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DENTAL MEDICINE **ORIGINAL PAPERS**

FINITE ELEMENT ANALYSIS OF THE EFFECT OF INSERTION ANGLE AND DIAMETER ON STRESS, STRAIN, AND DISPLACEMENT IN ORTHODONTIC MINI-IMPLANTS

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FINITE ELEMENT ANALYSIS OF THE EFFECT OF INSERTION ANGLE AND DIAMETER ON STRESS, STRAIN, AND DISPLACEMENT IN ORTHODONTIC MINI-IMPLANTS (Abstract): Orthodontic mini-implants are widely used as temporary anchorage devices, and their clinical performance depends on biomechanical factors related to implant design and insertion technique. **Materials and methods**: A three-dimensional finite element model of an orthodontic mini-implant inserted into cortical and cancellous bone was developed. Three insertion angles relative to the cortical bone surface (60°, 90°, and 120°) and two mini-implant diameters (1.5 mm and 2.0 mm) were analyzed under standardized orthodontic loading conditions. Total displacement, equivalent von Mises stress, and equivalent linear strain were evaluated. **Results:** Higher insertion angles resulted in increased displacement and strain, with the highest values observed at 120°. Maximum von Mises stress values were comparable among different angles; however, stress distribution patterns and stress localization varied significantly. Mini-implants with a smaller diameter exhibited higher displacement and stress values, indicating reduced mechanical stiffness, while larger-diameter mini-implants demonstrated improved biomechanical performance. **Conclusions:** Both insertion angle and mini-implant diameter significantly influence the mechanical behavior of orthodontic mini-implants. Perpendicular insertion and increased implant diameter were associated with reduced deformation and more favorable stress distribution, suggesting improved primary stability and clinical performance. **Keywords**: FINITE ELEMENT ANALYSIS; ORTHODONTIC MINI-IMPLANTS; INSERTION ANGLE; IMPLANT DIAMETER; BIOMECHANICS.

INTRODUCTION

Orthodontic mini-implants, also referred to as Temporary Anchorage Devices (TADs), have gained significant traction in contemporary orthodontic treatments. The mechanical behavior of these implants is significantly influenced by geometric parameters such as insertion angle and diameter. Understanding these influences is crucial for optimizing the design and application of mini-implants in clinical settings.

TADs demonstrate variable success rates, with studies indicating that failure rates typically range from 9% to 30% (1). Various systematic reviews have reported success rates for TADs from 80% to 94% (2, 3). The relatively high reliability of mini-implants can largely be attributed to their design, which enables stable anchorage even under orthodontic loading conditions, crucial for effective tooth movement (4, 5).

The insertion of mini-implants is a minimally invasive procedure compared to traditional orthodontic anchorage methods, such as palatally installed implants or miniplates (6). The ability to insert these devices without the need for extensive surgical interventions enhances patient comfort and expedites the treatment process (7, 8).

Research has indicated that mini-implants can significantly broaden the range of treatment strategies available to orthodontists. For example, they have been effectively utilized in complex cases, such as maxillary protraction and closure of extraction spaces, allowing for more efficient treatment sequences (9, 10). Their versatility makes them suitable for various applications, including en-masse retraction and space closure procedures (11, 12).

Ongoing research is focused on improving the design and stability of mini-implants. Studies have explored surface modifications to enhance osseointegration and stability (13), and new findings on optimal insertion protocols continue to emerge (14). The stability of mini-implants, both during the healing phase and after mechanical loading, has been a primary focus, with findings suggesting that various lengths and diameters can impact their success rates (15, 16).

While mini-implants present numerous advantages, they are not without risks. Factors that may influence the failure of mini-implants include patient age, oral hygiene, the placement site's bone density, and the amount of force applied during orthodontic treatment (3, 16). Thus, careful patient selection and technique adjustments are crucial for optimizing their performance (5).

The interplay between insertion angle and diameter further complicates the mechanical behavior of orthodontic mini-implants. Wu *et al*. explored how design variables, including taper shape and diameter, jointly influence mechanical stability (17). They found that specific combinations of insertion angle and diameter could lead to optimized outcomes in terms of anchorage strength and resistance to mechanical loading.

FEA is favored in biomechanical studies of orthodontic mini-implants due to its ability to model complex structures and simulate physiological responses accurately. The application of FEA allows researchers to predict stress distribution patterns around mini-implants under different forces, thus facilitating the design of implants that can withstand significant loading without failure (18, 19). By employing FEA, orthodontists can assess the mechanical performance of mini-implants, unveiling insights about their interactions with surrounding bone and tissues that would be difficult to quantify through traditional *in-vivo* experiments (20, 21).

The aim of this study was to evaluate, using finite element analysis (FEA), the influence of insertion angle and diameter on the biomechanical behavior of orthodontic mini-implants. Specifically, the study investigated the effects of three insertion angles (60°, 90°, and 120° relative to the cortical bone surface) and two mini-implant diameters (1.5 mm and 2.0 mm) on total displacement, equivalent von Mises stress, and equivalent strain distributions within the mini-implant.

The objective of this analysis was to identify biomechanically favorable insertion configurations that minimize displacement and stress concentration, thereby contributing to improved primary stability and providing biomechanical support for clinical decision-making regarding orthodontic mini-implant placement.

MATERIALS AND METHODS

A three-dimensional finite element analysis (FEA) was performed to evaluate the biomechanical behavior of orthodontic mini-implants under different insertion angles and diameters. The modeling process consisted of geometric modeling, material property assignment, mesh generation, application of boundary conditions and loads, and result analysis.

Geometric Modeling. The mandibular model, including teeth and periodontal ligament (PDL), was reconstructed from computed tomography (CT) images, which were digitized and converted into three-dimensional solid models. The periodontal ligament was modeled with a uniform thickness of 0.25 mm based on the external geometry of the tooth roots. Commercially inspired mini-implant models were created according to Leone® and Dual Top Jeil Medical Corporation® (Seoul, Korea) designs.

Two mini-implant diameters (1.5 mm and 2.0 mm) and a total length of 12 mm with a maximum insertion depth of 9 mm were analyzed. Mini-implants were virtually inserted at depths of 5, 6, and 7 mm into cortical and cancellous bone. The insertion site was defined as the interradicular space between the premolar and molar region.

All geometric models were created and assembled using SpaceClaim (ANSYS Inc., USA).

Finite Element Model

The assembled models were imported into ANSYS Workbench (version 2021, ANSYS Inc., USA) and discretized using three-dimensional 10-node tetrahedral elements. A mesh convergence study was

performed with element sizes ranging from 0.3 mm to 1.2 mm. An element size of 0.3 mm was selected in the mini-implant insertion region, while a size of 0.8 mm was used for the remaining volume.

All materials (bone, teeth, PDL, and mini-implants) were assumed to be linear elastic, homogeneous, and isotropic. Material properties were assigned based on values reported in the literature. Mini-implants were modeled using Ti-6Al-4V alloy for Dual Top Jeil Medical Corporation® implants and stainless steel 316L for Leone® implants.

Contact Conditions and Boundary Condition. The interfaces between teeth and periodontal ligament were assumed to be perfectly bonded. A frictionless contact (coefficient of friction = 0) was defined between the mini-implant and bone. The proximal and distal surfaces of the mandibular bone were fixed in all directions to simulate boundary constraints.

Loading Conditions. Orthodontic forces ranging from 0.1 N to 10 N were considered. A force magnitude of 2 N, corresponding to the upper limit of clinically accepted immediate loading, was applied to the head of the mini-implant. The force was oriented obliquely in the proximal direction to simulate en-masse tooth retraction and to allow comparative analysis between different insertion angles and implant diameters.

Outcome Measures. The numerical simulations evaluated total displacement, equivalent von Mises stress, and equivalent linear strain distributions within the mini-implant and surrounding bone structures. The results were analyzed to assess the influence of insertion angle and implant diameter on the biomechanical behavior of orthodontic mini-implants.

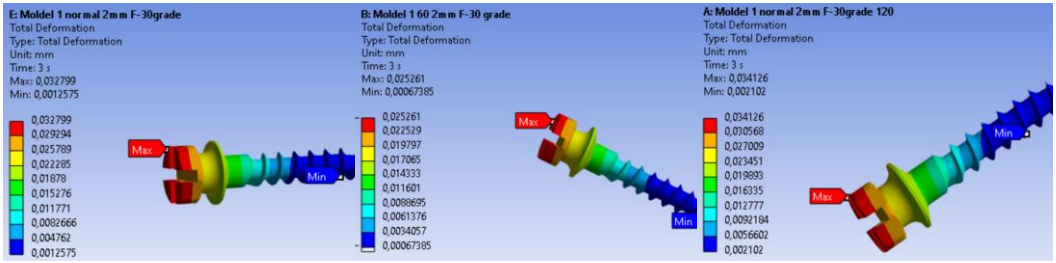
RESULTS

Influence of the mini-implant inclination angle relative to the Y-axis

Total displacements

The total deformation state of the mini-implant as a function of the inclination angle relative to the cortical bone surface is presented in first figure. Higher values are obtained for an inclination angle of 120°. The results indicate that the inclination angle significantly influences the displacement state.

The comparative values of the maximum total displacements in the mini-implant as a function of the inclination angle relative to the cortical bone surface are presented in figure 2.



90º 60º 120º

Fig. 1. Total deformation state of the mini-implant
as a function of the inclination angle relative to the cortical bone surface.

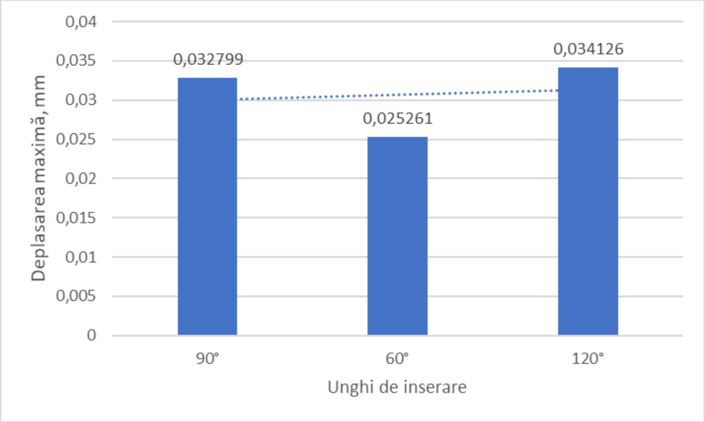
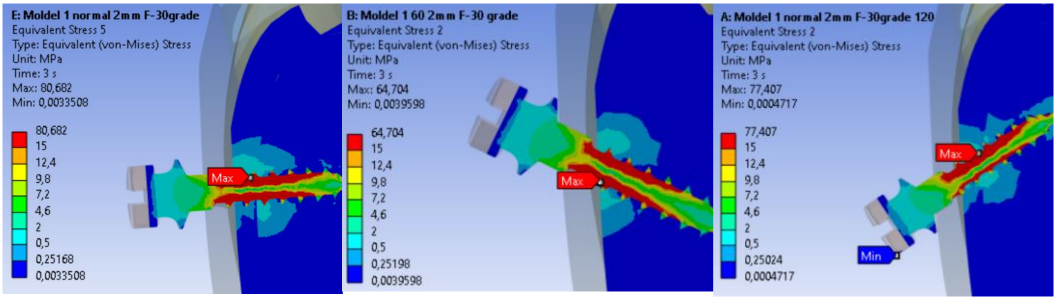


Fig. 2. Comparative values of the maximum total displacements in the mini-implant
as a function of the inclination angle relative to the cortical bone surface.

Equivalent von Mises stresses

The stress distribution for the three inclination angles relative to the cortical bone surface, shown in cross-section, is presented in figure 3. The maximum value obtained is 138.92 MPa for the case of an insertion length of 5 mm into the bone. The maximum values for the three analyzed cases are relatively close. The results indicate that the stress distribution pattern differs significantly among the analyzed cases, with the maximum stress located at a shallower depth for the 60° inclination.

The comparative values of the maximum stress as a function of the inclination angle relative to the cortical bone surface are presented in fourth figure.



90° 60° 120°

Fig. 3. Stress distribution for the three inclination angles relative to the cortical bone surface, shown in cross-section.

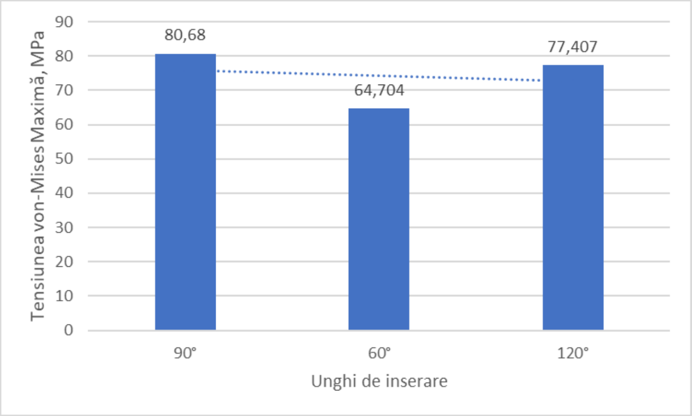


Fig. 4. Comparative values of the maximum stress as a function of the inclination angle relative to the cortical bone surface.

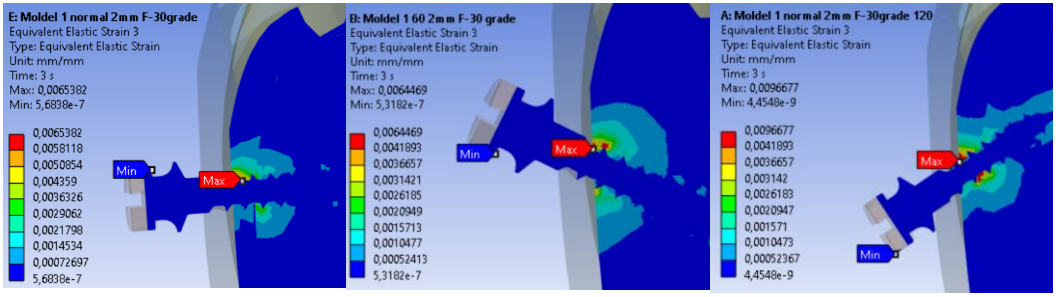
Equivalent strains

The equivalent linear strain distribution for the three inclination angles relative to the cortical bone surface is presented in figure 5. The maximum value obtained is 0.009677 mm/mm for the inclination angle of 120°. The volume of stressed material is greater for the 60° and 120° cases compared to the 90° case.

The comparative values of the equivalent strains as a function of the inclination angle relative to the cortical bone surface are presented in figure 6

Influence of the mini-implant Diameter. Total displacements

The total deformation state of the mini-implant as a function of the mini-implant type is presented in Fig. 7, with the mini-implant of 1.5 mm diameter shown on the left and the 2 mm diameter mini-implant shown on the right. Higher values are obtained for the smaller-diameter implant. The results indicate that the diameter significantly influences the displacement state, which is physically consistent, as the bending moment of inertia for a circular cross-section increases with diameter, resulting in a stiffer system.



90° 60° 120°

Fig. 5. Equivalent linear strain distribution for the three inclination angles relative to the cortical bone surface.

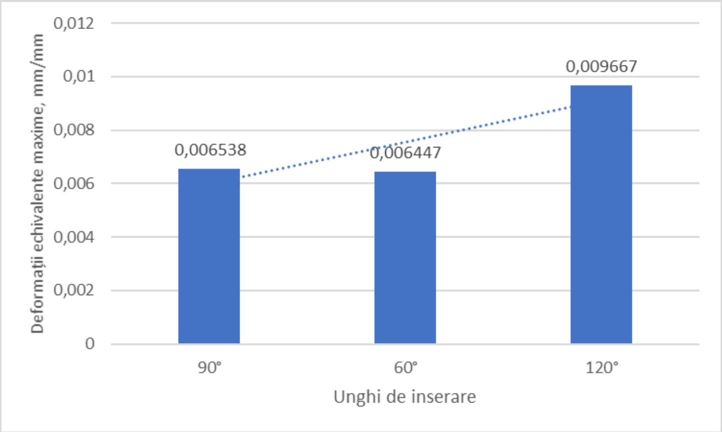
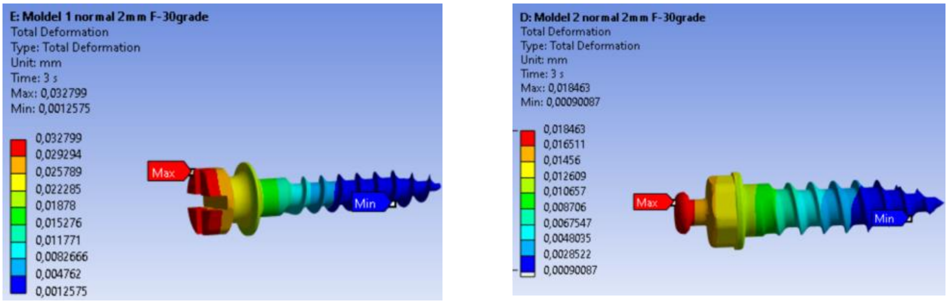


Fig. 6. Comparative values of the equivalent strains
as a function of the inclination angle relative to the cortical bone surface.



Model 1 d = 1,5 mm Model 2 d = 2 mm

Fig. 7. Total deformation state of the mini-implant as a function of the mini-implant type.

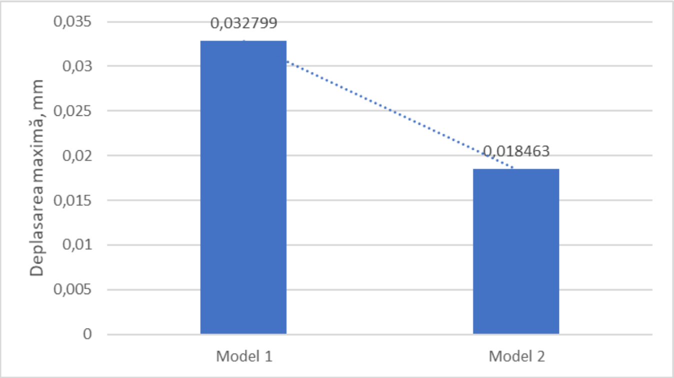
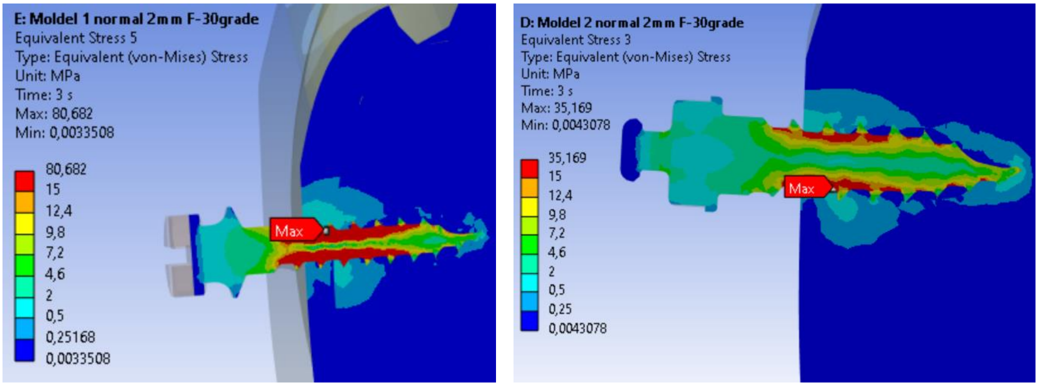


Fig. 8. Comparative values of the maximum total displacements in the mini-implant as a function of its type.

Equivalent von Mises stresses

The stress distribution for the different insertion lengths of the implant, shown in cross-section, is presented in Fig. 9 The maximum value obtained is 80.682 MPa for the model 1 mini-implant with a diameter of 1.5 mm, while the minimum value is 35.169 MPa for the model 2 mini-implant with a diameter of 2 mm. The results indicate that the stress distribution differs significantly between the two analyzed cases. It can also be observed that the volume of affected material is greater for the model 2 mini-implant.



Model 1 d = 1,5 mm Model 2 d = 2 mm

Fig. 9. Stress distribution for the different insertion lengths of the implant, shown in cross-section.

The comparative values of the maximum stress as a function of the mini-implant model are presented in figure10.

Equivalent strains

The equivalent linear strain distribution for the two mini-implant models is presented in figure 11. The maximum value obtained is 0.0066167 mm/mm for model 2. The results indicate that the distribution of equivalent strains differs between the two analyzed cases, with the maximum located at different positions.

Figure 12 presents the comparative values of the equivalent strains as a function of the mini-implant type.

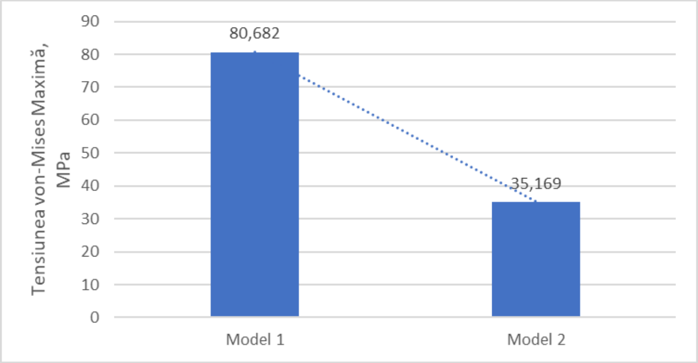
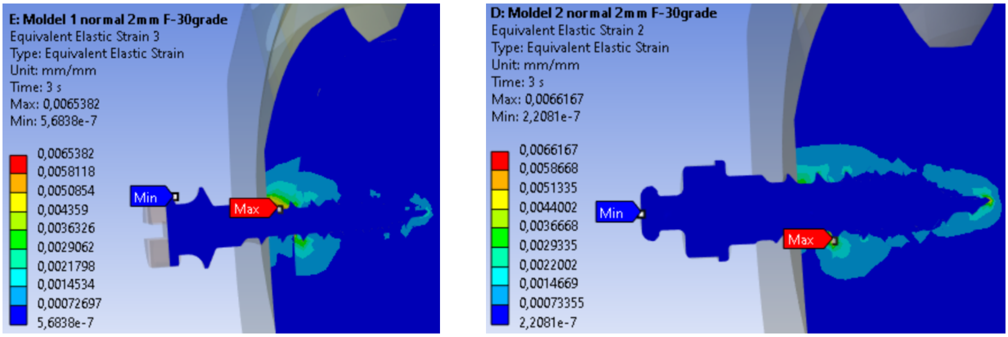


Fig. 10. Comparative values of the maximum stress as a function of the mini-implant model.



Model 1 d = 1,5 mm

Model 2 d = 2 mm

Fig. 11. Equivalent linear strain distribution for the two mini-implant models.

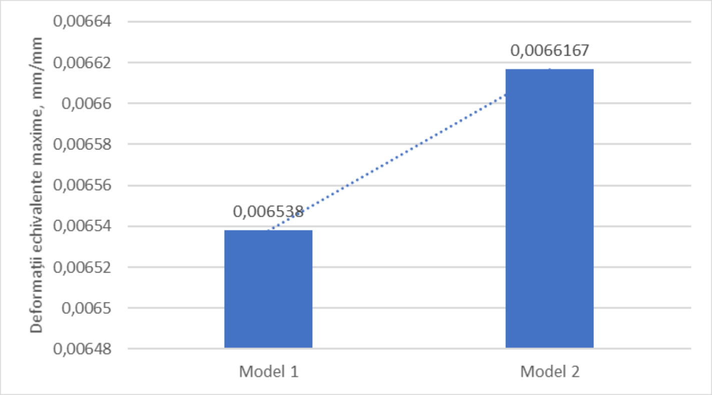


Fig. 12. Comparative values of the equivalent strains as a function of the mini-implant type.

DISCUSSION

Orthodontic mini-implants serve as pivotal anchorage devices in modern orthodontics, enabling effective treatment outcomes through strategic force application. The insertion angle of these implants significantly affects their displacement and overall stability. This article discusses the findings from various finite element studies regarding the impact of increased insertion angles, such as 120°, compared to perpendicular placements at 90° (TABLE 1).

Several studies establish a correlation between the angle of insertion and the displacement of orthodontic mini-implants. For example, a study by Motoyoshi *et al*. emphasizes that increased angles of insertion can lead to heightened stress on surrounding cortical bone, consequently increasing the displacement experienced by the implants (22). This claim is supported by the findings of Sana *et al.*, who concluded that oblique angles can create longer lever arms, thereby impacting engagement between the implant threads and the bone (23).

Moreover, a finite element analysis (FEA) study conducted by Xavier *et al*. indicated that an increase in insertion angle from 90° to 45° resulted in greater strain and insertion torque, which was correlated to increased displacement (24).

TABLE I.

Influence of insertion angle on displacement: comparison between present study and literature

Parameter	**Present FEM Study**	**Findings from Literature**
Insertion angle	60°, 90°, 120°	45°-120° (22, 25)
Total displacement	Highest displacement observed at 120°; lowest at 90°	Increased displacement reported for oblique angles compared to perpendicular insertion (22, 23)
Mechanical explanation	Increased lever arm and reduced thread engagement at higher angles	Oblique insertion increases bending moments and reduces cortical bone engagement (23, 24)
Clinical implication	Higher angulation may compromise primary stability	Oblique insertion associated with increased risk of micromovement and instability (25)

The primary stability of mini-implants is critical for their success, and the insertion angle plays a vital role in this regard. Wilmes *et al*. report that the insertion angle significantly impacts the primary stability of these implants, with angular placements at 120° being more susceptible to movement than perpendicular placements (25).

A thorough understanding of stress distribution patterns surrounding mini-implants is necessary to evaluate their performance under different insertion angles (tables 2). Sivamurthy and Sundari’s study highlights significant alterations in axial load reactions with varying insertion angles (26). The outcomes of this study align with those from Chaddad *et al.*, which examined how surface characteristics, including angle of insertion, influence stress on the mini-implant interface and subsequently affect displacement (27). The correlation between insertion angle and stress allows for deeper insights into how misalignment can increase the risk of failure in clinically modeled scenarios (28).

TABLE II.

Influence of insertion angle on stress distribution

Aspect	Present FEM Study	Literature Findings
Maximum von Mises stress	Similar peak stress values for all angles	Comparable peak stresses reported across angles (26)
Stress distribution	Significant variation in stress localization; shallower stress concentration at 60°	Stress concentration shifts With insertion angle (27, 28)
Risk of failure	Altered stress distribution may increase localized bone overload	Misalignment linked to higher failure risk due to uneven stress (28)

Study limitations

This finite element study is subject to certain limitations.

a. The finite element models assumed all materials (bone, teeth, periodontal ligament, and mini-implants) to be linear elastic, homogeneous, and isotropic, which does not fully reflect the complex anisotropic behavior of biological tissues in vivo.

b. A frictionless contact condition was defined at the bone-mini-implant interface, which may underestimate the effects of interfacial friction and mechanical interlocking occurring in clinical situations.

c. The geometry of the mandibular bone was simplified to reduce computational time, potentially affecting the accuracy of stress and strain distribution in anatomically complex regions.

d. Only static loading conditions were considered, whereas cyclic and dynamic orthodontic forces may influence long-term mini-implant stability.

e. Biological factors such as bone remodeling, osseointegration, and patient-specific variability were not included in the finite element simulations.

f. The study evaluated a limited range of insertion angles and implant diameters; therefore, the results may not be directly generalizable to all commercially available mini-implant designs.

g. The findings are based on numerical simulations and should be interpreted as comparative biomechanical trends rather than absolute predictors of clinical performance.

CONCLUSIONS

This finite element study demonstrated that both insertion angle and mini-implant diameter significantly affect the mechanical behavior of orthodontic mini-implants. Higher insertion angles increased displacement and strain, while larger diameters improved mechanical stability and stress distribution. These findings may support optimized clinical placement of orthodontic mini-implants.

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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