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DENTAL MEDICINE **ORIGINAL PAPERS**

KEY FACTORS FOR MINI-IMPLANT SUCCESS: THE CRITICAL ROLE OF CORTICAL BONE THICKNESS AND ORTHODONTIC FORCES IN ENHANCING STABILITY AND PREVENTING FAILURE

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KEY FACTORS FOR MINI-IMPLANT SUCCESS: THE CRITICAL ROLE OF CORTICAL BONE THICKNESS AND ORTHODONTIC FORCES IN ENHANCING STABILITY AND PREVENTING FAILURE (Abstract): This study **aims** to analyze the biomechanical performance of titanium (Ti6Al4V) mini-implants (MIs) under orthodontic forces using finite element analysis (FEA) and to evaluate stress, strain, and displacement behavior within cortical and spongy bone under realistic clinical conditions. **Materials and methods:** A three-dimensional finite element model of a mini-implant (2.0 mm diameter, 12 mm length) was developed using CT-based reconstruction of the mandible and periodontal ligament. The model was meshed with tetrahedral elements and simulated in ANSYS Workbench 19.2. Material properties for bones, teeth, ligament, and implant were defined as linear elastic, homogeneous, and isotropic. Orthodontic forces of 2N and 10N were applied at a 30° angle to replicate molar intrusion scenarios. Stress, strain, and displacement distributions were analyzed for cortical and spongy bone, with special attention to localized areas of maximum impact. **Results:** Maximum von Mises stress and equivalent strain values were localized around the implant insertion site. Cortical and spongy bone demonstrated high resistance to applied forces, with stress and strain levels remaining below their fracture thresholds. The results highlighted the critical role of cortical bone thickness in ensuring primary stability. Displacement was minimal, with a maximum value of 0.028948 mm at the implant head under a 2N force, demonstrating functional stability. Forces exceeding 3N were identified as the threshold for potential spongy bone failure, reinforcing the appropriateness of 2N for orthodontic applications. **Conclusions:** The study confirms that mini-implants can effectively withstand orthodontic forces when inserted into adequate cortical bone thickness. The integration of finite element modeling with clinical insights provides valuable guidance for optimizing mini-implant performance and minimizing adverse effects. These findings contribute to improving treatment strategies and ensuring the longevity of orthodontic anchorage systems. **Keywords:** FINITE ELEMENT METHOD (FEM); FRACTURE; MINI-IMPLANT; ORTHODONTIC FORCES; STRESS DISTRIBUTION; BONE-IMPLANT INTERACTION.

INTRODUCTION

Cortical bone serves as a structural barrier during orthodontic tooth movement, and its thickness can significantly affect the mechanical stress experienced by the bone when orthodontic forces are applied. For instance, studies have shown that the stress in cortical bone can increase dramatically in response to orthodontic forces, potentially leading to microfractures and bone loss, especially in areas where the bone is already thin (1). The remodeling of alveolar bone around moving teeth is a well-documented phenomenon in orthodontics, yet the specific impact of cortical bone thickness on this process remains underexplored (1). Understanding this relationship is essential, as inadequate bone support can lead to mini-implant failure, which has been reported to occur in up to 28% of cases due to insufficient cortical bone quality and quantity (2). Moreover, the application of orthodontic forces must be carefully calibrated to avoid overloading the cortical bone, which can result in adverse outcomes such as periodontal tissue loss and compromised tooth stability (3, 4). The interaction between orthodontic forces and cortical bone thickness is particularly relevant when considering the use of temporary anchorage de-vices (TADs), where the primary stability of mini-implants is heavily influenced by the surrounding bone characteristics (5, 6). Research indicates that the quality and thickness of cortical bone at the insertion site are critical determinants of the success of these devices (7, 8).

The simultaneous study of cortical bone thickness and orthodontic forces is critical for advancing orthodontic practices and improving patient outcomes. A significant gap in current orthodontic research lies in the understanding of how variations in cortical bone thickness influence the response to orthodontic forces, particularly in the context of mini-implants used for anchorage.

Moreover, patient-related factors such as age, oral hygiene, and systemic health conditions can significantly influence the success rates of mini-implants (9). The impact of mechanical factors on bone stress and strain in orthodontic mini-implants is a critical area of study that integrates biomechanics, material science, and biological responses. Experimental research in orthodontics today aims to investigate the usefulness of recent technology and advancements into predictable methodology by incorporating tools such as finite element analysis (FEA), 3D CAD CAM, low-level laser therapy (LLLT) and digital simulations (10-12). These technologies enable more accurate predictions of treatment outcomes, better understanding of biomechanical forces, and the development of customized, patient-specific approaches.

Through these advancements, researchers can refine diagnostic techniques and optimize the performance of orthodontic appliances, making treatments more efficient, reliable, and less invasive. Research has shown that the insertion angle of mini-implants plays a crucial role in stress distribution within the bone. For instance, Popa *et al.* (13) demonstrated that increasing the insertion angle from 30° to 120° results in decreased stress on the bone, indicating that a more oblique insertion can lead to better stress distribution and potentially lower the risk of implant failure. An increase in insertion angle can influence stress levels, the torque required for removal does not consistently correlate with stress distribution across all angles, suggesting a more complex interaction (14). The mechanical properties of the materials used for mini-implants also significantly affect their performance. The use of titanium alloys, particularly Ti6Al4V, is prevalent due to their favorable mechanical properties and biocompatibility, which are essential for maintaining stability during orthodontic treatment (15).

However, discrepancies in Young's

modulus between the implant material and the surrounding bone can lead to stress-shielding effects, potentially resulting in implant loosening over time (15). This highlights the importance of selecting materials that closely match the mechanical properties of bone to optimize the performance of mini-implants. Furthermore, the dimensions of mini-implants, including their diameter and length, have been shown to influence their mechanical stability. Kovuru’s finite element study indicated that larger diameter and longer mini-implants resulted in decreased mobility, which correlates with reduced stress on the adjacent bone (2). This finding is consistent with other studies that emphasize the importance of implant design in minimizing stress concentrations in the peri-implant bone (16, 17). The biological response of the periodontal ligament (PDL) to mechanical forces is also a critical factor in understanding bone remodeling around mini-implants. Mechanical stress applied during orthodontic treatment induces various cellular responses in the PDL, which are essential for bone remodeling. For example, moderate mechanical loading has been shown to promote osteogenesis, while excessive forces can lead to cellular damage and dysregulation of bone remodeling processes (18, 19). The balance of mechanical forces is vital; while moderate stress supports bone formation, excessive stress can trigger bone resorption and negatively impact the stability of mini-implants (20, 21). The Finite Element Method (FEM) has emerged as a pivotal tool in the biomedical field, especially in orthodontics and the design of medical implants such as hip prostheses, surgical instruments, and external fixators, offering the advantage of simulating complex biological systems and enabling detailed analysis of stress and strain distributions in tissues like the periodontal ligament (PDL), alveolar bone, and surrounding structures, as well as predicting the mechanical behavior of medical devices under various loading conditions to enhance their design and functionality . (22-24). An increase in cortical bone thickness is hypothesized to significantly improve the primary stability of mini-implants in ortho-dontic treatments, reducing the likelihood of implant failure under standard orthodontic forces. Conversely, thinner cortical bone is expected to result in higher stress concentrations, which may decrease implant longevity and increase the likelihood of failure when subjected to higher orthodontic forces. Optimal loading conditions are hypothesized to increase the mechanical stability of orthodontic mini-implants by reducing stress, strain, and displacement in both the implant and surrounding bone, thereby enhancing long-term success in orthodontic applications.

MATERIALS AND METHODS

In this study, a titanium (Ti6Al4V) mini-implant, with dimensions of 2.0 mm in diameter and 12 mm in length, was modeled using the finite element method (FEM) (Figure 1). The mandible’s geometry was derived from scanned data, with computed tomography (CT) images being processed and digitized (Figure 1). Three-dimensional solid models of both the mini-implants and the mandible were created and integrated using SpaceClaim, a commercial computer-aided design (CAD) software (Figure 1). The periodontal ligament was represented with a 0.25 mm thickness, corresponding to the outer geometry of the dental roots. The mini-implant’s insertion point was positioned midway along the depth of the roots of both premolars, specifically in the space between the premolar and molar. The entire model was imported into the finite element analysis software (version 2021; ANSYS, Inc., Canonsburg, Pennsylvania, USA) and discretized using automatically generated 10-node tetrahedral structural elements (fig. 4). The materials for the bones, teeth, periodontal ligament, and mini-implant were modeled as linear elastic, homogeneous, and isotropic, with mechanical properties sourced from published literature. To ensure convergence in the finite element model, various element sizes, ranging from 0.3 mm to 1.2 mm, were tested. It was concluded that an element size of 0.3 mm was optimal for the mini-implant insertion area, while 0.8 mm was suitable for the rest of the model.

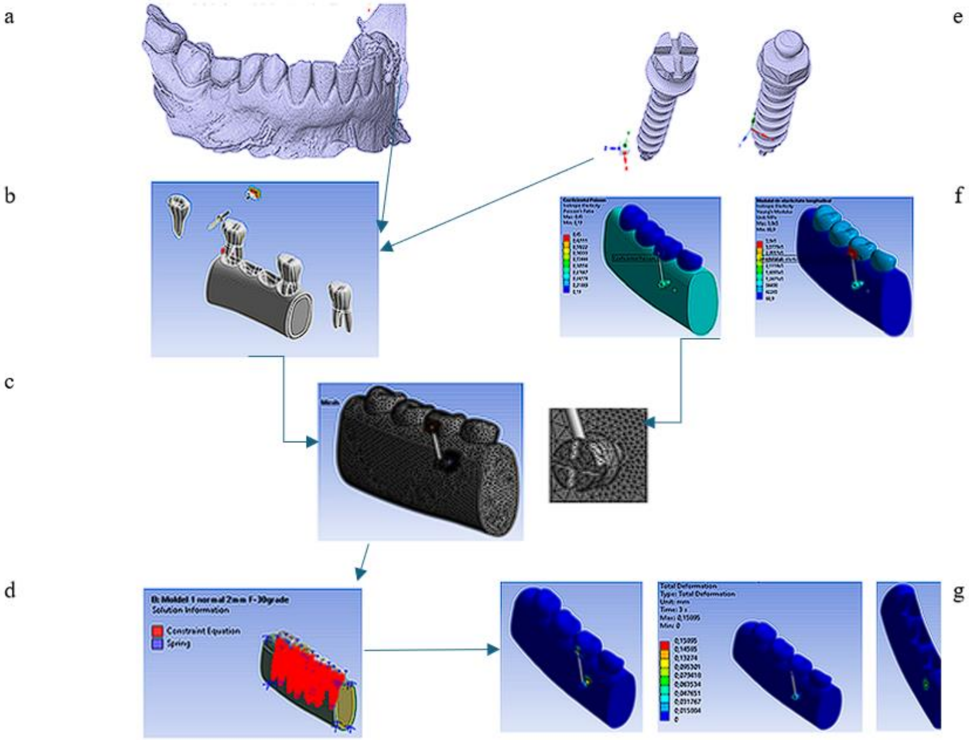

Fig. 1. Digital workflow for structural analysis of mini-implants using CT data:
a. Mandible STL file; b. Geometric model (CAD): Teeth, PDL, Adhesive, Mini-implant, Mandible (cortical bone and spongy bone), Bracket; c. Discretized model; d. Analysis settings; e. Mini-implant STL file; f. Material model; g. Obtained results.

The interfaces between the teeth and the periodontal ligament were assumed to be bonded, while a frictional contact (friction coefficient = 0) was assumed between the bone and the mini-implant. Orthodontic forces ranging from 0.1 N to 10 N were applied. A force of 2 N and an additional 10 N force were applied at a 30° angle relative to the vertical axis (Y) to simulate real-world orthodontic conditions. These forces were directed from the mini-implant toward the molar via the connector tube, accurately representing the biomechanics involved in a molar intrusion scenario with skeletal anchorage. This angled application reflects clinical load transfer during orthodontic treatments and allows for a realistic assessment of stress and strain distributions within the periodontal ligament, alveolar bone, and surrounding tissues.

The inclined force direction plays a crucial role in controlling the intrusion of the first molar, making this model a precise simulation for evaluating biomechanical responses during this specific orthodontic movement. These models were created using SpaceClaim software, (19.2, ANSYS, Inc., Canonsburg, Pennsylvania, U.S) which allowed for the import and remodeling of CT images in STL format. The models were geometrically simplified to ensure stability during finite element analysis without compromising realism (fig. 1). Finite element modeling involved discretizing the 3D models into a large number of elements and nodes (fig. 1). The mesh was finer in critical areas, such as the insertion site of the implant and the adjacent region. The CAD model was automatically meshed into finite elements using ANSYS Workbench 19.2 software (ANSYS Workbench 19.2, Canonsburg, Pennsylvania, U.S). Material properties, such as Young's modulus and Poisson's ratio, were specified for each component of the implant system (fig. 1). Contact conditions were also defined to simulate interactions between the different parts of the model.

RESULTS

Results obtained for the loading scenario with 2N, 30° to the normal

Figure 2 provides a visual representation of the results from the finite element analysis for the loading scenario where a 2N force is applied at a 30° angle to the normal. This analysis is crucially important in understanding the stress, strain, and displacement behavior of the bone-implant system under orthodontic loading conditions.

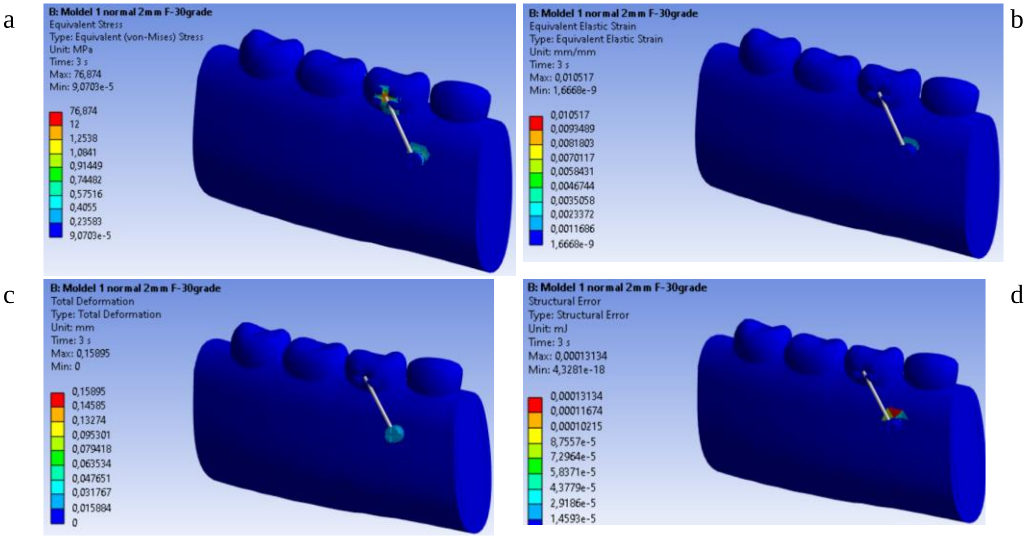

Fig. 2. The von Mises equivalent stress state, strain state, total displacements, and structural error on the global model: a. The von Mises equivalent stress state on the global model; b. The equivalent strain states on the global model; c. Total displacements on the global model; d**.** Structural error on the global model.

Figure 2 (a) displays the von Mises equivalent stress state on the global model. This indicates the distribution of stress throughout the model. Areas with higher stress concentrations can be observed, which are essential in predicting potential failure points or areas of concern regarding structural integrity. Figure 2 (b) shows the equivalent elastic strain state on the global model. This provides insights into how the material deforms under load, with higher strain regions indicating areas where the material undergoes significant deformation. Figure 2 (c) represents the total displacements on the global model. This gives an overall picture of how much the mini-implant and surrounding structures move or displace in response to the applied force, crucial for assessing the functional stability of the mini-implant in a clinical setting. Figure 2 (d) highlights the structural error on the global model. Structural error maps are essential for verifying the reliability of the simulation, ensuring that the model's results fall within acceptable error margins and the analysis is valid.

Results obtained in cortical bone

In Figure 3a, the von Mises equivalent stress state on the cortical bone is presented. The maximum value obtained is 5.29 MPa in the area immediately surrounding the orthodontic anchorage. It can be observed that relatively high values are obtained in a relatively small volume of material, with the area indicated as "Max" in the image. The stress values are five times lower or more for the areas adjacent to the recorded maximum.

Based on the results obtained for the compressive strength of the cortical bone (200 MPa) and the tensile strength (110 MPa), it can be concluded that the bone is not affected by the orthodontic anchorage. The value obtained is much lower than the fracture limit of the cortical bone.

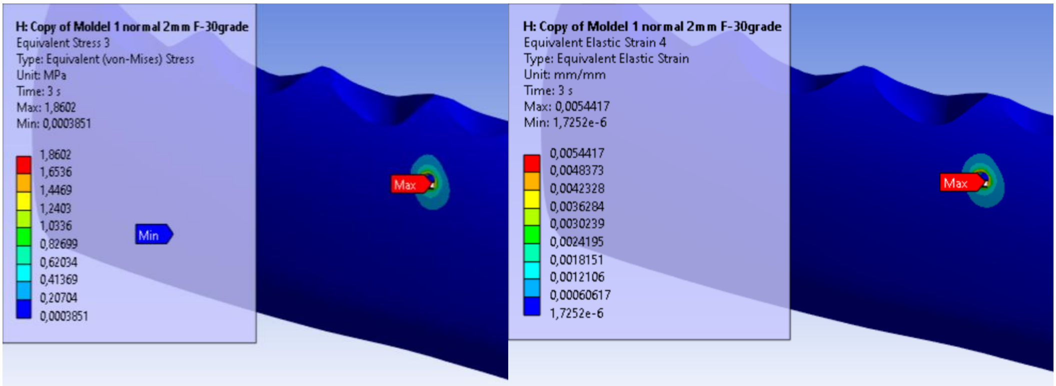

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Fig. 3. Results obtained in the cortical bone in the mini-implant insertion area: a. The von Mises equivalent stress state in the cortical bone in the mini-implant insertion area; b. The equivalent strain state in the cortical bone in the mini-implant insertion area.

In Figure 3b, the equivalent linear strain state on the cortical bone is presented. The maximum value obtained is 0.016378 mm/mm in the area immediately surrounding the orthodontic anchorage, at the node with the maximum von Mises stress value.

Relatively high values are observed in a relatively small volume of material, with the area indicated as “Max” in the image.

Based on the results obtained for the cortical bone’s resistance to compression (0.0085 mm/mm) and to tension (0.007 mm/mm), it can be concluded that the bone is affected by the orthodontic anchorage only at the node where the maximum value was recorded. The value obtained for the rest of the material in the area immediately surrounding the anchorage is lower than the specific linear deformations obtained experimentally for cortical bone.

In Figure 4, the graph of maximum von Mises equivalent stresses as a function of loading force in the cortical bone section is presented. The maximum value obtained is 17.972 MPa in the most stressed area, which is the same area shown in Figure 3a for a force magnitude of 10N, while the value door 2N orthodontic force is 5.2914 MPa. The nonlinear graph is a result of the application of nonlinear contact between the mini-implant and the cortical bone. The graph shows that the fracture limit values of the cortical bone are not exceeded for all applied force values, indicating that the cortical bone withstands forces greater than 10N

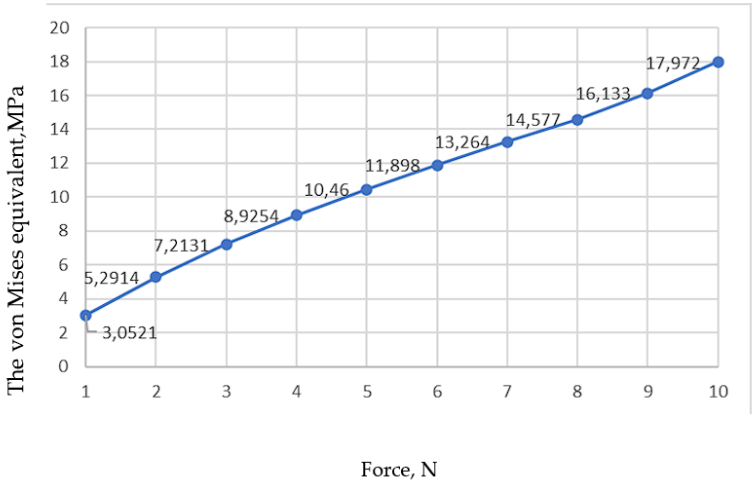

Fig. 4. The von Mises equivalent stress state in the cortical bone.

Results obtained in the spongy bone

In Figure 5a, the von Mises equivalent stress state in the spongy bone is presented. The maximum value obtained is 1.86 MPa in the area immediately surrounding the orthodontic anchorage. It can be observed that relatively high values are concentrated in a relatively small volume of material, with the area indicated as "Max" in the image. The stress values are five times lower or more for the areas adjacent to the recorded maximum. Based on the results obtained for the compressive strength of the spongy bone (2.6 MPa) and the tensile strength (2.3 MPa), it can be concluded that the bone is not affected by the orthodontic anchorage. The value obtained is much lower than the fracture limit of the spongy bone. In Figure 5b, the equivalent linear strain state in the spongy bone is presented. The maximum value obtained is 0.0054417 mm/mm in the area immediately surrounding the orthodontic anchorage, at the node with the maximum von Mises stress value. Relatively high values are observed in a relatively small volume of material, with the area indicated as "Max" in the image. Based on the results obtained for the compressive strain resistance of the spongy bone (0.08 mm/mm) and tensile strain resistance (0.13 mm/mm), it can be concluded that the bone is affected by the orthodontic anchorage only at the node where the maximum value was recorded. The value obtained in the rest of the material in the area immediately surrounding the anchorage is lower than the specific linear deformations obtained experimentally for spongy bone.

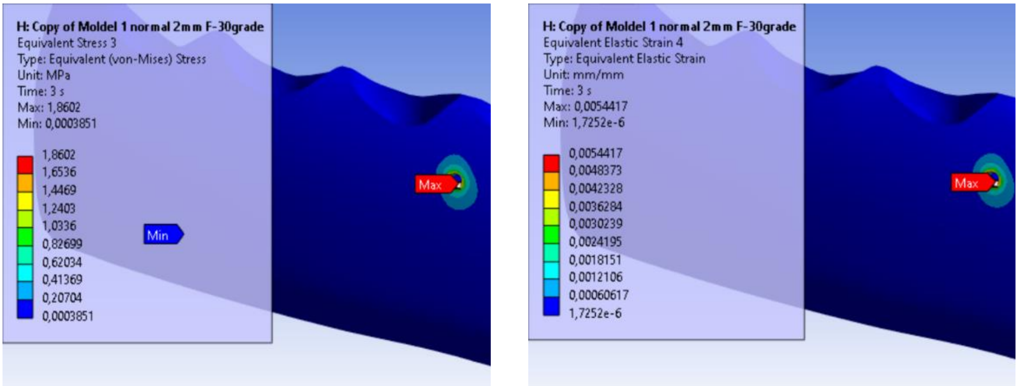

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Fig. 5. Results obtained in the spongy bone in the mini-implant insertion area:
a. The von Mises equivalent stress state in the cortical bone in the mini-implant insertion area; b. The equivalent strain state in the cortical bone in the mini-implant insertion area.

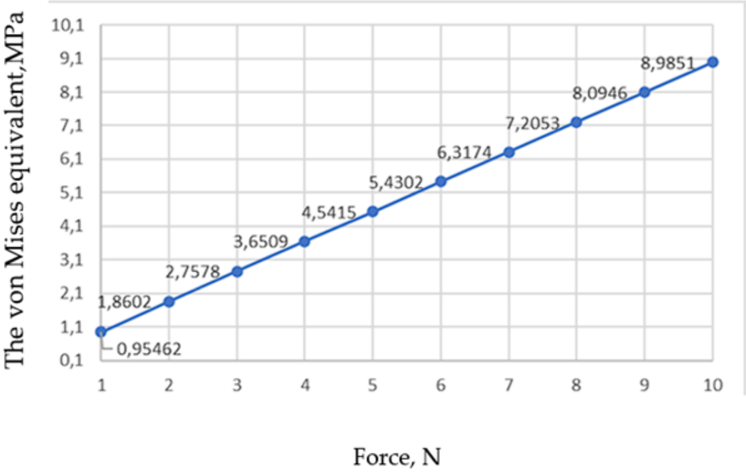

Fig. 6. The von Mises equivalent stress state in the cortical bone.

In Figure 6, the graph of maximum von Mises equivalent stresses as a function of loading force in the spongy bone section is presented. The maximum value obtained is 8.98 MPa in the most stressed area, which is the same area shown in Figure 14 a for a force magnitude of 10N, while the minimum value is 1.8602 MPa for an orthodontic force of 2N. The graph indicates that the fracture limit values of the spongy bone are exceeded for applied forces greater than 3N, suggesting that the spongy bone withstands forces up to 3N. If this force is exceeded, there is a likelihood of cracks forming. It is also observed that a force of up to 2N, chosen for orthodontic treatment, is appropriate, as this value is supported by most studies.

TABLE I.

Results for cortical and spongy bone.

Parameter	Result	Threshold/Limit
Maximum Von Mises Stress	5.29 MPa near anchorage	Compressive: 200 MPa, Tensile: 110 MPa
Maximum Equivalent Linear Strain	0.016378 mm/mm near anchorage	Compression Resistance: 0.0085 mm/mm, Tension Resistance: 0.007 mm/mm
Maximum Von Mises Stress	1.86 MPa near anchorage	Compressive: 2.6 MPa, Tensile: 2.3 MPa

The results suggest that both cortical and spongy bone (tab. I) largely remain within the safe limits of their mechanical strength. However, the slight deformation exceeding the permissible limit in the cortical bone at maximum stress may indicate a vulnerable area, especially under repetitive loading scenarios.

DISCUSSION

FEA is a powerful computational tool used to predict the mechanical behavior of structures under various loading conditions. However, the accuracy of FEA results is highly dependent on the assumptions made during modeling. The presumption of 100% osseointegration simplifies the model but neglects the variability inherent in biological systems. This can lead to erroneous predictions regarding stress distribution, load transfer, and potential failure modes of implants (25).

Impact of von Mises equivalent stress on cortical bone: The maximum values of von Mises equivalent stress are recorded in the area immediately surrounding the orthodontic anchorage. These high values indicate a concentration of stresses in this region, which may be associated with the risk of deformation or bone damage. However, it is important to note that the relative stress values are lower in the areas adjacent to the recorded maximum, suggesting that the orthodontic impact on the cortical bone is localized and does not significantly affect the entire bone. Equivalent linear strain in cortical bone: The maximum values of equivalent linear strain are also recorded in the area immediately surrounding the orthodontic anchorage.

These strains may indicate excessive loading or a weakness in the bone in this region. However, similar to von Mises stress, the strains are localized and do not significantly affect the entire cortical bone. Cortical bone resistance to compression and tension: By comparing the cortical bone’s resistance to compression and tension with the deformations and stresses induced by the orthodontic anchorage, it can be observed that the bone is not significantly affected. The resistance values of the cortical bone are much higher than the deformations and stresses induced by the orthodontic anchorage, indicating the bone’s ability to withstand the applied orthodontic forces. Importance of the localization of maximum stress and strain: The fact that maximum stress and strain are localized in a small area of the cortical bone suggests that orthodontic treatment has a concentrated impact, which can be effectively managed and monitored. This aspect can be considered in developing and implementing orthodontic treatment strategies that minimize adverse effects on the cortical bone.

Impact of von Mises equivalent stresses on spongy bone: The maximum values of von Mises equivalent stresses are recorded in the area immediately surrounding the orthodontic anchorage on the spongy bone. These high values indicate a concentration of stresses in this region, which may be associated with the risk of deformation or bone damage. However, the relative stress values are lower in the areas adjacent to the recorded maximum, suggesting that the orthodontic impact on the spongy bone is localized and does not significantly affect the entire bone. Equivalent linear strain in spongy bone: The maximum values of equivalent linear strain are also recorded in the area immediately surrounding the orthodontic anchorage on the spongy bone. These strains may indicate excessive loading or a weakness in the bone in this region. However, similar to von Mises stresses, the strains are localized and do not significantly affect the entire spongy bone. Spongy bone resistance to compression and tension: By comparing the spongy bone’s resistance to compression and tension with the deformations and stresses induced by the orthodontic anchorage, it can be observed that the bone is not significantly affected. The resistance values of the spongy bone are much higher than the deformations and stresses induced by the orthodontic anchorage, indicating the bone’s ability to withstand the applied orthodontic forces. Importance of contact pressure distribution: The distribution of contact pressure between the mini-implant and the spongy bone can influence the stability and durability of the orthodontic anchorage. The maximum contact pressure highlights areas of maximum load and can provide information on the potential for bone damage or weakening in the anchorage area. Evaluation of stress and strain in cross-section: The analysis of stresses and strains in the anchorage section provides detailed information on the structural behavior of the bone in the mini-implant insertion area. The maximum values of stress and strain are localized in the areas adjacent to the mini-implant and can be considered in the design and adjustment of orthodontic treatments to minimize adverse effects on the bone.

The maximum displacement value of 0.028948 mm is observed at the head of the mini-implant, in the area where the orthodontic force is applied. This information is useful for evaluating the structural behavior of the orthodontic anchorage system and identifying areas of greatest mobility during treatment. Von Mises equivalent stress in cross-section: This analysis is important for evaluating the mechanical stress to which the orthodontic anchorage system is subjected and for identifying critical areas concerning material resistance and deformation. To accurately model the interactions between mini-implants and bone tissue, several crucial factors must be considered. Research has indicated that the insertion angle of mini-implants into the bone significantly influences stress reduction and stability (5). It is recommended that mini-implants be inserted at a 30° angle to achieve optimal results. The fit of the mini-implant threads into the bone is vital for stability and the ability to withstand applied forces (26).

Cortical bone thickness is a crucial factor in determining the primary stability of mini-implants. Thicker cortical bone has consistently been associated with increased initial stability of mini-implants, while thinner cortical bone has been linked to a higher risk of implant failure (5). Studies have highlighted the importance of cortical bone thickness in influencing primary stability, with some research emphasizing it as the most critical factor affecting the success rate of mini-implants (6). Research has shown that increasing cortical bone thickness significantly increases the pull-out force, underscoring the importance of bone quality for primary stability. Studies have indicated that mini-implants achieve greater primary stability in denser cortical bone (5, 27-31). The choice of mini-implant design and size is crucial for establishing sufficient primary stability, particularly considering the insertion region and local bone quality (30, 32).

Cortical bone thickness has been identified as a critical factor in stabilizing mini-implants, with some studies suggesting that it may be the most important factor in ensuring stability (33, 34). The influence of cortical bone thickness on primary stability has been further supported by research showing that greater cortical bone thickness increases the initial stability of the implant (35, 36). The primary stability of mini-implants is significantly affected by the quality and thickness of the cortical bone at the insertion site. Thicker cortical bone is associated with increased stability and a higher success rate for mini-implants, emphasizing the importance of considering both bone quality and quantity when planning mini-implant placement. There is a consensus in various studies that cortical bone thickness is a key determinant of the initial stability of mini-implants in orthodontics.

Thin cortical bone presents a risk of implant failure, while adequate cortical bone thickness -typically greater than 1 mm- is essential for ensuring the stability and success of orthodontic mini-implants. The mechanical properties of biological tissues, including bones and the periodontal ligament, are well-known to be viscoelastic and highly dependent on the rate of deformation. Orthodontic treatment is a progressive process that uses small-magnitude orthodontic forces, as the deformation and displacement of dental tissue require time to modulate. Based on this condition and assuming that alveolar bone is a ductile material, von Mises stress has been widely accepted in orthodontic research.

The selection of this stress index has been advantageous because it is a scale designed to quantify stress without directional orientation. This stress index makes it easier for clinicians to predict where stress concentrators may appear; this is important because higher stress levels can lead to potential mini-implant failure. The results of our study indicated that the equivalent stress and strain state in the cortical bone was primarily affected by the exposed length of the mini-implant, the type of mini-implant, and the material from which the mini-implant is made. Previous research has mainly focused on the insertion length of mini-implants. In 2011, Chatzigianni *et al.* reported that the displacement of longer mini-implants under a force of 2.5 N was greater than that of shorter implants (37). Several studies have shown that longer mini-implants have higher success rates than shorter ones. Sometimes, the head of the mini-implant may become covered by the alveolar mucosa. In such cases, intervention with orthodontic devices such as elastic chains or coil springs could lead to inflammation of the alveolar tissue, which is strongly correlated with mini-implant failure. Partial insertion of longer mini-implants could minimize the possibility of the alveolar mucosa covering the head of the mini-implant, thereby reducing the chances of failure. Studies have shown that variations in cortical bone thickness can influence the stress distribution around mini-implants during orthodontic loading. For instance, Hirai *et al.* utilized 3D FEA to demonstrate that the insertion depth of miniscrews affects the stress distribution in both the screws and the surrounding bone, indicating that optimal insertion depth is crucial for minimizing stress concentrations and enhancing stability (38).

Clinical implications

These results can be discussed in the context of clinical orthodontic practice, highlighting the importance of understanding the mechanical behavior of mini-implants and identifying strategies to improve their performance during orthodontic treatment. This could include modifications to insertion techniques, improvements in mini-implant materials, or adjustments to the treatment protocol to minimize the risk of complications or failures.

Future research directions: Based on these results, future research directions could be suggested to further investigate the mechanical behavior of mini-implants and develop new strategies or technologies to improve their stability and performance in clinical practice. This could include additional computer simulation studies or experimental tests to validate and expand upon the current findings.

Reasons for the selection of 12 mm length in mini-implants. The decision to utilize a 12 mm length for the mini-implants (MIs) was made based on several key considerations: *(i)Enhanced stability*: longer mini-implants have the potential to offer superior primary stability, particularly in cases where bone density is lower (32); *(ii)Improved bone anchorage*: in certain clinical scenarios, the thickness of both the cortical and spongy bone layers may necessitate the use of longer mini-implants to achieve adequate depth of anchorage (12)*;* *(iii) Supporting literature*: while the minimum recommended length for mini-implants is typically around 6 mm, existing studies indicate that longer implants can lead to improved long-term performance, particularly in regions with varying bone density (1). The selection of the 12 mm length was informed by both theoretical evidence and practical applications observed in prior research. *(iv) Clinical experience*: our clinical experience further supports the use of 12 mm mini-implants, as they have consistently demonstrated favorable outcomes in terms of stability and osseointegration, particularly in more complex cases where additional length may provide a critical advantage.

CONCLUSIONS

The findings demonstrated that von Mises stress and equivalent strain were localized around the mini-implant anchorage, without significantly affecting the surrounding bone structure. Both cortical and spongy bone showed resistance levels far exceeding the applied forces, confirming their capacity to withstand orthodontic loading. However, areas of maximum stress and strain require careful consideration to avoid localized damage or potential failure. Additionally, the role of cortical bone thickness as a key determinant of primary stability was reinforced, with thicker bone consistently linked to better outcomes. this study underscores the value of understanding the mechanical behavior of mini-implants to ensure their effective use in orthodontic practice. By integrating FEA insights with clinical observations, orthodontic treatments can be tailored to maximize outcomes while minimizing complications, paving the way for more predictable and reliable MI applications.

CONFLICT OF INTEREST AND FUNDING

The authors declare no conflicts of interests.

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