BIOMECHANICAL BEHAVIOR OF PMMA PROVISIONAL PROSTHODONTIC RESTORATIONS IN MAXILLARY POSTERIOR TEETH WITH REDUCED PERIODONTAL SUPPORT: A FINITE ELEMENT ANALYSIS

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BIOMECHANICAL BEHAVIOR OF PMMA PROVISIONAL PROSTHODONTIC RESTORATIONS IN TEETH WITH REDUCED PERIODONTAL SUPPORT: A FINITE ELEMENT ANALYSIS (Abstract): **Aim**: The aim of this study was to evaluate the biomechanical response of PMMA provisional prosthodontic restorations replacing a missing maxillary first molar under progressive horizontal periodontal bone loss using finite element analysis. **Materials and methods:** Three-dimensional finite element models incorporating PMMA provisional prosthodontic restorations were developed to simulate healthy periodontal support and 10%, 20%, and 30% horizontal bone loss. Five occlusal loading conditions (300, 500, 800, 1000, and 1200 N) were applied. Equivalent von Mises stress, compressive stress magnitude, and structural displacement were analyzed using descriptive statistics, two-way ANOVA, Tukey post-hoc comparisons, and linear trend analysis. **Results:** Increasing occlusal force produced a progressive increase in equivalent stress, compressive stress magnitude, and displacement across all periodontal conditions. Occlusal loading represented the main determinant of the biomechanical response, whereas periodontal bone loss exerted its greatest effect on structural displacement. The model with 30% horizontal bone loss exhibited the highest displacement, showing a 25.7% increase compared with the healthy model under a 1200 N occlusal load. Stress-related parameters were influenced predominantly by load magnitude, while displacement increased consistently with progressive periodontal support reduction. **Conclusions:** PMMA provisional prosthodontic restorations demonstrated predictable biomechanical behavior under increasing occlusal loading. Progressive periodontal bone loss primarily affected structural displacement, indicating that teeth with reduced periodontal support may require individualized occlusal management during provisional prosthodontic rehabilitation. **Keywords:** PMMA, PROVISIONAL PROSTHO-DONTIC RESTORATIONS, FINITE ELEMENT ANALYSIS, PERIODONTAL BONE LOSS, OCCLUSAL LOADING, BIOMECHANICS, PERIODONTAL SUPPORT, PROVISIONAL RESTORATIONS.

INTRODUCTION

Periodontal bone loss progressively reduces the supporting tissues of the tooth and alters the biomechanical behavior of the tooth-periodontium complex during functional loading. As periodontal support decreases, identical occlusal forces may generate different stress distributions and

greater structural displacement, potentially contributing to increased tooth mobility, traumatic occlusal loading, and long-term structural damage (1-4).

Finite element analysis (FEA) has become an important method for investigating dental biomechanics because it allows controlled evaluation of stress distribution and deformation under standardized conditions that cannot be reproduced clinically (5,6). Previous FEA studies have shown that both occlusal force magnitude and periodontal bone loss influence biomechanical behavior (7,8). However, their relative contribution remains incompletely understood.

Most available studies have focused either on isolated loading conditions or on comparisons between healthy and severely compromised periodontal support, with limited evaluation of multiple force levels combined with progressive horizontal bone loss (9,10). Furthermore, few investigations have statistically quantified the independent effects of occlusal loading and periodontal status on stress distribution and structural displacement (11,12).

A better understanding of these relationships may improve the biomechanical interpretation of periodontal breakdown and support clinical decision-making regarding occlusal management in patients with reduced periodontal support (13,14).

Therefore, the aim of the present study was to evaluate the effects of increasing occlusal force and progressive horizontal periodontal bone loss on equivalent von Mises stress, compressive stress magnitude, and displacement using finite element analysis. We hypothesized that occlusal force would be the primary determinant of stress generation, whereas periodontal bone loss would have a greater influence on structural displacement.

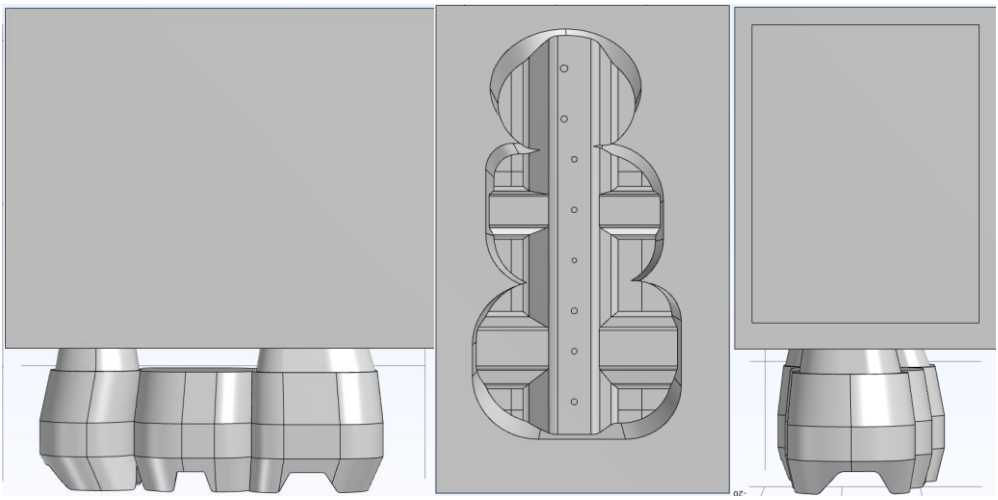
MATERIALS AND METHODS

Development of the mathematical model

The finite element model was developed entirely using *COMSOL Multiphysics® version 6.3* (COMSOL Inc., Burlington, MA, USA), which was employed for both computer-aided design (CAD) and finite element analysis. The initial stage consisted of constructing a geometric model that was sufficiently detailed to provide reliable numerical results while remaining computationally efficient for the numerical solver (fig. 1). The model comprised cortical and trabecular maxillary bone, the maxillary second premolar and second molar with their corresponding periodontal ligaments and cement layers, and a three-unit provisional polymethyl methacrylate (PMMA) fixed dental prosthesis replacing a missing maxillary first molar.

To improve numerical stability and reduce computational complexity, several geometric simplifications were introduced:

- The root apices were represented by flat terminal surfaces instead of anatomical pointed apices to minimize artificial stress concentrations and improve mesh quality.
- The molar furcation was simplified by modeling the three roots as emerging from a common flat surface rather than reproducing the exact anatomical furcation morphology.
- The dental roots were assumed to consist entirely of dentin. Because the mechanical properties of root cementum closely resemble those of dentin, the cementum layer was not modeled as a separate structure.
- Small circular loading areas were created on the occlusal surface of the provisional PMMA crown to simulate the functional contact points with the opposing mandibular teeth.



(a) (b) (c)

Fig. 1. Geometric configuration of the finite element model representing a maxillary three-unit provisional fixed dental prosthesis replacing the first molar shown from the three principal orthogonal views: (a)-frontal, (b)-lateral and (c)-occlusal.

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics, version 29.0.0 (IBM Corp., Armonk, NY, USA). Data were analyzed descriptively and inferentially for each FEM outcome: equivalent von Mises stress, σ ech, compressive stress, σ C, and displacement, F. Because compressive stress values were negative by convention, they were analyzed as absolute magnitudes, |σ C|. For each combination of occlusal force and periodontal condition, mean values and standard deviations were calculated.

An a priori sample size calculation was performed using G*Power, version 3.1.9.7 (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany). The calculation was based on an F-test for fixed-effects ANOVA, assuming a medium effect size, Cohen's f = 0.35, a significance level of α = 0.05, and a statistical power of 0.80. For the main effects in the two-way ANOVA design, the minimum required total sample size was 200 observations. The final dataset included 200 observations, corresponding to 10 observations for each combination of occlusal force and periodontal status.

The effects of occlusal force and periodontal status were assessed using two-way analysis of variance, with occlusal force as a five-level factor, 300, 500, 800, 1000, and 1200 N, and periodontal status as a four-level factor< healthy, 10%, 20%, and 30% horizontal bone loss. The model included the main effects of both factors and their interaction. Effect size was reported as partial eta squared, η^2p. When appropriate, Tukey post-hoc comparisons were used to identify relevant between-group differences.

Linear trend analysis was performed to evaluate the rate of change of FEM outcomes with increasing occlusal force. Re-

gression slopes were expressed per 100 N increase in load. Relative percentage changes were calculated using the healthy periodontal condition as the reference at each occlusal force level. The threshold for statistical significance was set at $p < 0.05$.

RESULTS

Descriptive overview of FEM outcomes

Across all periodontal conditions, increasing occlusal force was associated with a progressive increase in equivalent stress, compressive stress magnitude, and displacement. Equivalent stress values ranged from approximately 520-550 MPa at 300 N to 2400-2500 MPa at 1200 N. A similar load-dependent increase was observed for compressive stress magnitude, which increased from approximately 650-690 MPa at 300 N to 2780-2900 MPa at 1200 N.

Displacement values were low and relatively similar between periodontal conditions at 300 N, ranging from 0.027 to 0.031 mm. At higher loads, however, differences between periodontal conditions became more evident. At 1200 N, mean displacement increased from 0.109 mm in the healthy model to 0.137 mm in the model with 30% horizontal bone loss. This corresponded to a 25.7% increase relative to the healthy periodontal condition.

Overall effects of occlusal force and periodontal bone loss

Two-way ANOVA confirmed that occlusal force had a significant effect on all FEM outcomes. The effect was particularly strong for equivalent stress, σ ech, $F(4,180) = 2701.71$, $p < 0.001$, $\eta^2p = 0.984$, and compressive stress magnitude, |σ C|, $F(4,180) = 2579.70$, $p < 0.001$, $\eta^2p = 0.983$. A strong effect of occlusal force was also observed for displacement, $F(4,180) = 528.24$, $p < 0.001$, $\eta^2p = 0.921$. Two-way ANOVA results for the effects of occlusal force and periodontal status on FEM outcomes are presented in the first table.

TABLE I.
Two-way ANOVA results for the effects of occlusal force and periodontal status on FEM outcomes

FEM outcome	Effect	df effect	df error	F value	p value	Partial η^2
Equivalent stress, σ ech	Occlusal force	4	180	2701.71	<0.001	0.984
Equivalent stress, σ ech	Periodontal status	3	180	11.71	<0.001	0.163
Equivalent stress, σ ech	Occlusal force × periodontal status	12	180	1.70	0.071	0.102
Compressive stress magnitude, |σ C|	Occlusal force	4	180	2579.70	<0.001	0.983
Compressive stress magnitude, |σ C|	Periodontal status	3	180	5.03	0.002	0.077
Compressive stress magnitude, |σ C|	Occlusal force × periodontal status	12	180	2.42	0.006	0.139
Displacement, F	Occlusal force	4	180	528.24	<0.001	0.921
Displacement, F	Periodontal status	3	180	23.87	<0.001	0.285
Displacement, F	Occlusal force × periodontal status	12	180	1.67	0.077	0.100

Periodontal bone loss also significantly influenced all three parameters, although its effect was smaller than that of occlusal force. The effect of periodontal status was moderate for equivalent stress, $F(3,180) = 11.71$, $p < 0.001$, $\eta^2p = 0.163$, and lower for compressive stress magnitude, $F(3,180) = 5.03$, $p = 0.002$, $\eta^2p = 0.077$. In contrast, periodontal bone loss had a more pronounced effect on displacement, $F(3,180) = 23.87$, $p < 0.001$, $\eta^2p = 0.285$.

The interaction between occlusal force and periodontal status was significant only for compressive stress magnitude, $|\sigma C|$, $F(12,180) = 2.42$, $p = 0.006$, $\eta^2p = 0.139$. For equivalent stress and displacement, the interaction did not reach statistical significance, suggesting that the increase in these parameters was mainly driven by the magnitude of the applied load rather than by a changing load-periodontal status relationship.

Stress-related outcomes

Both equivalent stress and compressive stress magnitude showed a clear load-dependent increase across all periodontal conditions. Equivalent stress increased from mean values of approximately 520-550 MPa at 300 N to 2400-2500 MPa at 1200 N. The separation between occlusal force levels was more pronounced than the separation between periodontal conditions, supporting the dominant influence of load magnitude on the von Mises stress response.

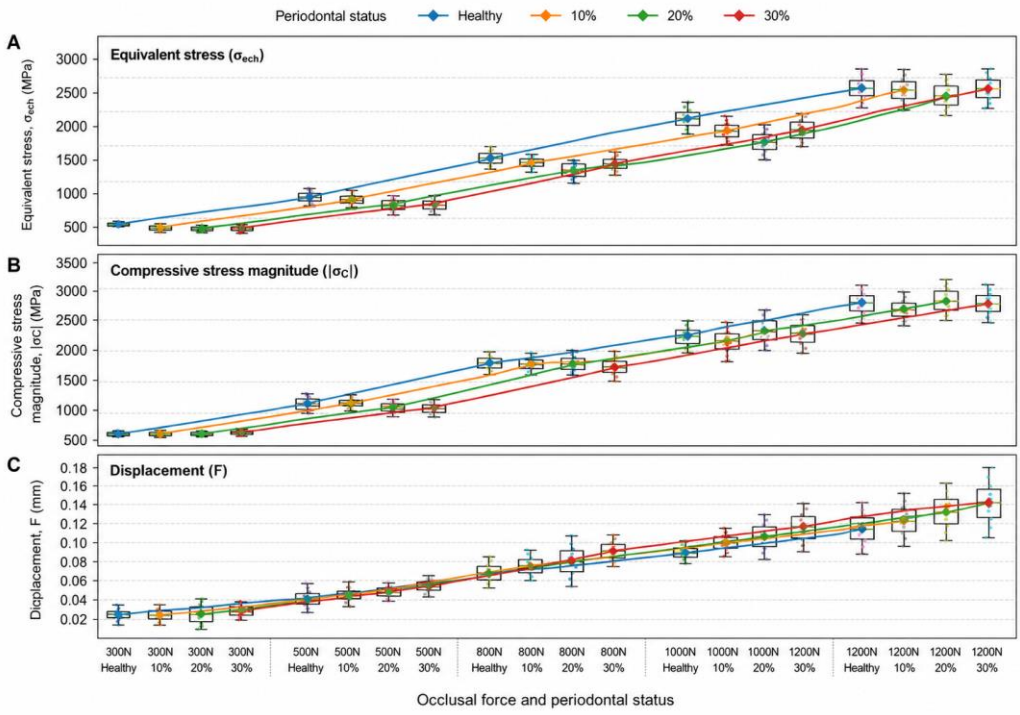


Fig. 2. Distribution of FEM outcomes according to occlusal force and periodontal status: A, equivalent stress; B, compressive stress magnitude; C, displacement.

A similar pattern was observed for compressive stress magnitude. Mean |σ C| values increased from approximately 650-690 MPa at 300 N to 2780-2900 MPa at 1200 N. Although the effect of occlusal force was predominant, compressive stress also showed a significant interaction between occlusal force and periodontal status, indicating that periodontal bone loss modified the distribution of compressive stresses depending on the applied load.

Overall, stress-related outcomes were mainly governed by occlusal force. Periodontal bone loss produced statistically detectable changes, but these were less consistent and less pronounced than the load-dependent increase observed across the five force levels.

Distribution of FEM outcomes according to occlusal force and periodontal status is presented in second figure.

Representative finite element stress maps illustrating the influence of increasing occlusal force and progressive periodontal bone loss are presented in figures 3-6. The maps demonstrate that the location of peak stress remained concentrated around the cervical and supporting structures, whereas the magnitude and spatial distribution of stresses increased progressively with occlusal loading and periodontal support reduction.

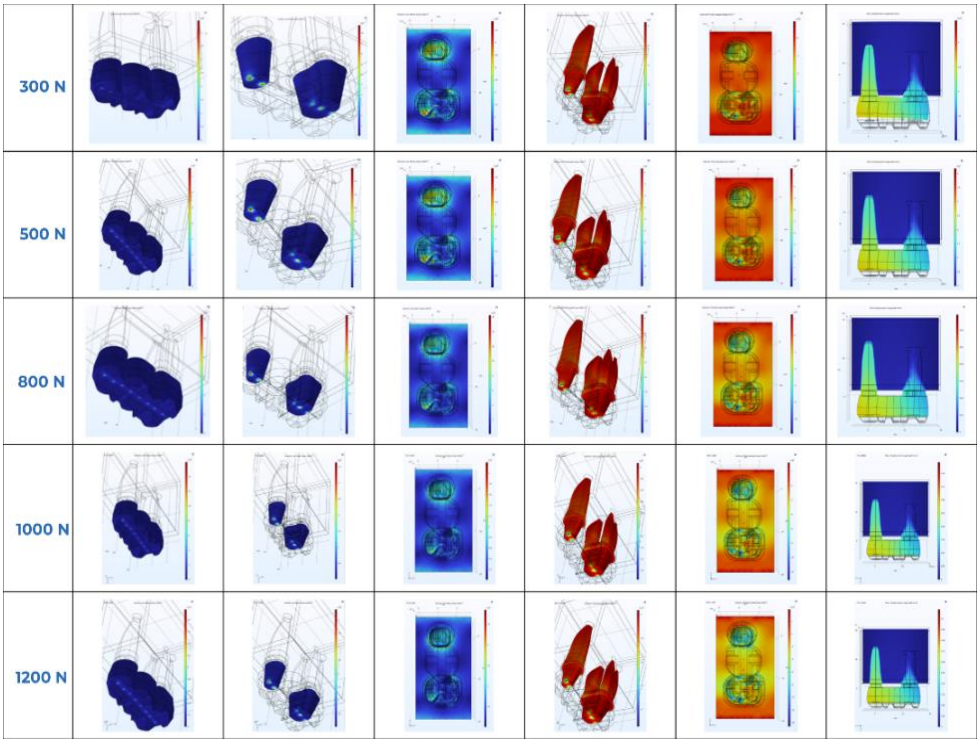


Fig. 3. Representative finite element analysis (FEA) contour plots for the healthy periodontal model under increasing occlusal loads (300, 500, 800, 1000, and 1200 N).

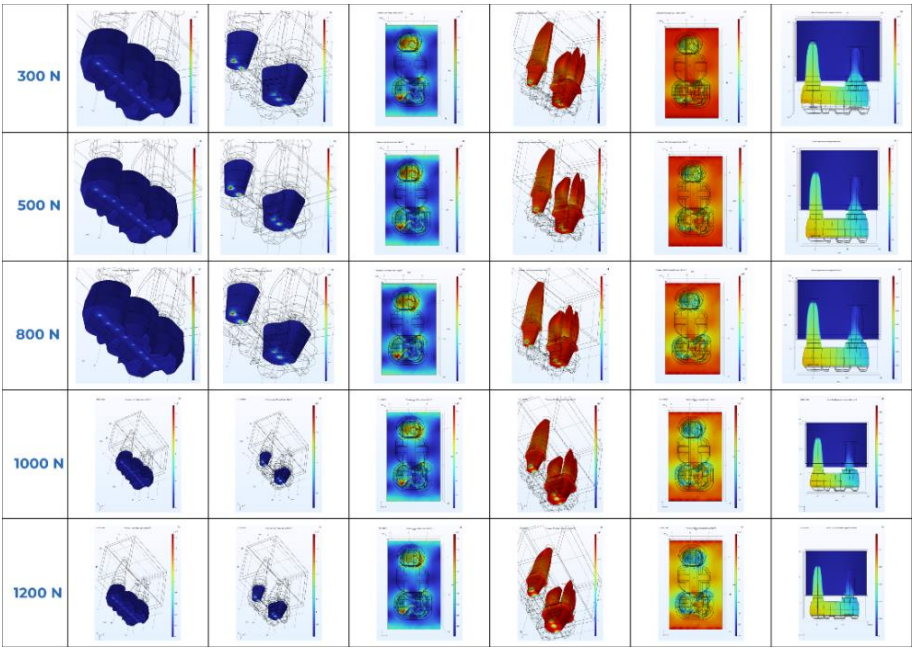


Fig. 4. Representative finite element analysis (FEA) contour plots for the model with 10% horizontal periodontal bone loss under increasing occlusal loads (300, 500, 800, 1000, and 1200 N).

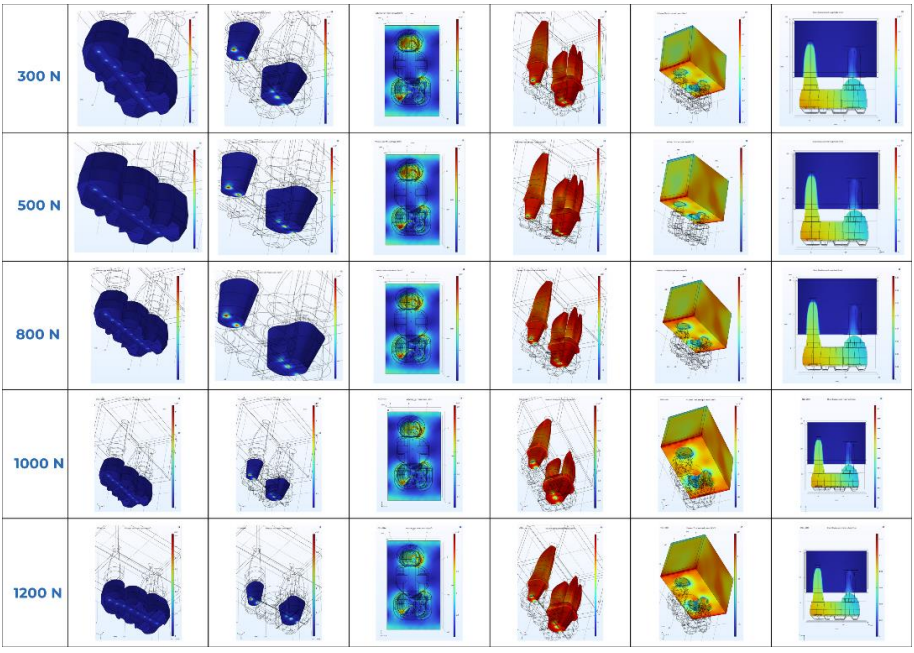


Fig. 5. Representative finite element analysis (FEA) contour plots for the model with 20% horizontal periodontal bone loss under increasing occlusal loads (300, 500, 800, 1000, and 1200 N).

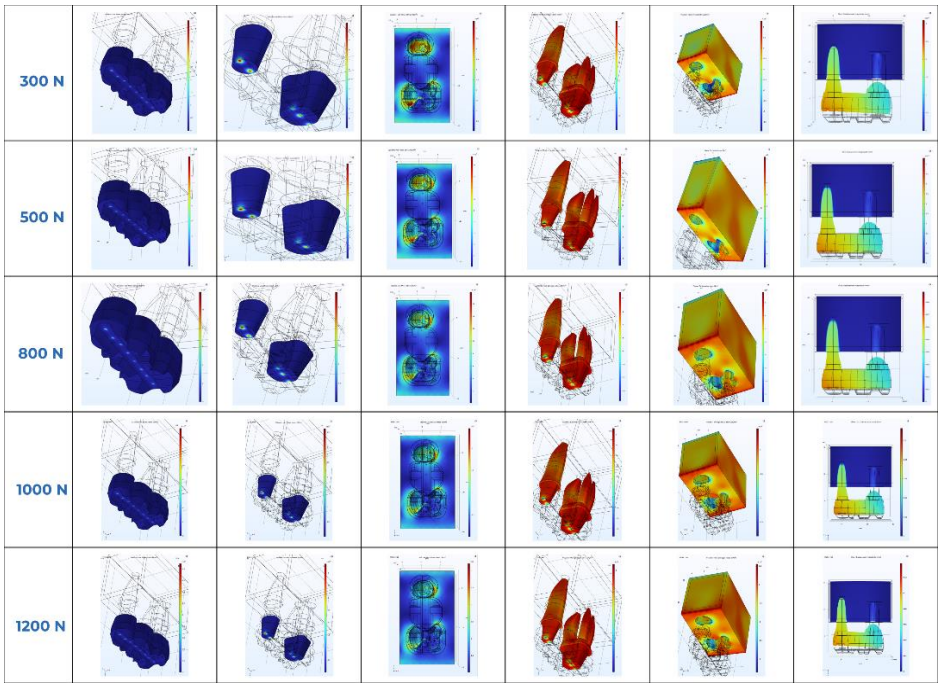


Fig. 6. Representative finite element analysis (FEA) contour plots for the model with 30% horizontal periodontal bone loss under increasing occlusal loads (300, 500, 800, 1000, 1200 N).

Displacement response

Displacement increased progressively with occlusal loading in all periodontal conditions, but the effect of periodontal bone loss became more apparent at higher force levels. At 300 N, mean displacement values were low and relatively close across groups, ranging from 0.027 mm in the 10% bone-loss model to 0.031 mm in the 30% bone-loss model. As the applied load increased, the separation between periodontal conditions became more evident, particularly in the 20% and 30% bone-loss models.

At 1200 N, mean displacement increased from 0.109 mm in the healthy model to 0.117 mm, 0.126 mm, and 0.137 mm in the 10%, 20%, and 30% bone-loss models, respectively. Thus, the model with 30% horizontal bone loss showed a 25.7% higher displacement compared with the healthy periodontal condition at the same load. This pattern is reflected by the progressive divergence in displacement between periodontal conditions as occlusal load increases.

Although occlusal force remained the strongest determinant of displacement, periodontal status had a more pronounced effect on displacement than on stress-related outcomes. This suggests that the reduction in periodontal support primarily affected the deformational behavior of the prosthetic complex, rather than producing a uniform increase in stress values.

Post-hoc comparisons

and linear trend analysis

Post-hoc Tukey comparisons confirmed that differences between occlusal force levels were significant for all FEM outcomes within each periodontal condition. This finding supports the strong load-dependent pattern observed in the descriptive analysis and confirmed by the two-way ANOVA.

For periodontal status, the most relevant differences were observed for displacement at higher loads. At 1200 N, displacement was significantly greater in the 20% bone-loss model than in the healthy model, with a mean difference of 0.017 mm, $p = 0.002$. The difference was even more pronounced for the 30% bone-loss model, which showed a mean increase of 0.028 mm compared with the healthy condition, $p < 0.001$. A significant difference was also observed between the 10% and 30% bone-loss models at 1200 N, with a mean difference of 0.020 mm, $p < 0.001$.

Linear trend analysis further supported these findings. Equivalent stress and compressive stress magnitude showed strong linear increases with occlusal force across all periodontal conditions. For displacement, the slope increased with the severity of periodontal bone loss, from 0.0090 mm/100 N in the healthy model to 0.0117 mm/100 N in the 30% bone-loss model. This indicates that reduced periodontal support was associated with a greater rate of structural displacement as occlusal loading increased.

Relative changes compared with the healthy periodontal condition

Relative changes were calculated using the healthy periodontal model as the reference for each occlusal force level. For equivalent stress, the percentage differences associated with periodontal bone loss were variable and did not follow a consistent increasing pattern. The largest relative reduction was observed in the 20% bone-loss model at 1000 N, where equivalent stress was 12.4% lower than in the healthy condition.

Compressive stress magnitude also showed moderate and non-uniform relative changes across periodontal conditions. The largest increase was observed at 1000 N, where both the 20% and 30% bone-loss models showed a 9.1% increase compared with the healthy model.

The clearest relative effect of periodontal bone loss was observed for displacement. In the 30% bone-loss model, displacement was consistently higher than in the healthy condition at almost all load levels, with increases of 26.2% at 500 N, 29.4% at 800 N, 26.1% at 1000 N, and 25.7% at 1200 N. These findings reinforce the observation that periodontal bone loss affected structural deformation more consistently than stress magnitude. These relative changes shows that displacement exhibited the most consistent and clinically relevant increase with periodontal bone loss, particularly in the 30% bone-loss model at higher occlusal loads (fig. 7).

Figure 7 provides a visual summary of the relative percentage changes in the three FEM outcomes compared with the healthy periodontal condition. The heatmap highlights that changes in equivalent stress and compressive stress magnitude were smaller and less consistent across periodontal conditions, whereas displacement showed a clear and progressive increase with bone loss, especially in the 30% bone-loss model under higher occlusal loads.

Fig. 7. Heatmap of relative percentage changes in equivalent stress, compressive stress magnitude, and displacement compared with the healthy periodontal condition

DISCUSSION

The present finite element study demonstrated that occlusal force was the dominant determinant of equivalent stress, compressive stress magnitude, and displacement, whereas progressive horizontal bone loss exerted its clearest and most consistent effect on displacement (15). The very large effect sizes observed for occlusal force, particularly for equivalent stress and compressive stress magnitude, indicate that the mechanical response was governed primarily by load magnitude (16). Conversely, periodontal status produced a comparatively stronger effect on displacement than on either stress-related outcome. At 1200 N, displacement increased from 0.109 mm in the healthy model to 0.137 mm in the model with 30% bone loss, representing a 25.7% relative increase.

The strong load-dependent increase in stress agrees with the findings of Poiate *et al*., who evaluated periodontal stress under progressively demanding loading conditions and reported substantial changes in stress distribution when the applied force increased from physiological mastication to parafunctional and traumatic loading (17). Their results support the present observation that the magnitude of the applied force has a greater influence on absolute stress values than moderate changes in periodontal support. The current study extends those findings by examining five load levels within the same analytical framework and by quantifying the independent contributions of force and periodontal condition using two-way ANOVA.

The influence of bone loss on periodontal biomechanics has also been demonstrated in earlier finite element studies. Geramy reported that alveolar bone loss increased periodontal ligament stress under an identical force vector and suggested that stress changes accelerated after a critical reduction in bone height (18). Similarly, Reddy *et al*. observed progressive changes in periodontal stress when occlusal loading was applied to models with increasing loss of alveolar support (19). Although these studies generally described higher stress concentrations with more advanced bone loss, the present findings showed that changes in equivalent and compressive stress were not uniformly proportional to the degree of horizontal bone loss. For example, equivalent stress was 12.4% lower in the 20% bone-loss model than in the healthy model at 1000 N, whereas compressive stress was approximately 9.1% higher in the 20% and 30% bone-loss models at the same load. These non-linear variations indicate that reduced support may redistribute stress spatially rather than simply increase every global stress measure.

This apparent discrepancy may be related to differences in model geometry, tooth type, loading direction, defect configuration, material properties, and the anatomical region selected for stress extraction. Geramy and Reddy *et al*. investigated anterior teeth and more advanced reductions in alveolar height, whereas the present analysis evaluated progressive horizontal loss of up to 30% under predominantly axial functional loading (18,19). Studies of localized periodontal defects have likewise shown that defect depth, width, location, and loading angulation substantially modify periodontal ligament stress patterns (20,21). Therefore, differences between published FEM results should not necessarily be interpreted as contradictory; rather, they reflect the high sensitivity of computed stress values to model-specific assumptions.

The displacement findings were more consistent with the broader literature. Zeng *et al*., using mandibular incisor models with different patterns and degrees of horizontal bone resorption, found progressively greater tooth displacement as periodontal support decreased (22). Geramy also reported accelerated biomechanical changes after the loss of a critical amount of alveolar support (18).

In tooth-supported prosthetic models, Naveau *et al*. similarly observed that vertical displacement increased as supporting bone height decreased (16). These findings agree with the present progressive increase in the displacement slope from 0.0090 mm/100 N in the healthy model to 0.0117 mm/100 N in the 30% bone-loss model. Collectively, these results suggest that loss of periodontal support affects the stiffness and deformational stability of the complex more predictably than it affects global stress magnitude.

The significant interaction between occlusal force and periodontal status for compressive stress, but not for equivalent stress or displacement, deserves particular consideration. This result indicates that the effect of bone loss on compressive stress depended partly on the magnitude of loading. A recent hydro-mechanical finite element investigation showed that occlusal loading produces oscillatory fluid movement within the periodontal ligament and that osseous defects intensify this response, particularly in furcation and apical regions (23). Although that study evaluated fluid mechanics rather than global compressive stress, its findings support the concept that

the biomechanical consequences of reduced periodontal support may become more complex under increasing loads (23).

By contrast, the non-significant interactions for equivalent stress and displacement suggest that their overall increases remained predominantly additive and load-driven within the present range of bone loss.

The present results also emphasize the importance of the periodontal ligament assumptions used in FEM. The periodontal ligament is non-linear, anisotropic, viscoelastic, and fluid-dependent, whereas it is frequently simplified as a homogeneous linear-elastic material. Experimental and computational research has shown considerable variation in reported periodontal ligament properties, and recent analyses have demonstrated that the selected elastic modulus can substantially alter both deformation and localized stress concentrations (24, 25). Therefore, the absolute values generated by the present model should be interpreted comparatively rather than as direct clinical thresholds. Nevertheless, because geometry, material properties, boundary conditions, and loading protocols were maintained consistently across all models, the relative differences between periodontal conditions remain informative.

From a clinical perspective, the findings indicate that reducing excessive occlusal loading may be particularly important because force magnitude was the strongest determinant of all evaluated biomechanical outcomes. At the same time, the progressive increase in displacement with periodontal bone loss suggests that teeth with reduced support become increasingly vulnerable to mobility and structural instability, especially under high functional or parafunctional loads. The results therefore support individualized assessment of occlusal contacts, mobility, periodontal support, parafunctional activity, and prosthetic design in patients with reduced periodontal support. However, the findings should not be interpreted as evidence that occlusal adjustment alone can prevent periodontal progression, because the present analysis was mechanical and did not reproduce inflammation, tissue remodeling, healing, or long-term biological adaptation.

Several limitations should be acknowledged. The FEM represented an idealized biomechanical environment and assumed standardized geometry and material behavior. Horizontal bone loss was modeled in predetermined increments, whereas clinical periodontal destruction is often irregular and may include angular defects, furcation involvement, cortical thinning, and heterogeneous ligament properties. Static loading does not fully reproduce dynamic mastication, fatigue, neuromuscular adaptation, or time-dependent periodontal ligament behavior (26). Moreover, the 200 observations represent repeated computational outputs rather than independent biological specimens; thus, inferential statistics quantify variability within the simulation framework and should not be interpreted as population-level clinical evidence.

In addition, no in vitro or experimental validation of the computational model was performed. Therefore, the present findings should be interpreted as comparative biomechanical simulations rather than direct experimental measurements. Furthermore, all materials were assumed to be homogeneous, isotropic, and linearly elastic, whereas biological tissues exhibit anisotropic, heterogeneous, and nonlinear me-

chanical behavior.

Future studies should incorporate patient-specific geometries, non-linear and viscoelastic periodontal ligament properties, oblique and dynamic loading, different prosthetic configurations, and experimental or clinical validation.

These findings support the concept that provisional prosthodontic restorations should not only restore function and aesthetics but also contribute to biomechanical stabilization during periodontal therapy. Careful occlusal adjustment and appropriate provisional prosthodontic therapy may reduce excessive displacement in teeth with reduced periodontal support and facilitate favorable periodontal healing.

CONCLUSIONS

Occlusal force was the main determinant of the biomechanical response, producing marked increases in equivalent stress, compressive stress magnitude, and displacement.

Periodontal bone loss significantly influenced all FEM outcomes, but its effect was smaller than that of occlusal force.

Stress-related outcomes were mainly governed by load magnitude, whereas periodontal bone loss produced less consistent changes in equivalent and compressive stresses.

Displacement was the parameter most sensitive to periodontal support reduction, especially under higher occlusal loads.

The 30% bone-loss model showed the most pronounced increase in displacement, reaching a 25.7% increase compared with the healthy model at 1200 N.

Overall, periodontal bone loss appeared to affect the deformational behavior of the prosthetic complex more clearly than the absolute stress response.

CONFLICT OF INTEREST AND FUNDING

The authors declare that there is no conflict of interest, and they received no specific funding regarding this scientific research.

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