A FINITE ELEMENT ANALYSIS OF MINI-IMPLANT EFFECTS ON THE PERIODONTIUM: FROM BIOMECHANICAL SIMULATION TO ORAL HEALTH AND MENTAL WELLBEING

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A FINITE ELEMENT ANALYSIS OF MINI-IMPLANT EFFECTS ON THE PERIODONTIUM: FROM BIOMECHANICAL SIMULATION TO ORAL HEALTH AND MENTAL WELLBEING (Abstract): Mini implants are widely used as temporary anchorage devices (TADs) in orthodontics, providing stable and minimally invasive anchorage. However, excessive or misdirected stresses at the bone-implant interface may compromise periodontal integrity and long-term success. To assess stress distribution and bone deformation around orthodontic mini implants under varying insertion angles and load magnitudes using finite element analysis (FEA), and to explore their clinical and wellbeing implications. **Materials and methods:** A 3D FEA model was developed in SolidWorks, based on CBCT data and manufacturer specifications for a titanium mini implant (8×1.7 mm). The bone model consisted of 2 mm cortical and 8 mm trabecular bone layers. Simulations were performed for insertion angles of 30°, 45°, 60°, and 90° under para-axial forces of 1 N and 5 N. Stress and deformation were evaluated using the von Mises criterion. **Results:** The highest stress values were recorded at the implant-cortical bone interface, particularly at 90° insertion, and increased with load magnitude. Stress rose from 27 MPa at 1 N to 266 MPa at 5 N, while bone deformation ranged from a few to several tens of micrometers. Insertion geometry and loading intensity significantly influence the biomechanical behavior of peri-implant bone. Moderate insertion angles (45-60°) ensured a more balanced stress distribution and greater stability. **Conclusions:** Finite element modelling supports personalized, safe, and psychologically comfortable orthodontic treatments, linking biomechanical precision with oral and mental wellbeing. **Keywords:** FINITE ELEMENT ANALYSIS, MINI-IMPLANTS, STRESS DISTRIBUTION, CORTICAL BONE, PERIODONTAL BIOMECHANICS, INSERTION ANGLE, ORAL AND MENTAL WELLBEING.

INTRODUCTION

Mini implants, also known as temporary anchorage devices (TADs), have revolutionized modern orthodontic and periodontal therapy by providing stable, minimally invasive, and cost-effective anchorage for tooth movement and skeletal correction. Their clinical success relies not only on the mechanical design of the implant but also on the complex biomechanical interactions with the surrounding periodontal tissues, including the cortical and trabecular bone, periodontal ligament, and gingival interface (1-4).

Despite their widespread use, the pre-

cise distribution of stress and strain within the peri-implant region remains a critical determinant of biological response and long-term stability. Inappropriate insertion angles or excessive loading may cause microdamage, localized bone resorption, or even implant failure. Conversely, controlled stress levels within physiological limits can stimulate bone remodeling and strengthen osseointegration (5-7).

Finite Element Analysis (FEA) has emerged as a powerful computational method for simulating these interactions in a non-invasive and highly reproducible manner. By combining imaging data (such as CBCT) with accurate material modeling, FEA enables the visualization and quantification of stress patterns within the implant-bone-periodontium complex. This allows clinicians to anticipate biological outcomes under various clinical conditions before treatment is initiated (8-11).

However, current literature has often emphasized mechanical optimization alone, overlooking the broader implications for oral and mental wellbeing. The stability of anchorage systems has direct effects on treatment duration, procedural discomfort, and aesthetic outcomes - all of which influence patient confidence, adherence, and emotional state during orthodontic therapy (12-14). The integration of biomechanical predictability with patient-centered psychological comfort thus represents a new paradigm in contemporary dental care.

Accordingly, the present study aims to perform a finite element analysis of stress distribution and bone deformation around orthodontic mini-implants under different insertion angles and loading conditions. Beyond quantifying mechanical performance, the study seeks to link these biomechanical outcomes with their potential clinical and psychosocial significance, providing a holistic view of mini-implant therapy as a bridge between functional precision and overall wellbeing.

MATERIAL AND METHODS

In this study, a finite element model was developed to determine the stress distribution at the interface between the bone and the orthodontic mini-implant, depending on the insertion angle and the applied force.

The analytical model was generated using imaging data (CBCT) and the characteristics of the mini-implant (8 × 1.7 mm) as specified by the manufacturer. A CBCT scan of the mini-implant inserted into a mandibular mould was performed to accurately observe and reproduce the contact established between the two structures.

For the construction of the analytical model, it was also necessary to determine the characteristics of the mini-implant, namely its dimensions and geometry (morphology). The following algorithm was applied:

I. Determination of the Thread Geometry

Determination of the length of segment (CD), expressed in pixels:

$$CD = \sqrt{(710 - 650)^2 + (565 - 395)^2} = 180 \text{ px}$$

Given that CD = 1.7 mm, we define the ratio:

$$\alpha = 180/1.7 = 106 \text{ px/mm}$$

Verification of the accuracy of the calculated ratio:

$$OB = \sqrt{(1333 - 680)^2 + (730 - 480)^2} = 700 \text{ px}$$

$$700/180 = 3.(8)$$

$$8/1.7 = 4.7$$

Since the ratios are not equal, another possible reference point was sought to

define the 8 mm length (fig. 1)

$$EB = \sqrt{(1333 - 565)^2 + (730 - 395)^2} = 840 \text{ px}$$

$$840/180 = 4.6 \approx 4.7 = 8/1.7$$

In this context, the ratio is corrected to α = 840 / 8 = 105 px/mm.

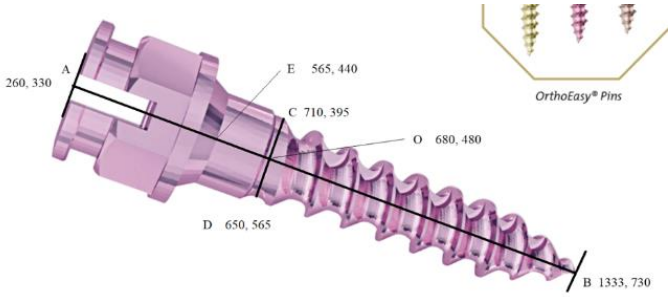

Fig. 1. Determination of the thread geometry using another reference point

II. Approximation of the Screw Geometry

The coordinates of the points are: A(915, 660), B(980, 680), C(980, 655), D(950, 649).Thus, the quadrilateral shown in the image has the following dimensions: AB = 68 px = 0.65 mm, BC = 25 px = 0.24 mm, CD = 30.59 px = 0.29 mm, DA = 46.32 px = 0.44 mm. Determination of the unthreaded segment length: OE = 121.76 px = 1.15 mm s (fig 2).

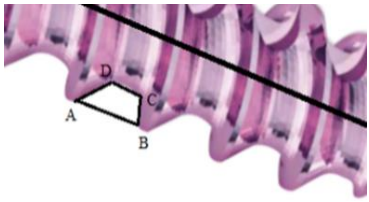

Fig 2. Approximation of the screw geometry

Once the dimensions and morphology of the mini-implant were calculated and analyzed, the 3D model could be created. Using the obtained data, the parameters were transferred into the SolidWorks software, where the analysis proposed in this study was performed using the Finite Element Method (FEM).

In this study, the bone sample was modeled as a cylinder (fig. 3) with a diameter of 10 mm and a height of 10 mm, of which 2 mm represented the cortical bone and the remaining 8 mm corresponded to the trabecular portion. For this geometric body representing the bone, the following material properties were assigned: Young's modulus of 1.5×10^{10} N/mm² (MPa) for the cortical layer and 1.5×10^{9} N/mm² (MPa) for the trabecular component, both with a Poisson's ratio of 0.3.

For the mini-implant, material properties corresponding to titanium were applied, with a Young's modulus of 1.05×10^{5} N/mm² (MPa) and a Poisson's ratio of 0.37. The materials were considered homogeneous, linearly elastic, and isotropic. Subsequently, the two bodies were brought into contact, thereby defining the interface between the mini-implant and the bone.

A total of 16 geometric models were developed according to the objectives of this study, each incorporating the proposed

variable specifically, the insertion angle of the mini-implant (90°, 60°, 45°, and 30°) and the para-axial force applied to it (1 N and 5 N). The stress generated by each applied force on both the mini-implant and the surrounding bone was evaluated, and the results were expressed according to the von Mises stress criterion.

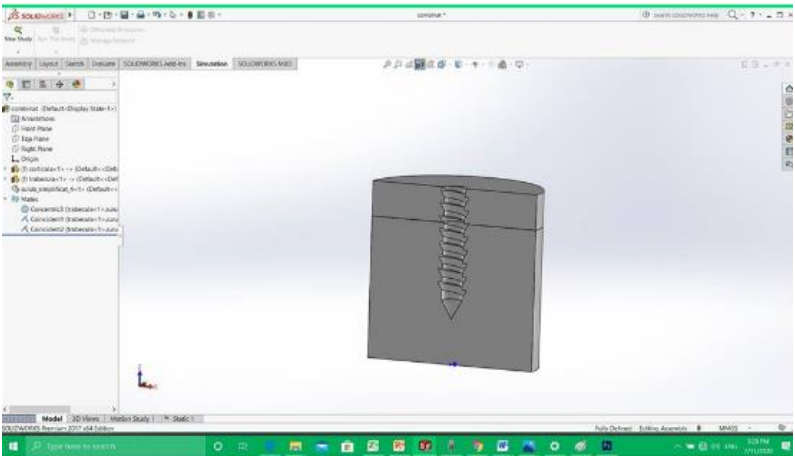

Fig. 3. Raw bone block (section view)

RESULTS

The stress evaluated for the mini-implant with constant dimensions of 8 × 1.7 mm, under different insertion angles (30°, 45°, 60°, and 90°) and applied forces (1 N and 5 N), increased proportionally with both the angle and the magnitude of the applied force. A similar trend was also observed for the stress distributed within the bone.

TABLE I.

Results of the static analysis under a 1 N load

Force value	Inclination relative to the screw axis	Inclination with respect to the screw axis	Maximum bone stress
1N	90 deg	27MPa	13MPa
	60 deg	24MPa	12MPa
	45 deg	18MPa	10MPa
	30 deg	10MPa	6MPa

TABLE II -

Results of the static analysis under a 5 N load

Force value	Inclination relative to the screw axis	Inclination with respect to the screw axis	Maximum bone stress
5N	90 deg	266MPa	70MPa
	60 deg	200MPa	55MPa
	45 deg	145MPa	40MPa
	30 deg	78MPa	23MPa

The maximum stress values on the mini-implant and on the bone were observed, for each applied force, at an insertion angle of 90°. The area subjected to the highest stress was located at the interface between the mini-implant (screw) and the cortical bone. This region exhibited the greatest concentration of stress, which was distributed across both the implant and the bone in all simulations.

The stress gradually decreased within the trabecular bone, where the lowest values were recorded. The bone underwent deformation in the micrometre range under a 1 N load, while at a 5 N load, the deformation increased, reaching values in the tens of micrometres.

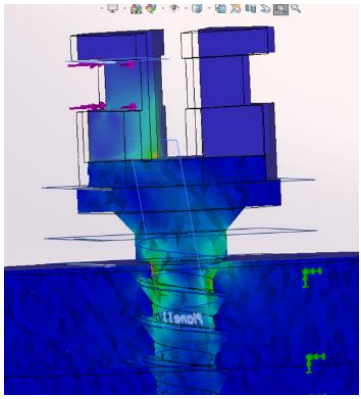

Fig. 4. Determination at 1 N, 90°

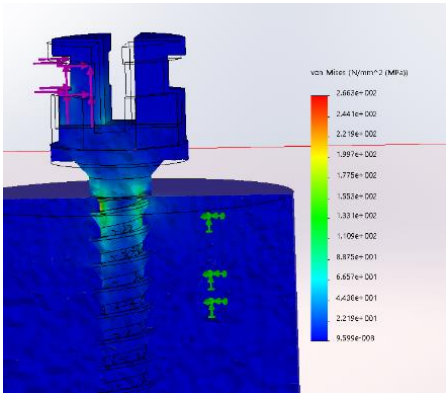

Fig. 5. Determination at 5 N, 90°

DISCUSSION

The current finite element analysis (FEA) offers a detailed exploration of the biomechanical interactions between orthodontic mini-implants and the periodontal support structures. The simulation revealed that both insertion angle and applied load significantly influence the magnitude and distribution of stress at the implant-bone interface. The highest von Mises stress values occurred at 90° insertion, increasing proportionally with force intensity (1N-5N). These results are consistent with previous studies indicating that axial loading amplifies stress transfer to the cortical bone and periodontal ligament, which are the primary structures responsible for implant anchorage and biological adaptation (1, 5, 8, 11, 15).

From a periodontal perspective, the findings highlight the delicate biomechanical balance required to preserve tissue integrity. The cortical layer, with its higher elastic modulus, absorbed the greatest load, while stress values decreased progressively toward the trabecular bone. This gradient is critical for maintaining physiological bone remodeling and preventing microdamage or localized resorption. Excessive compressive stress near the cortical interface can impair microcirculation, limit osteoblastic activity, and initiate inflammatory responses, potentially compromising periodontal health and long-term mini-implant stability (6-10).

In contrast, moderate insertion angles (45°- 60°) produced a more uniform stress distribution, reducing localized peaks within the cortical bone and promoting more favorable load sharing across the periodontium.

This supports the clinical rationale that proper angulation minimizes mechanical trauma to the alveolar crest and reduces the risk of microcracks or cortical perforation - factors that have been correlated with implant loosening or failure in vivo (15-17).

At the tissue level, bone deformation ranged from a few micrometers at 1 N to several tens of micrometers at 5 N, remaining within the physiological tolerance of the periodontal ligament (PDL) and alveolar bone. However, repeated loading, particularly at high forces, may induce micro strain accumulation and activate bone remodeling pathways through mechanic transduction mechanisms. Studies have shown that controlled stress within this range stimulates adaptive bone remodeling, while excessive mechanical input may trigger osteoclastic resorption and connective tissue damage (16-18).

Beyond the mechanical domain, this study aligns with the emerging concept of oral and mental wellbeing in modern orthodontics. The predictable stability of mini-implants contributes to functional efficiency, shorter treatment duration, and reduced anxiety, factors that significantly impact patient satisfaction and psychological comfort. Clinical research has shown that predictable biomechanical control and minimally invasive procedures improve the patient's emotional perception of therapy and enhance treatment adherence (12-14, 19-21). The integration of biomechanical precision with psychological safety thus represents a paradigm shift toward holistic orthodontic care, where success is measured not only by mechanical outcomes but also by quality of life and emotional balance (21).

While the FEA method offers valuable predictive insights, certain limitations must be acknowledged. The model assumes homogeneous, isotropic, and linearly elastic materials, which differ from the anisotropic and viscoelastic behavior of real biological tissues. Additionally, static loading cannot fully replicate the complex dynamic forces of mastication and orthodontic movement. Future research should incorporate patient-specific anatomical models, nonlinear material properties, and in vivo validation to strengthen the translational potential of simulation data (8, 10, 22-24).

In summary, the present study bridges the gap between biomechanical simulation and clinical reality, demonstrating that optimal stress management at the mini-implant-periodontium interface supports both tissue health and patient psychological wellbeing. Such an integrated perspective underscores the future direction of orthodontic innovation: the alignment of engineering precision with human-centered care.

Nevertheless, the present study has limitations inherent to computational simulations. The materials were considered homogeneous, isotropic, and linearly elastic, whereas real biological tissues exhibit anisotropy and viscoelasticity. Moreover, the static loading conditions do not fully replicate the dynamic forces present in vivo. Future research should combine patient-specific 3D imaging, nonlinear material models, and longitudinal clinical validation to establish more precise correlations between simulated stress values and biological outcomes.

CONCLUSIONS

The present finite element analysis demonstrated that both insertion angle and applied load play a crucial role in determin-

ing stress distribution at the mini-implant-bone interface. The highest von Mises stress values were observed at a 90° insertion angle and increased proportionally with load intensity, localizing predominantly in the cortical bone. These findings confirm the cortical layer's key role in load transfer and underline the importance of selecting optimal angulation to minimize concentration zones and prevent microdamage.

From a mechanical standpoint, moderate insertion angles (45°-60°) produced more favorable stress distributions and may contribute to enhanced primary stability, particularly in regions with reduced cortical thickness.

Although the observed bone deformation remained within the physiological range, sustained or excessive loading could initiate localized remodeling or resorption if not properly controlled.

Clinically, the integration of finite element modeling provides a predictive framework for optimizing orthodontic anchorage design, improving safety margins, and individualizing treatment according to bone density and anatomical morphology.

Beyond mechanical optimization, the stable and minimally invasive use of mini implants has positive implications for oral function, aesthetics, and patient mental wellbeing, contributing to reduced anxiety and improved overall quality of life.

CONFLICT OF INTEREST AND FUNDING

The authors declare that there is no conflict of interest and they received no specific funding.

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