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Impact of Different Digital Fabrication Techniques of Substructure Materials on Stress Distribution in all-on-4 Mandibular Restorations. A Finite Element Analysis

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ABSTRACT

Statement of the problem: All-on-four concept is used as an outstanding choice for edentulous patients. Framework characteristics of such restoration play a crucial role in its long-term success, affecting all aspects from biomechanical stability through osseointegration to patient satisfaction. **Study aim:** Utilizing finite element analysis (FEA) to investigate the biomechanical performance of different framework materials with solid conventional geometry and topographically optimized ones, as a substructure of all-on-four restorations. **Materials and methods:** A 3D model was created. The framework materials were Titanium, and Titanium Dioxide- reinforced PEEK (TiO_2-PEEK) fabricated by 3D printing, one conventional, and one with optimized topography. Deformation and stress were assessed under vertical and oblique loads. **Results:** No failure occurred in any component. Titanium absorbed high internal stress with less stress transferred to model components, but TiO_2-PEEK underwent minimal internal stress with high stress on the model components. Topology optimization contributed to redistribution of structural stress, mitigating peak stress concentrations at critical cantilever junctions and minimizing excessive deformation. **Conclusion:** The tested materials and designs were found to be competent as all-on-four frameworks. Optimized topography offered excellent biomimetic compromise for both selected materials, avoiding the structural stress peaks of rigid metal designs while protecting the peri-implant bone from the excessive strains associated with standard flexible polymers.

Keywords: All-on-four, FEA, Optimized topography, Titanium, TiO2, PEEK

1. Introduction

Convenient rehabilitation of edentulous patients using implant overdentures was considered for a long time as an acceptable, predictable and successful way to regain good quality of human life (Kutkut *et al.,* 2018; Amaral *et al.,* 2018). Mutilated ridges, especially the mandible, always represent serious obstacles for the conventional dental implants. Clinicians were not convenient with applying invasive and costly treatment to solve the problem (Ravidà *et al.,* 2019).

All-on-four systems represented an excellent alternative, as they merged using implant angulation, decreasing cantilever and instant functioning restoration. Regaining chewing capability, could necessitate extending the prosthesis posteriorly beyond the last implant. The tilted posterior implants induce adequate masticatory support for the prosthesis (Malo *et al.,* 2005). Posterior angulation of this implant minimizes the cantilever and grants superior force distribution, as well as reducing prosthetic complexity, abutment loss, prosthetic fragmentation, also implant integrity, which are the hindrances of cantilever prosthesis (Malo *et al.,* 2005).

Wide range of materials can be used conveniently to construct the prosthesis substructure system. Metallic alloys exhibit elevated elastic modulus as well as tensile strength ample to avert

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disfigurations and fragmentation. Titanium (Ti) with its well-known resistance to corrosion, biocompatibility, financial merit, and mechanical characteristics correspondent to auric alloy, was qualified to be the most appropriate material for construction of substructures. Unfortunately, because of its stiffness it may cause stress shielding and deprive the bone of its normal physiological stimulation leading to peri-implant bone loss (Ferreira *et al.,* 2014). Fabricating titanium by 3D-printing produced excellent biological & mechanical properties, suggesting that it can be utilized safely in dental applications, including implant prosthodontics (Kim *et al.,* 2020).

3D printing is now the regular practice in dental restorations, despite all its advantages as the reduction in material waste, it may have some dimensional and volumetric changes together with little distortion which can affect accuracy (Tuan *et al.,* 2023; Palaszkó *et al.,* 2024; Grande *et al.,* 2022). This technological shift has sparked interest in high-performance polymers like Polyetheretherketone (PEEK) as alternative framework material. Unreinforced PEEK has an elastic modulus that closely matches human bone, yet its low tensile strength poses a risk of catastrophic fracture under heavy cantilever loading. To address this vulnerability, titanium dioxide nanocrystal-reinforced PEEK (TiO_2 PEEK) was developed. TiO_2-PEEK is a pure PEEK blended with 5% to 15% nano titanium dioxide particles having a white shade with good esthetics to be used in dental applications. This composite enhances the polymer's ultimate tensile strength and rigidity while retaining its low-weight, and shock-absorbing properties. The nanoparticles act to elevate the structural reinforcement of the material. Its uniform particle distribution allows it to behave in a nearly isotropic manner (Ding *et al.,* 2021).

The quest for individualized interventions is one of the recent contented scientific disciplines in current medical practice, as it guarantees the optimization of clinical results, minimizing adverse events, and optimizing patients' well-being. Topology optimization is a recognized engineering method that removes unnecessary material under minimal loading areas, while preserving stiffness of the material. Full arch frameworks usually are excessively heavy and bulky leading to inconvenience for the patients which will be decreased by topology optimization. Integrating topology optimization with additive fabrication introduces fresh concepts about solving the problem of customization of the frameworks to the proposed mechanical challenges, because of such a combination, an enhancement in mechanical properties, biocompatibility and deformation can be expected (Liu, 2025). It maximizes structural integrity, together with minimizing weight up to 50% and material waste, furthermore the hollowed areas reduce modulus of elasticity (Naghavi *et al.,* 2022; Park *et al.,* 2019). Currently, this technology has inherent limitations such as delicate balancing mechanical properties with biological functions, scarce clinical trials, costly and suboptimal algorithmic efficiency. In the future, it would be integrated with metamaterials and AI technology to promote its refinement (Liu, 2025; Lin *et al.,* 2024). The point of interest is whether the intelligent geometry optimization of the framework will reduce the dependence on material stiffness or not.

To analyze stress distribution in peri-implant bone, divergent techniques could be used including photo-elastic evaluation, strain gauge, and finite element analysis. 3D Finite Element Analysis is considered as a robust approach to investigate the quantity and stress distribution scheme, which possess an edge over alternative approaches. FEA is a reproducible, repeatable and non-intrusive procedure that could effortlessly imitate any biological situation at various stages. It is applicable to both linear and nonlinear analysis, besides solid and fluid structural interactions (El-Anwar *et al.,* 2017; Mohamed, 2020). Additionally, it is achievable to assess the stress affecting peri-implant bone tissue as a prophylactic measure using FEA (Carneiro *et al.,* 2014).

This study aims to use FEA to investigate the biomechanical efficiency of two contrasting framework materials constructed as conventional solid bars versus topographically optimized internal architectures, that are employed in all-on-four mandibular restorations. To investigate if topographic optimization can compensate the difference in material stiffness while reducing framework weight. The null hypothesis was that different materials and framework designs would not affect stress/strain distribution in the different components of the model.

2. Materials and Methods

In the current study, FEA emulated a clinical situation where an edentulous mandible was restored with an all-on-four implant system. Two different materials were utilized as frameworks,

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which were Titanium, and TiO_2-PEEK for each material two types of fabrication techniques were adopted to obtain one conventional solid framework and one optimized topographic framework, to assess the impact of materials and differently fabricated frameworks on the different model components.

A 3D model (3-dimensional geometry) of an edentulous mandible was reassembled based on a set of CBCT images, consisting of cortical bone, cancellous bone, mucosa, with a prosthetic all-on-four restoration complex, was designed.

2.1. Software

The model components were designed on "Autodesk Inventor" Version 8 (Autodesk Inc., San Rafael, CA, USA) as revealed in (Figure 1). These components were exported as STEP files to be assembled and meshed in ANSYS environment (ANSYS Inc., Canonsburg, PA, USA). The meshing software was ANSYS, Release 24.1. Mesh density was analyzed and optimized for accuracy and calculation. Sharp and narrow characteristics within the jaw model were smoothed to enhance mesh quality and stability. ANSYS Topology Optimization of the second geometry of the framework was used to obtain frameworks with material omitted at the non or minimal loaded areas designated by the software.

Number of nodes and elements of each component were displayed in (Table 1), and meshed components were presented in (Figure 2).

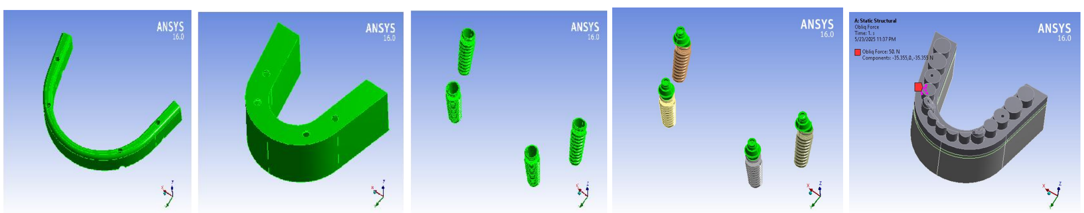

Fig. 1: Shows model components

Table 1: Nodes and elements of each component

	Nodes	Elements
Prosthesis	107.050	70.814
Framework	20.496	12.779
Mucosa	14.636	2.652
Cortical bone	132.260	81.475
Cancellous bone	299.817	207.147
Implants	138.145	89.763
Abutments	58.921	38.325

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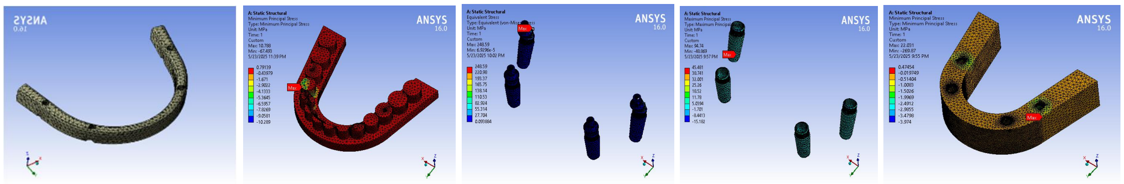

Fig. 2: Shows meshed components

2.2. Model and prosthesis design

To construct the virtual mandibular model, the bone structure was mirrored from the midline, allowing symmetry between the antimere mandibular sides. Bone height was set to be 24 mm, and gingival height of 2 mm.

Four implants of 11.5 mm length and 4.0 mm diameter (Neobiotech Co., Ltd., Los Angeles, CA, USA) were employed, the two anterior implants were vertically fixed in the canine region, and the posterior two implants were fixed with posterior angulation of (17º) at the second premolar area. Two straight multiunit abutments were secured to the vertical implants, and two angled multiunit abutments were attached to the angled implants. These components were modeled according to the manufacturer data. Twelve points were manually selected on the alveolar ridge to fit the arc curvature, which allows the implants to be placed on. Complete osseointegration was hypothesized at the implants-bone interface, no crater-like deficits were present around the implants' necks, no gaps were in the implant-abutment and abutment framework connections, meaning all contacts were assumed to be bonded.

The framework used had a height of 5 mm, and a width of 4 mm, with a length extending to the center of the first molar area on both sides. The first conventional geometry in the form of standard full contour framework with uniform thickness, the second optimized topographic framework had internal reinforcing structure distributed by the algorithm according to the expected sites of high, moderate, and low stress, replacing the solid bar with a configuration featuring structural webbing around the multi-unit cylinders and smoothly tapered cantilever transitions. This technique is a crucial part of component design producing the best structure for a specific design space while considering boundary conditions and the material characters.

The prosthetic replacement was designed to have 12 teeth, with a cantilever length of 10mm. on each side.

All employed materials were assumed to be isotropic, homogenous and linearly elastic to ensure accurate reflection of the mechanical behavior of each component. The employed materials' characteristics including Young's Modulus and Poisson's ratio are sorted in (Table 2).

Table 2: Properties of the model's components

	Young's modules [MPa]	**Posison's ratio**
Prosthesis	2.700	0.35
Framework 1: Titanium (Solid)	110.000	0.33
Framework 2: Titanium (Optimized)	110.000	0.33
Framework 3: TiO2PEEK (Solid)	5.500	0.40
Framework 4: TiO2PEEK(Optimized)	5.500	0.40
Implant complex	130.000	0.35
Gingiva	3.00	0.47
Cortical bone	13.700	0.30
Cancellous bone	1.370	0.30

2.3. Load application

To fix the system, the jaw model base was secured, restricting the movement to be on the Z axis only, which will facilitate computing the generated deformation in all directions.

To investigate and compare the stress pattern on the bone implant interface, two loading scenarios were emulated using load values approximating functional bite. The first loading scenario was applying bilateral concurrent static axial load of (150 N) on the occlusal plane between the second premolar and the first molar area. The second loading scenario was unilateral oblique static load of (50 N) applied on the buccal side of first premolar at (45º).

Accordingly, eight cases were studied as follows, 2 framework materials each of them has two manufacturing geometry under two loading scenarios. The proposed groups were (Group 1) titanium solid framework, (Group 2) titanium optimized geometry framework, (Group 3) TiO_2-PEEK solid framework, (Group 4) TiO_2-PEEK optimized geometry framework.

Linear static assessment and solid modeling were executed on a Workstation HP Z820, with Dual Intel Xeon E5-2660, 2.2 GHz processors, 64GB RAM. The results of mathematical solutions were illustrated as image findings displaying various levels of color, ranging between red and blue, with the red color exhibiting the outmost stress measures. The color gradient table was standardized, and the outcome colors in all evaluated scenarios exhibited similar stress levels. The outcomes of the modeling were assessed in terms of deformation and Von Mises equivalent stress levels at the bone-implant interface and compared for the assessed conditions.

3. Results

Analysis created a huge set of graphical representations of different types of deformation and stress distribution exerted on each model component. They were seen as color visuals presenting various stress distribution in each condition. Under the chosen loads, no failure occurred in any of the model components.

The topology optimized frameworks showed feasible effects on stress distribution. Higher forces resulted in higher plastic deformations inside the component body which influenced the material structure. The complex internal geometry redistributed stress better than the conventional geometry. The optimized titanium framework stands out as the most efficient, due to material present only where it is really needed creating a structure both effective and light weight, thus spreading stress quite evenly with stress values within the elastic range of the material.

The distribution pattern and values of total deformation and Von Mises stress were found to be different among different substructure materials and their manufacturing techniques. Maximum values of deformation were noted at loading cites, while maximum Von Mises stress was usually located in the vicinity of the nearest supporting implant complex.

The prosthesis showed variable deformations considering conventional Titanium and TiO_2-PEEK frameworks, in which (group 3) increased the prosthesis total deformation by the amount of 10 microns which was the highest noticed. (Group 2) showed the least deformation, thus less deformation than its conventional opponent (group 1), (group 3) caused slightly more deformation than (group 4). On the other hand, the prosthesis Von Mises stress was insensitive to framework material or its manufacturing technique.

Framework body total deformation was low with (group 1) while (group 2) showed slightly higher values. As for (group 3) it showed higher deformation than both titanium groups, and (group 4) showed the maximum framework deformation of the four groups under investigation. The opposite was noticed on Von Mises stress, where (group 4) received the lowest values while (group 1) received the highest values, followed by (group 2) then (group 3). Conversely, whatever the framework material employed, the optimized frameworks received less stress (about 16%) and showed slightly more deformation (3-5%) in comparison to conventional geometry as shown in (figure 3).

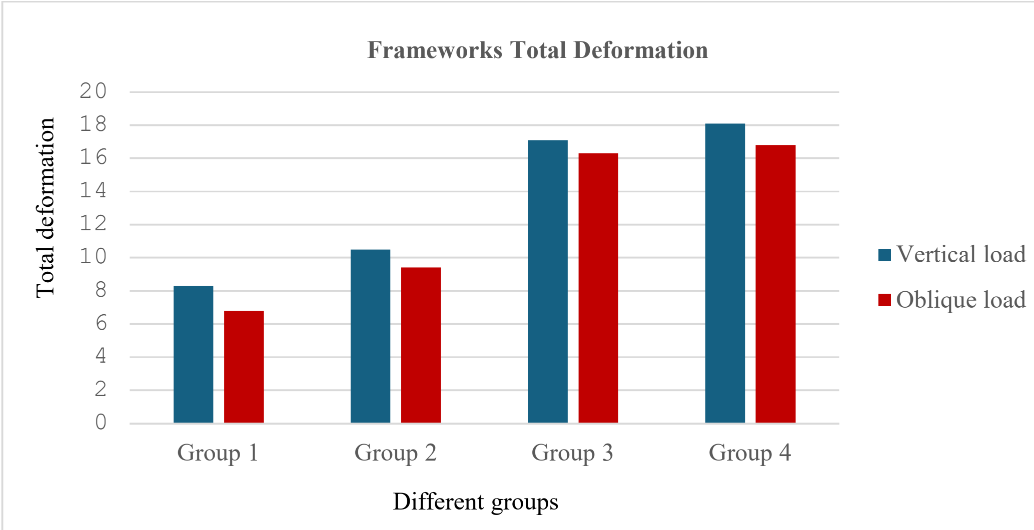

Fig. 3: Shows framework total deformation

All other components of the implant complex showed superiority of (group 2) behavior, followed by (group 1), then (group 4) and lastly (group 3) exerted the highest deformation and stress values on implant complex. The highest stress values appeared on abutments, then copings, while other parts of the complex showed less differences between different groups, with better results obtained by optimized topographic frameworks.

Distal implant neck serves stress hotspot in case of conventional TiO_2-PEEK framework (group 3), while in optimized configuration (group 4) there was a stress reduction of about 25%. (Group 3) exhibited the highest localized stress concentration surrounding the crestal bone margin of the furthest distal implant, followed by (group 4), (group 2), and (group 1) respectively.

Mucosa showed insignificant values of deformation and stress. The superiority of (group 2) continued by showing the lowest values of deformation and stress on mucosa. Meanwhile, (group 1) and (group 3) showed higher values of deformation and stress respectively on mucosa, as these values were about 30% and 16% respectively less than the values exerted by (group 4).

Cortical bone showed the same order of groups effect on cortical bone. (Group 1) caused the lowest bone strains followed by (group 2), shielding bone from normal stimulation. (Group 3) produced the peak strains around the tilted implant during cantilever loading. However, (group 4) mitigated this effect, keeping peak bone strains at a more moderate value between (group 2) and (group 3). These effects are shown in (figure 4).

As for the differences in deformation and Von Mises stress between the two loading conditions, the axial loading exhibited slightly higher effects on all the model components than the oblique loading. It followed the following order, in which (group 1) was the lowest then (group 2), (group 4), while (group 3) was the highest. It was found that the lowest stress concentration under vertical loading was around the first implant thread, but under oblique loading the least stress concentration was observed at the implant apex.

The total deformation was higher in (group 4) then (group 3) then (group 2) and the lowest was observed with (group 1), and the stress transmitted from the framework to the model different components were higher as well in the same order, while the maximum stress absorbed by the framework material itself was with (group 1), (group 2), (group 3) and (group 4) respectively.

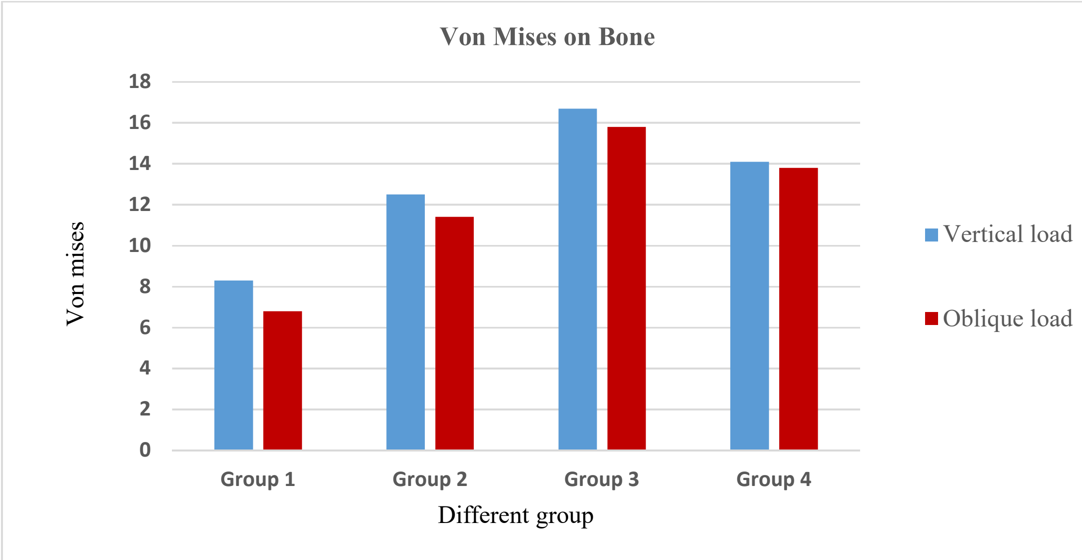

Fig. 4: Shows bone Von Mises

4. Discussion

This study explores how framework materials and geometric layouts interact within an All-on-4 implant restoration. The data confirms that combining 3D-printed TiO_2 PEEK with topology optimization balances system rigidity with healthy, physiological bone loading but the increased elasticity of this framework will make the best performance obtained is by the optimized titanium framework. It was found that there were variances in stress distribution on all the complex components with different materials and different fabrication geometries, using axial and oblique loading. The importance of the present results is its influence on the long-term implant and prosthesis longevity.

FEA was utilized in this study due to its confirmed convenience as a technique analyzing intricate or unfavorable systems that are impossible to standardize especially in clinical studies. That's why the model and the correlation between its parts were evaluated first before starting the analysis, as several studies have executed FEA on all-on-four restorations and validated its efficiency (Mohamed, 2020; Jemaa *et al.,* 2023; Çolak *et al.,* 2025; Ozan and Kurtulmus-Yilmaz, 2018). Multiple simplifications had to be conducted in the FEA to reduce the complexity of the tested model while enhancing computing efficiency leading to some limitations as expected.

Cortical bone characters might vary within cadavers which were previously used as models, since they have anisotropic performance which brings out varying elastic properties, according to cells and fibers alignment. Thus to assimilate in-vitro studies and eliminate biological parameters, polymeric materials with elastic modulus near to bone tissue are utilized in the construction of the FEA models (Chang *et al.,* 2024).

The distal implant used in the present study was chosen to be tilted at 17°, as it was listed previously, that despite the stress around the distally tilted implant was considered questionable, it was observed that there is limited stress and flexing in the rear implant angulation of 15° to 30° (Sannino, 2015). Stress on the implants weather straight or tilted, and their surrounding bone tissues were found to be concentrated at their necks, with significantly higher stress on cortical bone than on the cancellous (Rani *et al.,* 2023). The same results were observed too in the present study with all materials and techniques tested.

It was insinuated that different framework materials having different elastic moduli utilized with all-on-four appliances are a notable variable modifying stress and strains on implants and peri-implant bone, thus previous studies (Iyer *et al.,* 2019; Zoidis, 2018) proposed a metal bar on account of its firm structure and well known merits. On the contrary, another previous study (Tribst *et al.,* 2017) deemed that stress generated in all components of the system were not crucially affected by the framework's material. As revealed in this study, the framework material and geometric configuration have deep impact on stress, deformation, and long-term survival of all on 4 restoration different components, accordingly the null hypothesis proposed in this study was rejected.

Titanium is highly biocompatible and strong material, but its Young's modulus (stiffness) is about 110 GPa, whereas human cortical bone is only 10 to 30 GPa. This vast difference causes what is known as "stress shielding" titanium absorbs all the mechanical load, causing the bone to resorb over time due to lack of stimulation. Severe stress concentration was developed within the framework and its connections, over time, these sustained stress peaks can lead to clinical complications like screw loosening, abutment fractures, or framework fatigue (Wang *et al.,* 2023). That was the same as what the present study revealed with titanium conventional framework. Better results, decreased stress shielding effect, less stress concentration on different connections, were obtained with optimized topography of the titanium framework that may be a result of slightly lowered elastic modulus and better load distribution.

Topology optimization generates intricate, porous lattice structures within the titanium part. By systematically hollowing out sections and varying the density of the metal lattice, the software lowers the effective stiffness of the titanium framework. This preserves structural strength while promoting bone health (Liu*,* 2025; Jemaa *et al.,* 2023). Full-arch dental frameworks experience less maximum stress when processed through a topology optimization compliance-minimization model. Even when forcing a strict 50% volume mass reduction constraint, the optimized geometries distributed chewing loads across the implant abutments much more evenly than conventional solid frameworks (Liu*,* 2025; Naghavi *et al.,* 2022; Park *et al.,* 2019; Memon et al., 2020). As the results of this study demonstrated, the effect of optimized topology of the frameworks reduce cantilever deflection, lowered peak strains in the peri-implant bone encouraging bone health and remodeling without crossing into pathological overload.

Desired features from optimization and its various functionalities may be considered in the artificial intelligence algorithm used for optimal personalization. There is a tendency to produce designs that are often complex, which may not be readily manufacturable using traditional milling techniques, instead be manufactured with additive manufacturing techniques, especially the recent advances in the 3D printing technology that made the intricate tiny designs be easily conducted (Park *et al.,* 2019).

Metal frameworks have an unaesthetic character, along with considerable impact on abutments leading to failures and allergies in vulnerable people. PEEK and its variants overcome these downsides that are validated as an effective solution for manufacturing all on 4 frameworks, as it is as resilient as bone, consequently diminishing stress on the abutments. Additionally the white color of the material gives an esthetic look (Iyer et al., 2019; Zoidis, 2018). These were the main reasons for including TiO_2PEEK in the study with the titanium reinforcement having better mechanical behavior than conventional PEEK thus expecting better results.

In the current research it was declared that TiO_2PEEK indicated more deformation and stress in comparison to titanium, since quick elevation of stress levels in respecting minute strains equivalent to the viscoelastic performance of PEEK family, in which it consumes more energy from exerted force leading to unfavorable load distribution. Flexible materials reduce internal stress due to greater material deflection with shifting the stress toward the implant -abutment interface. This annotation was concurring with the outcomes of earlier studies (Çolak et al., 2025; Chang *et al.,* 2024; Bhering *et al.,* 2016; El-Qoubaa *et al.,* 2015; Bilgi-Ozyetim *et al.,* 2026). But the conventional TiO_2PEEK framework showed some sort of exceeding results as regard to its internal deformation than the optimized one, that may be due to its slightly higher elastic modulus coming from its solid structure. As revealed in the present study, the conventional framework configuration showed lower deformation due to the compact nature of the solid material. In case of optimized topography framework, the weight was lowered with less stiffness and fair stress distribution approaching the conventional with less material used.

On the contrary of what was observed in the present study, a former study (Chen *et al.,* 2025) found that the use of a PEEK family framework provided more favorable stress distribution in bone due to its lower elastic modulus.

Oblique loading produced higher stress values than anticipated in relation to vertical loading across all components, mostly due to the lateral direction of force and bending moment, that may be the reason for the insignificantly higher stress values of the vertical loading than the oblique load found in the present study. Furthermore, posterior implant regions exhibited more pronounced stress variations, particularly under unilateral loading conditions, which may be attributed to cantilever effects and asymmetric load distribution found in the conventional frameworks, which were not as much noticed with the optimized frameworks.

There are few limitations of this study including, the models used were defined as linear elastic, homogeneous, and isotropic, while these assumptions are common in FEA, the actual clinical behavior cannot be fully simulated. The different quantity and quality of the residual ridge bone are not considered, which limits the patient specific studies. Systematic clinical trials on optimized topography are scarce, high cost, and inadequate computing efficiency of topology optimization algorithms. The application of unidirectional and static force may not fully represent real-life conditions of multidirectional cyclic loading during mastication. Long term clinical studies and validation are crucial to support this study' results.

5. Conclusion

Given the constraints of this study, it was deduced that the materials and geometries explored can be considered competent in all-on-four restorations.

Titanium frameworks absorb more stress shielding the peri-implant bone, while TiO_2 PEEK frameworks protect internal components but transfer higher strains to the surrounding bone.

Topology optimization improves load distribution especially in titanium material. It lowered peak stresses in titanium frameworks and minimized excessive deflection in polymer frameworks.

6. Recommendations

1- Extending clinical trials on optimized frameworks as they provide an ideal biomechanical middle ground between metal and polymers.
2- As 3D printing technology is in its developing and evolving state, enormous material and technique upgrades should be investigated.

Ethical approval:

This study was conducted in accordance with the principles of the Declaration of Helsinki (WMA, 2008), and approved by the ethical committee of the Faculty of Dentistry, Ahram Canadian University (Approval No IRB00012891#154).

Conflict of interest:

The authors declare no conflict of interest.

Fund statement:

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