEK - Ti6Al4V alloy	The study revealed that under three-body abrasion tests with hydrated silica suspensions, PEEK showed higher volume loss and lower wear resistance than Ti6Al4V, which consistently outperformed PEEK across different abrasive contents and loads
2016					
Title: Effects of PEEK veneer thickness on the reciprocating friction and wear behavior of PEEK/Ti6Al4V structures in artificial saliva Author: Sampaio <i>et al.</i> Keywords: Biotribology, Ti6Al4V, PEEK, sliding wear, thickness, FEM model Reference: [37]	Type: Dental/FEA	The study examines how varying thicknesses of PEEK veneers impact friction, wear rate, and contact stress on Ti6Al4V substrates, crucial for the durability and effectiveness of biomedical materials in oral applications	PEEK veneers from 0.1 to 2 mm thick were synthesized on Ti6Al4V substrates, tested for friction and wear against alumina in artificial saliva at 37°C, and analyzed <i>via</i> simulations to study the effect of thickness on contact stress	- PEEK - Ti6Al4V alloy - Alumina (Al₂O₃)	Thinner PEEK veneers show higher coefficients of friction and wear rates due to increased contact stress, underscoring the importance of considering veneer thickness in designing biomedical devices, particularly for oral applications requiring optimal friction and wear resistance for long-term success
Title: Pressure behavior of different PEEK materials for dental implants Author: Schwitalla <i>et al.</i> Reference: [38]	Type: Dental/experimental study	Evaluate the mechanical properties of different PEEK composites under static pressure	Nine PEEK composites (11 applications biomedical, 2 applications industrial) tested under static pressure	- VESTAKEEP® M4 R - PEEK-OPTIMA® LT1 - PEEK-CLASSIX® BICI	Mechanical properties: Elastic modulus, yield limit, resistance to compression

(Continued)

Table 2: Continued

Articles	Type of literature and study design	Objectives	Methods	Types of biomaterials studied and their composition	Results
2015 Title: FEA of the biomechanical effects of PEEK dental implants on the peri-implant bone Author: Schuitalla <i>et al.</i> Reference: [39]	Type: Dental/FEA	Show the biomechanical behavior differences of three implants (two PEEK vs one titanium)		1. Endolign® 2. PEEK 3. Titanium	Mechanical properties: Modulus of elasticity, coefficient of Poisson Stresses at the bone/implant: Ultimate tensile stress, von Mises, deformation and pressure on the peri-implant bone
2015 Title: Flexural behavior of PEEK materials for dental application Author: Schuitalla <i>et al.</i> Reference: [40]	Type: Dental/experimental study	Evaluate the mechanical properties of different PEEK composites by the three-point bending test	In vitro study: 150 specimens in the form of a bar made from 11 PEEK composites (9 applications biomedical, 2 applications industrial) tested by three-point bending test	1. VESTAKEEP® M4 R 2. PEEK-OPTIMA® LT1 3. PEEK-CLASSIX® 4. VESTAKEEP® 5. ...	Mechanical properties: Bending modulus, resistance to flexion
2015 Title: Applications of PEEK in oral implantology and prosthodontics Author: Najeeb <i>et al.</i> Reference: [41]	Type: Dental/review	Synthesize the results of research conducted on PEEK in dental applications and provide perspectives on the use of PEEK and its potential clinical applications	Electronic research of English publications over the last 15 years on PubMed using a combination of keywords “polyetheretherketone” and “dental” and “dentistry”	1. Unmodified PEEK 2. CFR-PEEK 3. Modified PEEK: A. PEEK nano-structures B. PEEK nano-composites (TiO ₂ , PEEK, HAF-PEEK)	Mechanical properties: Elastic modulus, resistance to traction PEEK nano-composites (TiO ₂ , PEEK, HAF-PEEK)
2012 Title: Stress shielding and fatigue limits of poly-ether-ether-ketone dental implants Author: Lee <i>et al.</i> Reference: [42]	Type: Dental/experimental study	To evaluate fatigue limits of PEEK and its effects on stress shielding in comparison to traditional titanium dental implants	The study used compressive loading tests on GFR-PEEK, CFR-PEEK, and titanium rods, with GFR-PEEK tested as per ISO 14801. FEA involved 3D models of dental implants and bone. PEEK layer coating was applied to implants for further testing and analysis	1. PEEK 2. GFR-PEEK 3. CFR-PEEK 4. Titanium rods	GFR-PEEK's fatigue limit reached 310 N, exceeding static strength. PEEK implants displayed elevated SED near bone. Both GFR and CFR-PEEK implants are suitable for anterior tooth replacement, potentially reducing stress shielding
2010 Title: A “metal free” material in implantology: the Biopik®	Type: Dental/Review	Presentation of the mechanical and biological properties of “Biopik®” with a view of its application in implantology	Presentation of Biopik®	Biopik®: Tricalcium phosphate (TCP) 10% + titanium oxide (TiO ₂) 10% + PEEK matrix	Mechanical properties: Young's modulus

(Continued)

Table 2: Continued

Articles	Type of literature and study design	Objectives	Methods	Types of biomaterials studied and their composition	Results
Author: Cougoulic <i>et al.</i>					
Reference: [43]					
2010					
Title: Evaluation of the stress distribution in CFR-PEEK dental implants by the three-dimensional FEM Author: Sarot <i>et al.</i> Reference: [44]	Type: Dental/FEA	The stress dispersion around peri-implant bone was evaluated using FEM across four configurations: titanium abutment on titanium implant, CFR-PEEK abutment on titanium implant, titanium abutment on CFR-PEEK implant, and CFR-PEEK abutment on CFR-PEEK implant	<i>In vitro</i> study of the interface human osteogenic cells/material	1. Titanium 2. CFR-PEEK 3. Cortical and medullar bone tissues 4. Feldspathic porcelain for the crown structure 5. Chrome-cobalt structure within the crown	The titanium implant distributes the stresses in a more homogenous manner in relation to the CFR-PEEK implant due to the smaller deformation of this material. The CFR-PEEK implant did not present any advantages in relation to the titanium implant regarding stress distribution to the peri-implant bone
			<i>In vivo</i> study, animal experimentation on osseointegration at 4 weeks		
2006 Title: The long-term mechanical integrity of non-reinforced PEEK-OPTIMA polymer for demanding spinal applications: Experimental and finite-element analysis Author: Ferguson <i>et al.</i> Keywords: PEEK, material properties, creep, cages, fusion Reference: [45]	Type: Dental/experimental study and FEA	Compare the biomechanical performances of PEEK and titanium under constraints and analyze their diffusions	<i>In vitro</i> study: creep and quasi-static compression tests at one and three times in dry conditions and in saline solution (NaCl) at 37°C on cylindrical specimens of PEEK and titanium	1. PEEK-OPTIMA® LT1 (Grade 1 LT1R30) 2. Titanium	Mechanical properties: Modulus of elasticity, creep Stresses at the bone/implant interface: Analysis of the stress distribution after compression, bending, lateral bending, and axial rotation constraints
			Finite element study: 3D modeling of vertebrae and simulation of intervertebral cage implant placement based on PEEK and titanium to compare stress diffusion under different constraints		

3 PEEK

The PEEK is a thermally stable semi-crystalline thermoplastic material. Introduced in 1977 by ICI (Imperial Chemical Industries), this material entered the market between 1978 and 1979. It gained traction in the 1980s across orthopedics, traumatology, and spinal surgery, particularly in the creation of interbody cages [46–49]. By the late 1990s, it was recognized as a premier non-metallic counterpart to titanium in these specialties [10]. The literature on implantology began highlighting this material around 1995 [50]. In April 1998, the debut PEEK implant product, branded as PEEK-OPTIMA™ and compliant with both European Community and Food and Drug Administration standards, was launched [10,51]. PEEK boasts superior mechanical, physical, and chemical attributes. Notably, it has a hardness rating between 99 and 126 on the Rockwell scale [42,52] and an elasticity modulus (4 GPa) that is more akin to cortical bone (20 GPa) than titanium (110 GPa).

3.1 Biocompatibility

From a biomedical perspective, recent studies assert that the results of various experiments conducted on systemic toxicity, inflammatory response, and genotoxicity tests of PEEK and PEEK composite biomaterials support its biocompatibility [53–55]. This blend of biocompatibility and mechanical robustness has solidified PEEK's standing as a preferred material in medical device manufacturing, including but not limited to, spinal fusion cages and dental implants [10]. However, Najeeb *et al.* [41], noted that despite the bio-inertia of unmodified PEEK, this does not present any conclusive evidence of osteo-conductive or osteo-inductive effects *in vivo* and *in vitro* unlike conventional implant materials (zirconium oxide and titanium). Thus, in its unmodified form, the long-term survival rate of PEEK implants is questionable.

To overcome this gap in osteo-integration and to enhance the biological and physical properties of PEEK, numerous nano-modifications have been explored (Table 3).

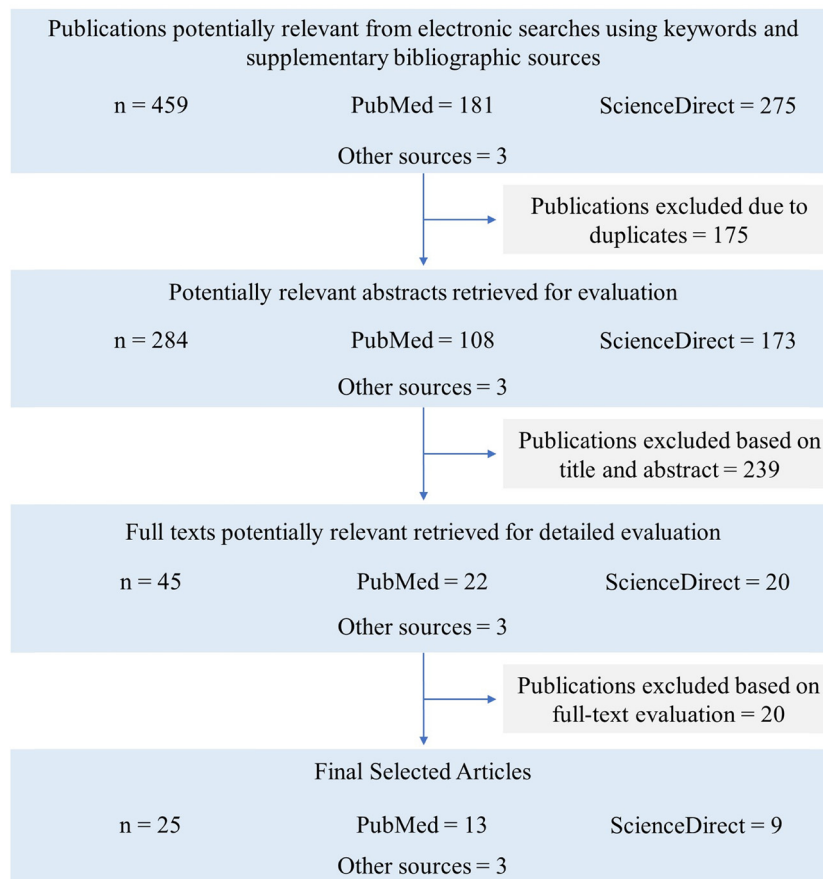


Figure 2: Flow diagram of the search strategy.

3.2 PEEK reinforcement

3.2.1 PEEK/HA

Early investigations to improve PEEK bioactivity focused on the incorporation of hydroxyapatite (HA) particles, a calcium phosphate mineral celebrated for its capacity to facilitate bone attachment and regeneration [56]. By merging HA with PEEK, the aim is to combine PEEK's structural advantages with the bioactive capabilities of HA, thus amplifying the implant's potential for successful and durable integration into bone structures [57]. Research around this hybrid material has yielded positive indications, with PEEK-HA dental prosthetics showing improved bone response and superior bonding than their PEEK-only counterparts [58–60]. While HA incorporation promotes bioactivity, it might compromise the overall mechanical strength of PEEK, a trade-off that requires careful balance [10,41,61]. Further research is pivotal in establishing the optimal ratio of HA in PEEK to maximize both bioactivity and mechanical integrity.

3.2.2 PEEK/beta-tricalcium phosphate (β -TCP)–TiO₂

Studies on the incorporation of beta-tricalcium phosphate into a PEEK matrix has shown that cell proliferation was gradually inhibited when these particles were present. Moreover, the osteo-conduction on the surface of these implants, resulting from the inherent properties of β -TCP, promoted osteo-integration [10].

Cougoulic *et al.* [43] introduced an implant made from this material, marketed under the name SMARTPIK®, which has received EC marking after meeting the ISO 10993 standard: “Biological Evaluation of Medical Devices.”

In addition to the PEEK matrix, which provides the primary mechanical properties of the implant, and the β -TCP (17%) enhancing its osteoconductive potential, the addition of titanium dioxide (8% TiO₂) provides radiopacity. A specific surface treatment optimizes its biological properties[10].

3.2.3 CFR-PEEK

From a biological perspective, CFR-PEEK composites are considered biologically stable, and it has been demonstrated that carbon fibers possess osteo-inductive activity promoting tissue integration and show no toxicity [10,62]. To achieve a strong bond to the matrix, carbon fibers undergo oxidation, allowing them to form a covalent bond robust enough to resist dislocation when a force is applied to the material [63].

The mechanical properties of CFR-PEEK composites can be controlled by the content, dimensions, and orientation of the fibers [64]. The volume percentage of carbon fiber can vary between 30 and 60%. These fibers can be either continuous or short, and they can be unidirectional (oriented parallelly) or multidirectional [38,41,42,64,65]. All authors observe that adding these fibers to PEEK results increased creep, hardness, resistance to compression and fatigue, and also considerably reduced the stress-shielding experienced by the bone since the material's modulus of elasticity can adjust to that of the bone based on the percentage of fiber incorporated [38,41,42,64,65]. Then, the development of new implants requires adherence to established *in vitro* and *in vivo* tests before proceeding to manufacturing.

Due to their adjustable mechanical properties, researchers have suggested through their studies that CFR-PEEK composites are more suitable for use in both orthopedics and oral implantology. Indeed, they are more likely to counteract forces causing stress peaks, ensuring a more uniform distribution of load to the peri-implant bone than the gold-standard implants [38,41,61].

4 PEEK dental applications

As we delve deeper into the applications of PEEK in dentistry, we will explore the use of PEEK in various capacities: as implant abutments, a material for removable partial dentures, a foundation for fixed dental prostheses, and even as the core material for dental implants.

Table 3: Nano-modification of PEEK to increase its bioactivity

Nano structured surfaces	Bioactive nano-composites
Spin-coating with nano-Hap [66,67]	TiO ₂ /PEEK [68–70]
Plasma-gas treatment (O ₂ /Ar, NH ₄) [71,72]	
Plasma electron beam deposition (Ti, TiO ₂) [54,73]	HAF/PEEK [57,70]
Plasma ion immersion implantation (TiO ₂) [74,75]	

Note: TiO₂: Titanium dioxide nanoparticles and HAF: Hydroxy-fluorapatite nanoparticles.

4.1 PEEK implant abutments

In the field of implant dentistry, an abutment serves as the bridge between the prosthetic restoration and the implant itself (Figure 3). Abutments are crafted from a variety of materials, including titanium, gold, zirconium, and ceramics [76]. Recently, there has been an increased utilization of PEEK abutments. Notably, in instances of implant screw damage, PEEK screws offer ease of removal. Studies have shown that PEEK abutments can endure intraoral chewing forces akin to those experienced by titanium abutments. The soft tissue response to PEEK is commendable, often leading to optimal gingival tissue healing [77].

The semi-crystalline nature of PEEK contributes to its reduced brittleness, leading to deformation rather than breakage. Research has shown that when using PEEK for abutments, while the prosthesis remains unharmed, the abutment might deform. Nevertheless, the prosthesis' functionality can be restored by replacing the deformed abutment [78]. In a study by Koutouzis *et al.*, a randomized controlled clinical trial found negligible differences in bone loss and tissue inflammation between PEEK and titanium abutments (Figure 4). Furthermore, the composition of oral bacteria observed was consistent with that seen with titanium, zirconia, or PMMA abutments [79].

The distribution of occlusal forces and the manner in which stress is distributed during the implant healing period significantly impact the enduring outcomes of implant procedures. In a study by Taha *et al.* [25], they examined the interplay between various crown-abutment combinations and their impact on the force absorption properties of implant-supported restorations. Their findings indicated that pairing resin-based ceramic crowns with PEEK abutments did not amplify force absorption capabilities. This could be attributed to the notably reduced elastic modulus of PEEK custom

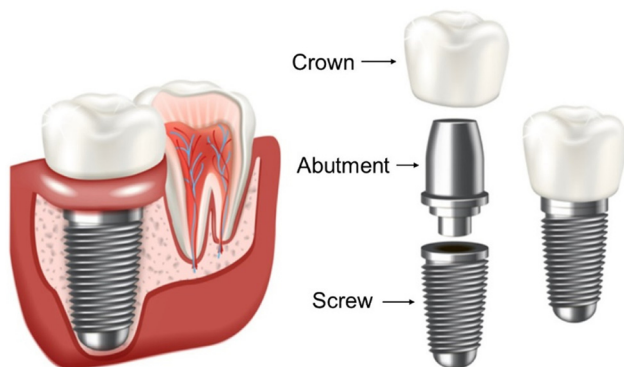


Figure 3: Schematic representation of the structure of a dental implant.

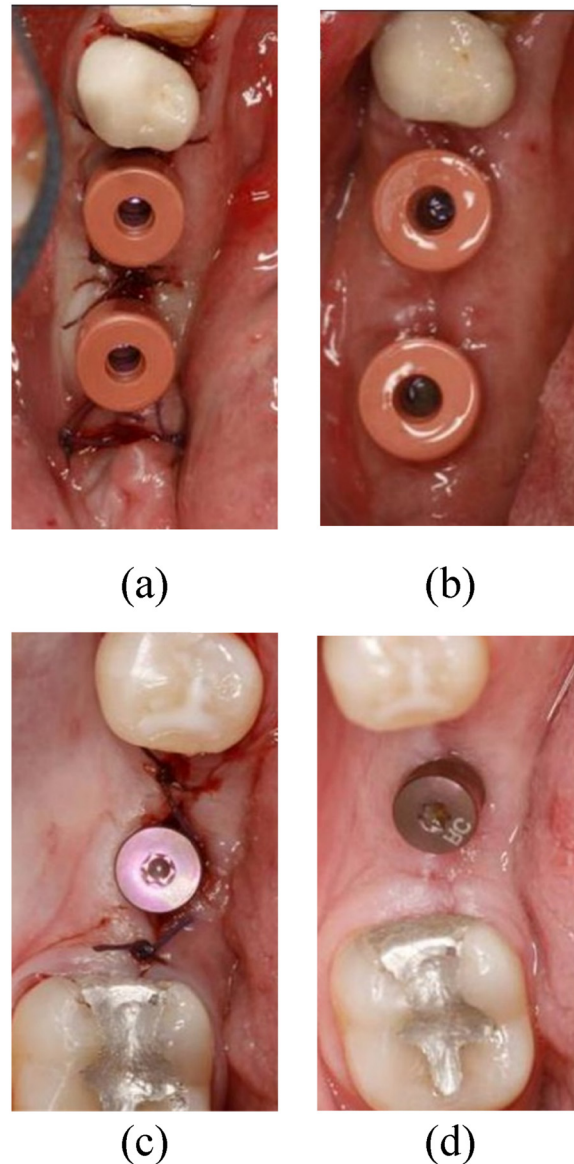


Figure 4: Occlusal view of implants with PEEK abutments (a) following installation and (b) at 3 months. And, occlusal view of implants with titanium abutments (c) following installation and (d) at 3 months [79].

abutments, leading to diminished stress within the abutment, but increased stress on the associated crown [35].

Ceramic-reinforced PEEK (RPEEK) is another variant used in implant abutments noted for its good biomechanical properties and biocompatibility, with Al-Rabab'ah *et al.* [80] reporting stable bone and soft tissue around implants over 2 years.

Otherwise, Al-Zordk *et al.* discussed the critical aspect of fixation techniques in implant-supported restorations, highlighting the advantages of cement-screws for their superior passive fit, aesthetic appeal, and force distribution [81]. Zarone *et al.* further asserted that cement-screw

systems have a greater load-bearing capability compared to screw-retained systems [82]. Freitas *et al.* [83] observed that restorations retained by cement and featuring internal connections display enhanced fracture resistance, leading to their preference in Atsu *et al.*'s work [84]. Yet, they caution against the potential for peri-implant diseases due to residual cement in the submucosal area, with prevalence rates ranging from 1.9 to 75% in such restorations [81]. The discussion also touches upon physiological bite forces, noting the range of occlusal forces across different teeth types. Atsu *et al.* reported that titanium abutments exhibit superior fracture toughness (943.67 N) compared to Zr and RPEEK (770.1 N), though the latter two materials show no significant difference in this aspect ($p = 0.001$). Ortega *et al.* presented findings on fracture toughness, with titanium abutments at 468.5 N and PEEK at 200.4 N. They noted that PEEK abutments withstand 1.2 million cycles at 140 N without failure, simulating 5 years of function, but fail under increased loads of 160 N after approximately 89,338 cycles, equating to 4–5 months of use [26]. This behavior indicates PEEK's role as a "sacrificial material," absorbing deformation to prevent damage to the implant or screw, in contrast to titanium where deformation affects the internal connection, potentially endangering the implant's longevity [26]. In another study by Mourya *et al.* [29], the stress distribution around abutments, subjected to both vertical and oblique forces, was assessed for both titanium and carbon-fiber-reinforced PEEK (CF/PEEK) implants. The findings propose that in patients with molar teeth, using straight abutments in conjunction with PEEK crowns could mitigate intraosseous stress levels and potentially avert implant complications.

The available evidence suggests that PEEK abutments may not meet the biomechanical criteria necessary to supplant traditional titanium abutments. Among available

options, zirconium is recognized for its superior biocompatibility as an abutment material [85]. Nevertheless, PEEK exhibits particular merits in applications like customized healing abutment [27], provisional restorations [24,28] for patients lacking functional deficiencies, and for shaping emergency contours during surgical interventions, especially relevant for implants in individuals subject to reduced stress loads.

Figure 5 shows the various PEEK abutments. PEEK healing abutment (Figure 5a) is used as an alternative for classic titanium healing abutment [86], and PEEK with titanium base temporary abutment (Figure 5b) is used for long-term interim restoration, especially in areas with aesthetic consideration [87].

4.2 PEEK as fixed dental prosthesis

For fixed dental prosthetics, PEEK offers a unique solution with its metal-free crowns and bridges, known for their outstanding biocompatibility and robust mechanical attributes (Figure 6). When assessing PEEK against traditional ceramic and metal materials, it becomes evident that PEEK's dental bridge infrastructure remains resilient, even when subjected to *in vitro* aging processes. For implant-linked prosthetic applications, PEEK crowns have showcased effective outcomes [88]. In terms of biocompatibility evaluations, PEEK consistently outperforms many metal-based ceramics. Nevertheless, some experts propose the integration of veneers over PEEK to achieve optimal precision [89]. Given its lightweight nature, PEEK emerges as a promising contender to replace traditional chrome-cobalt prostheses [90–92].



Figure 5: PEEK abutments: (a) PEEK healing abutment (GM customizable healing abutment, Neodent, Curitiba, Brazil), (b) PEEK with titanium base temporary abutment (GM PRO PEEK abutment, Neodent, Curitiba, Brazil).

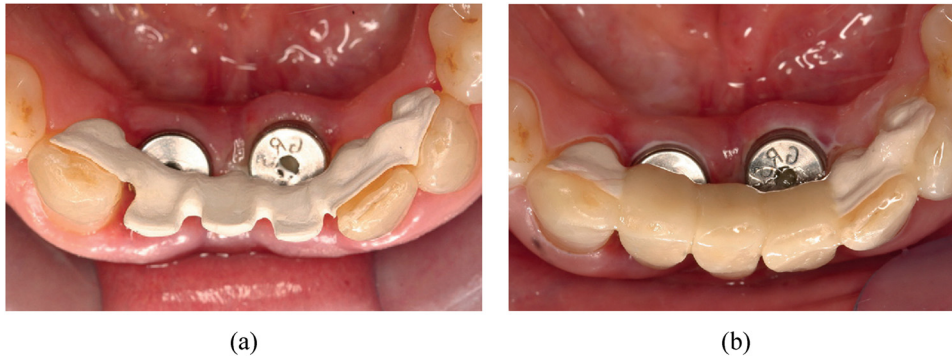


Figure 6: PEEK resin-bonded fixed dental prosthesis: (a) occlusal view and (b) after fixing the teeth [94].

PEEK restorations demonstrate satisfactory resilience against fractures, enduring anterior masticatory forces of around 300 N and forces of 600 N in posterior areas. Extended chewing simulations, replicating up to 5 years of intraoral utilization, revealed no structural damage or debonding incidents in these restorations [77].

4.3 PEEK implants

As mentioned previously, PEEK is emerging as a potential material in implant dentistry, offering a solution to both full and partial tooth loss.

Traditionally, titanium has been the go-to material for dental implants due to its osteoconductive properties. However, PEEK, having elasticity similar to human bone, is now being considered as an alternative to titanium [94]. The stability of an implant can be influenced by several elements, including the occlusal load, bone structure, and potential for bone loss [95]. Khaohoen *et al.* [21] highlight that PEEK is emerging as a viable option in the realm of dental implantology, countering some of the drawbacks associated with titanium such as aesthetic limitations, allergic reactions, and stress-shielding effects. Despite PEEK's outstanding biocompatibility and absence of cytotoxic effects, its osseointegration capabilities lag behind those of titanium, marked by a reduced bone-implant contact (BIC) area, diminished osteoblast activity, and lower osteoconductivity. However, enhancing PEEK's surface hydrophilicity and roughness through nanoscale modifications have been identified as a promising strategy to mitigate these limitations.

Ouldryerou *et al.* indicated that while standard titanium implants tend to concentrate stress in specific bone areas, those made of a titanium-PEEK combination distribute stress more evenly, potentially reducing bone degradation [30]. Interestingly, studies involving animals have shown that titanium-coated PEEK may support bone formation better than its uncoated counterpart [58]. Pure PEEK,

given its hydrophobic nature, might deter initial cell attachment. Yet, some investigations have noted enhanced mechanical bonding between bone and implants when using porous or titanium-coated PEEK, leading to better cellular interaction and integration [96]. Additionally, many studies have reported on methods to increase the bioactivity of PEEK, and various authors have highlighted the need to incorporate bioactive inorganic ceramic particles, such as HA, HAF, β -TCP, and TiO_2 to enhance the osteointegration of PEEK implants [10,67,73,97]. Therefore, while PEEK holds promise, comprehensive studies are crucial before its widespread adoption in dental implantology.

4.4 Commercial forms for dental use

Two leading commercial PEEK brands are widely recognized in the dental sector. PEEK-OPTIMA® is the preferred choice within the US, supplied by Invisio Biomaterial Solutions since 1999, and is primarily used for dental applications such as provisional prosthetic abutments and healing screws [98]. In contrast, Europe mainly utilizes BioHPP™ (Figure 7), produced by Bredent GmbH, which is specifically

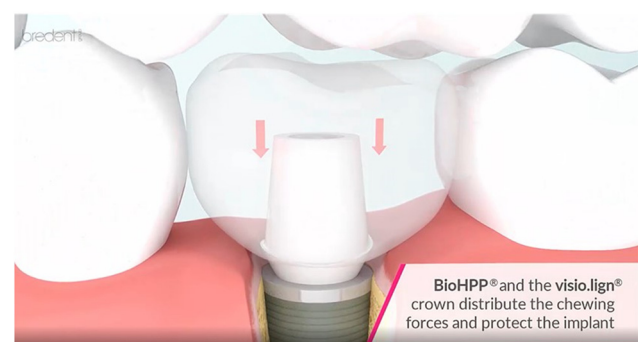


Figure 7: PEEK abutment made by BioHPP [99].

designed for dental applications. It is a modified PEEK material that incorporates ceramic fillers to enhance polishability and is suitable for various dental prostheses and frameworks through injection molding and CAD-CAM processing [99].

5 Mechanical behavior of PEEK and its composites

In this part, we will delve into an in-depth examination of the mechanical behavior properties of PEEK and its associated composites. This analysis will provide a comprehensive understanding of the material's strengths as well as their ability to withstand force stresses without fracturing or undergoing deformation.

5.1 Elastic behavior under tensile, compression, bending stress, and wear resistance

The tensile, compression, and flexural (bending) tests conducted on PEEK have led to determining its ability to deform after being subjected to a constantly increasing loading process.

The application of tensile forces results in a progressive elongation up to the material's breaking point and allows for defining many of its mechanical properties. These elastic properties are derived from the interpretation of a stress–strain curve defining both an elastic and a plastic domain. They are directly dependent on the crystallinity of PEEK, reflecting its thermal treatment history [100,101].

5.1.1 Elastic modulus, flexural and tensile strengths of PEEK

In medical and dental fields, the modulus of elasticity stands as a pivotal factor influencing the long-term durability and biocompatibility of a material [102]. Studies have highlighted PEEK's modulus of elasticity, noting that it does not match that of the human cortical bone but is closer to it than the traditional metals, which positions it as a potential candidate for medical and dental implant applications [103]. Previous studies have shown that rigid implants in Titanium or in zirconia had an elasticity modulus (110 and 210 GPa, respectively) that is 5–14 times greater than cortical bone (17 GPa). This significant difference can lead to

bone resorption and loss of osseointegration due to a phenomenon known as “Stress Shielding.” The difference in mechanical behavior between these biomaterials and bone results in poor distribution and uneven diffusion of forces arising from mastication stresses [42,39]. On the other hand, authors have reported values of the modulus of elasticity of the unmodified PEEK (Table 4) ranging between 3 and 4 GPa [104] and, as mentioned previously, this modulus can be increased significantly by reinforcing PEEK with various composite and ceramic materials (hydroxyapatite, glass fiber, carbon fiber, titanium oxide, tricalcium phosphate) to achieve results even more akin to cortical bone [42,104–106]. This promotes better stress distribution, preventing high stress peaks at the osseous/implant interface that lead to implant failure [40,42,44,107]. The elastic modulus of CFR-PEEK can reach up to 18 GPa [104,106] while GFR-PEEK can achieve around 12 GPa [42,105]. A comprehensive list of the mechanical properties related to these materials, especially the blended PEEK types, can be found in Table 4.

Schwitalla *et al.* [38,39] conducted studies on 11 different PEEK materials, assessing them through static compression and three-point flexural tests. Materials included grades of PEEK with various reinforcements, such as titanium dioxide, barium sulfate, carbon fibers, and glass fiber. During testing, specimens were subjected to a load from a wedge-shaped penetrator. The studies highlighted the suitability of these PEEK materials for dental implants, given their capacity to withstand high mastication pressures and compliance with the standard (EN ISO 10477).

Furthermore, Ferguson *et al.* [45] compared the modulus of elasticity of PEEK OPTIMA® samples through compression tests conducted both in a dry environment at room temperature (22°C) and under saline conditions (NaCl) at 37°C to simulate a natural physiological environment. The results suggested that the modulus of elasticity was 1.8% lower in the aqueous environment, indicating that

Table 4: Elastic modulus and the tensile strength of various materials

Material	Elastic modulus (GPa)	Tensile strength (MPa)	Ref.
Titanium	110	954–976	[108]
PMMA	3–5	48–76	[109]
PEEK	3–4	80	[104]
CFR-PEEK	18	120	[104]
GFR-PEEK	12		[110,111]
Cortical bone	14	104–121	[112]
Enamel	40–83	47.5	[113]
Dentin	15–30	104	[114,115]
Ti6Al4V	110–130	976	[111,116]

temperature and humidity had a statistically significant influence on it, even though the difference was relatively small.

Also, Schwitalla *et al.*'s study [40] employing a three-point flexural approach revealed that PEEK's strength surpasses the standard benchmark set for plastic materials at 65 MPa. When considering its applications in orthodontics, PEEK sets itself apart by displaying superior flexural strength and minimized creep when compared to other plastics like polyethersulfone and polyvinylidene fluoride [117]. Furthermore, with a tensile strength rating of 80 MPa [104], PEEK's mechanical properties are close to enamel and dentin [113,114,118], making it an ideal candidate for constructing prosthodontic framework.

5.1.2 Wear resistance

Recent advancements have explored novel PEEK-based composites as potential replacements for traditional metallic materials in biomedical implants and prosthesis. However, the performance of these materials under aggressive oral conditions, particularly in the presence of abrasive particles from toothpaste, remains a critical area of research. A significant study by Sampaio *et al.* [38] focused on evaluating the abrasive wear resistance of PEEK and Ti6Al4V, which are prevalently utilized in the fabrication of dental prosthetics and implants. The aim of this research was to closely mimic the oral environment, characterized by frequent exposure to abrasive compounds found in both food and dental care products. Such exposure is known to induce wear on the contact surfaces between the prosthetic structures and implants, posing challenges to the longevity and reliability of these materials. The researchers prepared surfaces of both materials and subjected them to micro-scale abrasion tests under varying loads and with different concentrations of hydrated silica, mimicking the abrasive action of chewing and tooth brushing. Their findings revealed that PEEK exhibits a higher volume loss compared to Ti6Al4V under these abrasive conditions, indicating that Ti6Al4V possesses superior wear resistance. The increase in wear for both materials was proportional to the abrasive content and load applied. This suggests that while both materials are susceptible to wear from common abrasive particles in the oral cavity, Ti6Al4V may offer better durability against such challenges.

In a parallel inquiry, Ragupathi *et al.* [31] conducted a detailed study on the wear characteristics of PEEK in comparison to titanium, specifically focusing on dental abutments subjected to cyclic loading. This method was intended to simulate the wear that occurs over a year of mastication.

Despite the hypothesis suggesting greater wear in PEEK abutments due to their lower elastic modulus, findings

revealed minimal difference in wear rates between the two materials. Advanced analytical techniques, including scanning electron microscopy (SEM), were utilized to meticulously evaluate wear patterns, demonstrating that both PEEK and titanium exhibited similar resilience to cyclic stress. This was quantitatively supported by surface roughness measurements before and after loading, indicating no statistically significant wear discrepancy between PEEK and titanium abutments. The study concluded that PEEK's wear resistance closely matches that of titanium, making it a viable alternative for implant abutments in dental applications. These results highlight PEEK's potential in dental implantology, although further research is encouraged to validate these findings over longer periods and in varied clinical conditions.

5.2 Mechanical testing

Mechanical testing in dental implants plays a vital role in assessing their robustness and functionality under the conditions of oral cavity. Such tests offer insights into the longevity and stability of these implants when subjected to continuous stress and environmental factors. In the following discussion, we will delve deeper into specific mechanical tests, namely, fatigue tests and wear resistance, to better understand their significance in evaluating dental implant performance.

5.2.1 Fatigue test for PEEK used in implant applications

Implant-supported prosthesis undergo stress from chewing in a wet environment and face sudden temperature changes between 0 and 65°C. Consequently, the materials chosen should meet specific standards concerning their robustness and rigidity. They should also resist against deformation and fatigue fracture [119].

During the chewing process, loads exerted can vary, sometimes remaining below the fracture load. However, even these variations can introduce weaknesses in the structure, resulting in the appearance of fissures and cracks. This is often termed as mechanical fatigue. Over time, these minor imperfections can evolve and spread, leading to a fatigue fracture [120,121]. The fatigue limit or endurance limit is the stress level below which an infinite number of loading cycles can be applied to a material without causing fatigue failure [122].

Lee *et al.* [42] assessed and compared the fatigue limits of PEEK polymers reinforced with carbon fibers (CFR-PEEK) and others with glass fibers (GFR-PEEK) against

titanium for potential dental implant applications. These tests were conducted in accordance with ISO 14801, which outlines the application of cyclic loads under dry conditions and at room temperature on cylindrical specimens with diameters of 4 and 5 mm. This was done to closely replicate the forces transmitted to the implant during chewing: cyclic impacts on the bone/implant over a limited time period. The fatigue limit of GFR-PEEK specimens with a diameter of 4 mm was found to be 310 N, and this was higher than its maximum static compression force of 256 N. According to the authors, this vital phenomenon is due to the fact that the deformation rate can increase the elastic limit of PEEK materials by 30%. This elasticity of PEEK might also explain the high fatigue limits. The authors concluded that implants made of this material could be suitable for replacing anterior teeth where the maximum chewing forces in the incisive zone reach 140–170 N. Otherwise, the fatigue limit of CFR-PEEK specimens with a diameter of 5 mm was found to be 450 N, which was also higher than their maximum static compression force. This material was therefore favored as it appears suitable for the replacement of both anterior and posterior teeth, where the maximum chewing forces in the molar zone range from 200 to 250 N. Dental implants with PEEK polymer coatings or those based on PEEK would thus be advantageous in reducing the effects of “stress shielding.” However, the authors note that the fatigue tests were conducted at room temperature, and even though PEEK is not affected by hydrolysis, concerns are raised regarding its ability to maintain good bonding at the interface between the resin and its reinforcements. There are still too few fatigue tests in saline solution, but the initial results on CFR-PEEK samples seem to indicate good *in vivo* stability and long-term physical and mechanical properties of PEEK.

6 Finite elements methods

The advancement of dental implant, abutment, and associated materials necessitates adherence to established *in vitro* and *in vivo* tests before they are fit for commercial use. Conducting *in vivo* tests on a substantial number of samples can be lengthy and may pose challenges to animals or patients involved. Moreover, potential inaccuracies in these assessments could lead to misleading outcomes, impacting both the materials and the results of the experiment. Therefore, the FEM emerges as a valuable tool for predicting potential mechanical complications using theoretical models coupled with *in vitro* tests [22,23,35,39,44,123]. The FEA is frequently used to assess the biomechanical behavior of implantable biomaterials *in vitro*,

whether in orthopedics, traumatology, or oral implantology. This method allows for the evaluation of stress distribution during the load transfer of an implant to the underlying bone structures and typically follows a consistent procedure.

The process involves obtaining a radiographic image of the bone section that will be studied. This image is then converted into a 3D model using computer-aided design (CAD) software. This model becomes the foundation for tests conducted on various models created with each implantable biomaterial.

The articles chosen for this section explore the utilization of FEA in examining the mechanical characteristics of abutments and implants. The process typically involves the creation of a 3D bone model through a CT scan, followed by importing into CAD software such as ANSYS, ABAQUS, SolidWorks, Creo Parametric, or Rhinoceros. A FEA package is then used to generate a 3D mesh which is linked to a suitable mathematical model that captures the properties of the corresponding material. While most of the studies employed ANSYS for simulation [22,23,32,33,39,44], some researchers favored ABAQUS, and CATIA [124–127]. Most of the selected studies assume a linear elastic, isotropic, and homogenous material model. In addition to using fewer parameters, in a linear elastic model, the correlation between these parameters and clinical medical imaging has been well established, which greatly enhances its potential for clinical application [127]. Whereas, an anisotropic material model is found to be more suitable for CFR-PEEK laminates [34]. CFR-PEEK laminates consist of carbon fiber-reinforced PEEK, which exhibits varying stiffness and strength properties in different directions relative to the orientation of the carbon fibers within the laminate. An anisotropic material model can accurately capture these directional dependencies, allowing for more precise simulations and prediction of mechanical behavior. This is particularly crucial in the context of dental implants and abutments, where a comprehensive understanding of material response under diverse loading conditions is essential (Figure 8).

The mechanical performance of implants, including factors such as von Mises stress, shear stress, contact stress, and stress shielding, is analyzed under varying loading conditions corresponding to clinical scenarios. An integral consideration in FEA methodologies is the assumption of forces to replicate masticatory loads encountered within the oral cavity of patients. However, defining this parameter precisely remains elusive due to its variability among individuals [39]. The magnitude of axial loading in the selected journals ranges widely from 100 to 1,000 N, while oblique loading typically spans from 50 to 500 N [29,33]. Notably, a predominant trend in these studies is the utilization of axial loading within the range of 100 to

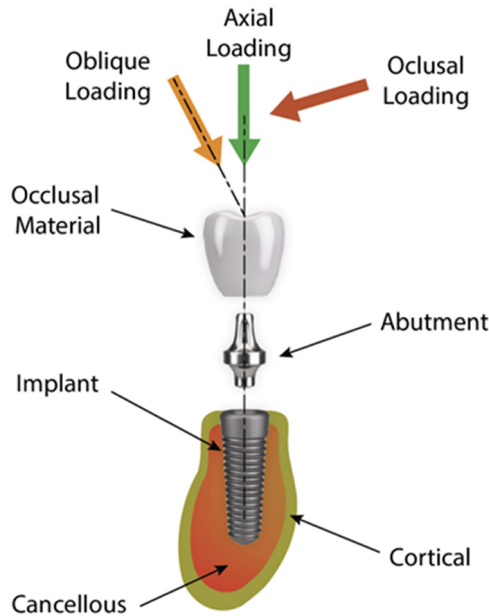


Figure 8: Schematic of an implant-supported prosthesis involving implant, abutment, and a single crown.

150 N. Furthermore, the angle of oblique loading has slight variation, typically falling between 30° and 45° .

The selected journals aimed to investigate the stresses developed in dental implants and bones using various prosthesis materials, including titanium, zirconium, unfilled, and CFR-PEEK, utilized in abutments and implants, and their combinations. Oblique loading typically results in higher stresses in cortical and cancellous bone, implant components, and restorative crowns compared to axial loading across all mentioned studies. The findings of all authors are consistent with each other. A higher stress concentration is generally observed in the cortical bone near the peri-implant region, gradually decreasing towards the cancellous bone under both axial and oblique loading conditions.

Most studies indicate no significant variation in stress distribution at the implant-bone interface for different material models. Mourya *et al.*'s study of stress distribution in straight and angled abutments supports this conclusion, suggesting similar stress results with CFR-PEEK and titanium implants in both straight and inclined cases [29].

Another study on the performance of titanium/PEEK dental implants simulating different levels of bone loss also indicates that stresses were independent of the implant material [30]. Similarly, Sarot *et al.*'s work on the stress distribution of CFR-PEEK dental implants concludes that CFR-PEEK implants offer no advantages over titanium implants concerning stress distribution to the peri-implant bone [44]. Shash *et al.*'s study on fixed prosthesis following the "all on four" framework indicates that 60% CFR-PEEK

distributes cortical bone stresses similar to the titanium framework [23] (Figure 9).

Studies by Wazeh *et al.* [33] and Kaleli *et al.* [35] agree that crown material does not affect biomechanical behavior concerning stresses in implants and peripheral bone.

However, Mourya *et al.*'s findings on stress distribution under parafunctional loading show that the stresses generated in bone with a PEEK crown layered with composite are lower compared to porcelain fused to metal (PFM) crown configurations [29] (Figure 10).

Implants with micro threads showed a reduction of maximum von Mises stress by 50–70% in peri-implant bone compared to conventional threading [33], as demonstrated by Wazeh *et al.* Specifically, micro-threaded titanium implants, when used with a zirconia crown, exhibited the lowest cortical bone stress values under vertical loading, approximately 10 MPa. In contrast, implants made of CFR-PEEK with 30% carbon fibers generated notably higher stresses, around 100 MPa, on the cortical bone.

Titanium implants may induce a stress-shielding effect, leading to implant and bone loss due to their high elastic modulus (110 GPa) compared to bone (14 GPa). The stiffness mismatch between bone and implant can result in stress-shielding phenomena, potentially leading to bone resorption during the bone remodeling stage. *In vivo*, PEEK material possesses biomechanical properties close to human bone, reducing the risk of bone resorption and osteolysis caused by the stress-shielding effect of implants. A study by Oulderyou *et al.* found that Ti-PEEK implants outperform conventional Titanium implants in reducing stress shielding and bone resorption [30]. The application of PEEK veneering on dental implants or abutments was also found to diminish the effects of stress shielding, as indicated by studies conducted by Lee *et al.* and Sampaio *et al.* [37,42]. Nevertheless, the thickness of PEEK veneering emerged as a critical factor influencing both stress distribution and the strength of hybrid abutments or implants, as highlighted in the research by Sampaio *et al.* [37].

Implants or abutments made of PEEK containing 30% carbon fiber exhibited increased stiffness compared to unfilled PEEK. The incorporation of such PEEK composites was found to enhance stress distribution and reduce the load concentration throughout the abutment and implant region, as suggested by Sarot *et al.* [44].

In weaving together, the detailed insights provided by the various studies, it becomes evident that FEA offers a robust framework for simulating and understanding the biomechanical behavior of dental implants and abutments under various conditions. Through meticulous modeling and simulation, FEA enables researchers and practitioners to predict and mitigate potential complications associated

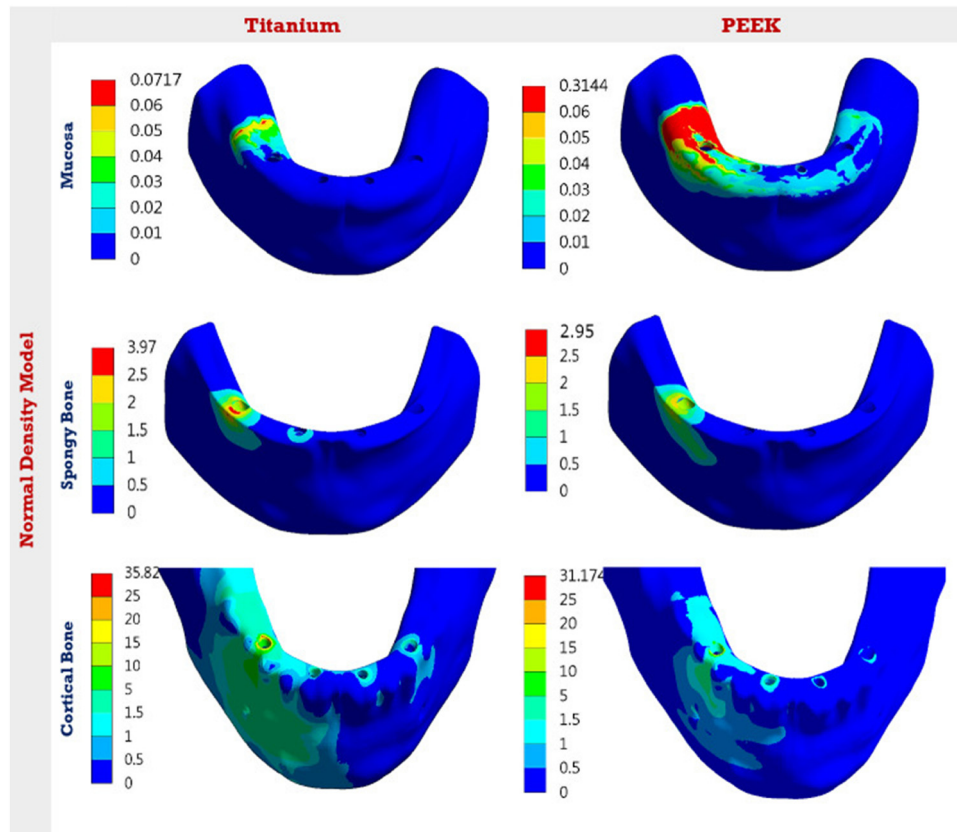


Figure 9: The distribution of von Mises stresses (MPa) on the mucosa, cortical and spongy bones, under unilateral force, using Ti and PEEK [27].

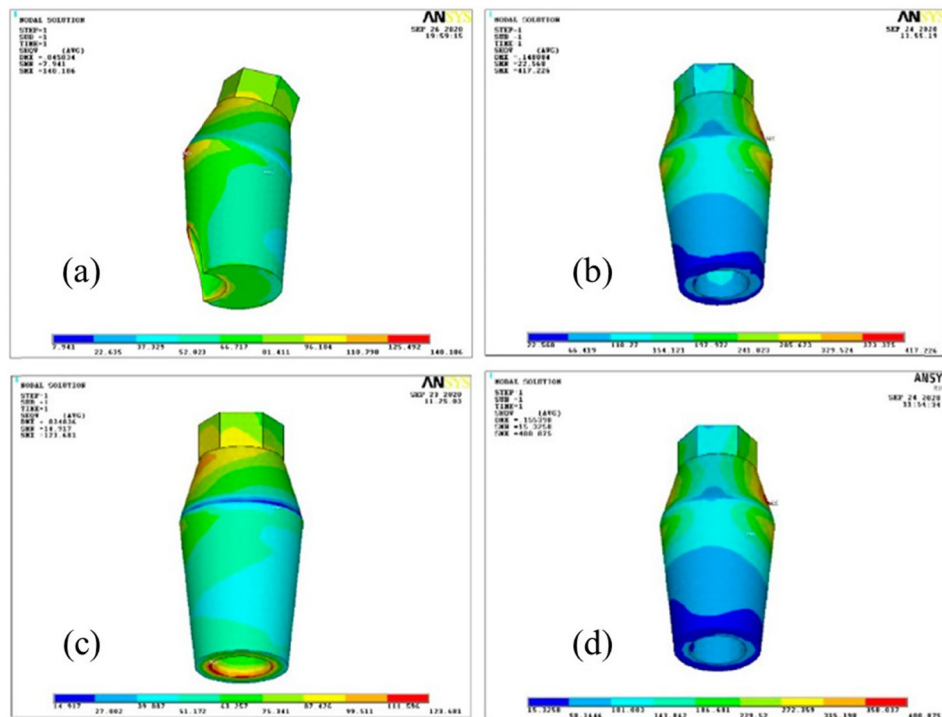


Figure 10: Stress in: (a) CFR-PEEK 15° abutment under vertical loading with PFM crown, (b) CFR-PEEK straight abutment under oblique loading with (PFM) crown, (c) titanium straight abutment under vertical loading with (PFM) crown, and (d) titanium straight abutment under oblique loading with (PFM) crown [29].

with implant materials and designs, thereby facilitating the development of more effective and safer dental restoration solutions. The consensus across studies on the efficacy of materials like CFR-PEEK and the nuances of stress distribution underlines the complexity of dental biomechanics and the indispensable role of FEA in advancing dental implantology. As the field evolves, the ongoing refinement of FEA methodologies and the exploration of new materials will undoubtedly contribute to enhancing the quality and longevity of dental implants, ultimately benefiting patients with more reliable and durable dental restorations.

7 Conclusion

The manuscript thoroughly examines the application and mechanical performance of PEEK and its composites in dental implantology, particularly regarding implant abutments and cores. Through FEA, it highlights PEEK's pivotal role in advancing dental implant technology.

7.1 Application of PEEK and its composites in dental field

The manuscript discusses PEEK and its composites' applications in dental implantology, citing their biomechanical compatibility and bioactivity. PEEK emerges as an alternative to titanium for abutments and dental implant cores due to its similar elasticity to bone and ease of removal. It outlines PEEK's advantages in creating abutments, frameworks, and core materials, including its commendable soft tissue response and customization potential for provisional restorations and shaping emergency contours during surgical interventions.

7.2 Mechanical tests on PEEK

The manuscript extensively explores PEEK's mechanical properties *via* tensile, compression, bending stress, wear resistance, and fatigue tests, revealing its robustness and suitability for dental implants. CFR-PEEK and GFR-PEEK composites show increased hardness, compression resistance, and fatigue endurance, reducing stress-shielding in bone. Tests, compliant with ISO 14801, demonstrate their ability to withstand chewing forces, suggesting PEEK-based materials could offer longer lasting implant solutions with more even load distribution.

7.3 Enhancement of understanding through FEA

The manuscript highlights FEA's crucial role in advancing dental implant technology, allowing simulation of biomechanical behavior and stress distribution analysis in CFR-PEEK implants and abutments. By generating 3D models from radiographic images and using software like ANSYS and ABAQUS, FEA predicts stress distribution during load transfer, crucial for implant-bone interface evaluation. This method effectively assesses CFR-PEEK composites' mechanical performance, reducing stress concentrations and improving load distribution, essential for implant longevity and success.

In conclusion, the widespread adoption of a new biomaterial is always a slow and cautious process. FEA emerges as a powerful tool in the development and evaluation of dental implants, providing valuable insights into material behavior and design efficacy. The ongoing evolution of this methodology, coupled with advancements in biomaterials, holds the promise of more effective, tailored, and biocompatible implant solutions, ultimately enhancing patient outcomes in dental and orthopedic implantology.

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