ORIGINAL RESEARCH

A Three-dimensional Finite Element Study of Stress and Strain Distribution around Orthodontic Mini-implants of Varying Geometry

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Abstract

Aim: The present study aims to generate finite element (FE) models of mini-implants (MIs) inserted in the bone at varying angles, with the purpose of examining the stress and strain distribution patterns within the bone encompassing an MI in response to forces of different magnitudes and applied in different directions. This investigation involves the digitization of the aforementioned models, which will enable a comprehensive analysis of the biomechanical behavior of MIs in bone.

Materials and methods: A comprehensive three-dimensional representation of a 35-mm segment of the alveolar bone located in the posterior maxilla, inclusive of a self-drilling titanium MI, was developed. Further models were produced, incorporating diverse lengths, diameters, and implant angulations. The Analysis Software (ANSYS) workbench version 19.1 FE analysis (FEA) program was utilized to calculate the stresses and strains on the MIs with insertion angles of 30 and 60°, diameters of 1.4 and 2 mm, and lengths of 6, 8, 10, and 12 mm. An analysis was conducted to determine the stress distribution at the interface between the implant and bone, using a simulated constant orthodontic force of 2 N, applied in different directions to simulate clinical situations.

Results: The stress distribution in cortical and cancellous bone surrounding MIs with dimensions of 1.4 × 6 and 1.4 × 8 mm, inserted at angles of 30 and 60° indicated that the maximum stress value was 61.92 MPa, while the minimum stress value was 20.26 MPa. Furthermore, the stress distribution in cortical bone was significantly higher for the 30° insertion angulation compared to the 60° insertion angulation for MIs with a dimension of 1.4 mm. The minimum stress distribution values obtained for the 30° insertion angulation were 6.61, 6.19, and 2.49 MPa for the three directions of force application calculated. The stress distribution in cancellous bone was minimal, ranging from 0.11 to 0.58 MPa, under altered directions of forces applied during simulated orthodontic tooth movement.

Conclusion: The impact of varied insertion angles of orthodontic MIs (OMIs) on stress values and distribution in bone and implant is significant. A 1.4 mm MI generates greater von Mises stress, particularly when inserted at a 30° angle, with strenuous stress at the neck and head of the MI, regardless of its length (6 or 8 mm). Moderate stress levels were observed for cortical bone stresses under horizontal loading for 1.4 mm MIs. Increasing the insertion angle from 30 to 60° resulted in decreased stress concentration around the implant threads. The evaluation of von Mises stress within cancellous bone yielded negligible results due to low-stress transmission.

Clinical significance: With the potential to enhance orthodontic treatment through skeletal anchorage, OMIs have gained global acceptance, and since the maintenance of MI permanence is contingent upon its stability, which is significantly impacted by the variables, such as length, diameter, and insertion angle, the utilization of FEA proves to be a more precise and dependable method for the simulation of such meticulous biological and biomechanical conditions.

Keywords: Anchorage, Cancellous bone, Cortical bone, Finite element analysis, Finite element method, Orthodontic mini-implants, Strain, Stress, Temporary skeletal anchorage devices, von Mises stress.

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Introduction

Anchorage has been a source of concern since the inception of orthodontics. Historically, orthodontists have employed teeth intraoral and extraoral appliances to regulate anchorage. However, the field of orthodontics has not discovered a satisfactory resolution to this issue. For a considerable duration, orthodontists have endeavored to attain effective management of anchorage.[1] The emergence of temporary skeletal anchorage devices (TSADs) has significantly broadened the scope of the orthodontic discipline. These devices, which come in diverse forms, sizes, surface textures, and materials, have become a crucial tool in the orthodontist's arsenal. Through the use of TSADs, complete anchorage can be attained without relying on patient compliance traits. Furthermore, the application of TSADs extends the limits of tooth movement beyond what was previously achievable with conventional

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orthodontic treatment.[2,3] Researchers have consistently exerted diligent efforts toward enhancing the efficacy of the mini-implant (MI), which is significantly impacted by the stress exerted on the bone surrounding it. Current research is primarily focused on regulating tooth movement *via* the MI in a singular direction and acknowledges that the MI's physical attributes, such as diameter and length, can influence stress levels.[4]

Despite the numerous advantages associated with miniscrew implants, their clinical behavior remains unclear. Nevertheless, given that these implants are intended for immediate loading, their primary stability is of paramount importance.[5] The failure of MIs has been reported as a concern primarily associated with infection, followed by biomechanical factors such as length, diameter, and the angle of insertion into the bone. By comprehending the stresses generated along the surfaces of an MI and in the contiguous bone, the optimization of the design and placement of the MI is feasible, thereby reducing the incidence of failures within the oral cavity.[6]

The present research study was therefore conducted to examine the distribution patterns of stress that arise in the vicinity of an MI upon the application of a simulated, unvarying orthodontic force. Additionally, the study focused on ascertaining optimal combinations of geometric parameters and the insertion angle of the MI for placement during diverse modeled tooth movements.

Materials and Methods

Inclusion Criteria

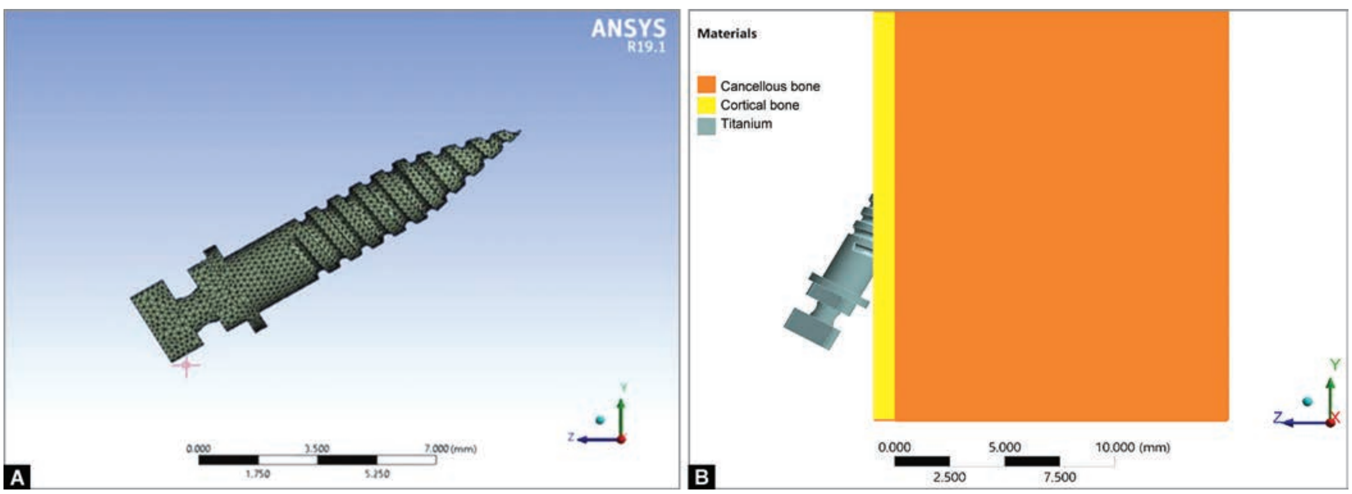
- Orthodontic MIs (OMIs) of different geometrics, that is, diameters and lengths *viz* diameter of 1.4 mm with lengths 6 and 8 mm and of 2 mm diameter with a length of 10 and 12 mm according to the dimensions and measurements of VectorTAS™ obtained from Ormco Corporation (United States of America).
- Orthodontic MIs (OMIs) of titanium alloy.

Methodology

The present study was designed based on the geometric configuration of the MIs devised from Solidworks 2018, based on the dimensions and measurements of VectorTAS™ acquired from Ormco Corporation, located in Orange, California, United States of America. The MI was designed as a triangular head-type tapered titanium alloy (Ti6Al4V) screw (Fig. 1A), with an external diameter of 1.4 mm and lengths of 6 and 8 mm, as well as a diameter of 2 mm and lengths of 10 and 12 mm. The thread depth was set at 0.12 mm, with a thread face angle of 50° and a thread interval of 0.54 mm. Four finite element (FE) models of the MIs with the aforementioned combinations were created.

A solid three-dimensional model of a 35-mm section of the alveolar bone of the posterior maxilla, featuring a single self-drilling titanium MI (Fig. 1B), was created. Successive simulations were generated with varying lengths, diameters, and implant angulation. The Analysis Software (ANSYS) workbench (version 19.1) FE analysis (FEA) program was utilized to produce the solid template, generate the mesh of discrete hexahedral elements and conduct postprocessing to determine the levels of stress and strain (Figs 2A and B). The number of elements used was 2,66,769 with an element size of 0.3 mm, and the computer workstation used was an Intel Core i7 processor with 16 GB random access memory and 2 TB hard disk space (Fig. 3). Gap elements were established between the MI and all surrounding bone nodes, featuring a friction coefficient of zero, thereby preventing any movement in any direction. The implant thread and hole diameters were standardized. The bone components were intentionally configured to measure 21 × 21 × 20 mm in size, with the purpose of providing sufficient space for the evaluation of the stresses and strains encompassing the MI.

The Analysis Software (ANSYS) was employed to generate meshes for both the MI and bone models and subsequently conduct FEA on the MIs at insertion angles of 30 and 60°, a diameter of 1.4 mm with lengths of 6 and 8 mm, and a diameter of 2 mm with lengths of 10 and 12 mm. This generated eight



Figs 1A and B: (A) Mini-implant (MI) with a triangular head-type tapered design; (B) Three-dimensional solid model of the MI and bone—a three-dimensional solid model of a 35-mm section of the alveolar bone of the posterior maxilla with a single self-drilling titanium MI with a triangular head-type and tapered screw. A cortical layer of the bone is depicted in yellow, and the cancellous bone in orange

FE models, sufficient to simulate and calculate the stress levels generated within the bone, and they were grouped as listed in Table 1A. A constant orthodontic force of 2 N was simulated and applied to each of the FE models. The stress distribution on the implant-bone interface was subsequently analyzed, with the assumption that the force was applied to the head of the MI. The direction of applied orthodontic force was simulated in clinical situations of anterior retraction (by applying a force at 90° to the vertical plane of the MI), anterior intrusion and retraction (30° to the vertical plane of the MI), and molar intrusion (90° to the horizontal plane of the MI) (Fig. 4). Ethical authorization as per the University protocol and IEC approval number (CPGIDSH/969/19) was obtained preceding the experimental study.

The experimental data recorded was subjected to statistical study to calculate and compare the stress distribution among FE models. Data were summarized as mean ± standard error. Groups were compared by one-factor analysis of variance, and the significance of the mean difference between the groups (intergroup) was done by Tukey's honestly significant difference

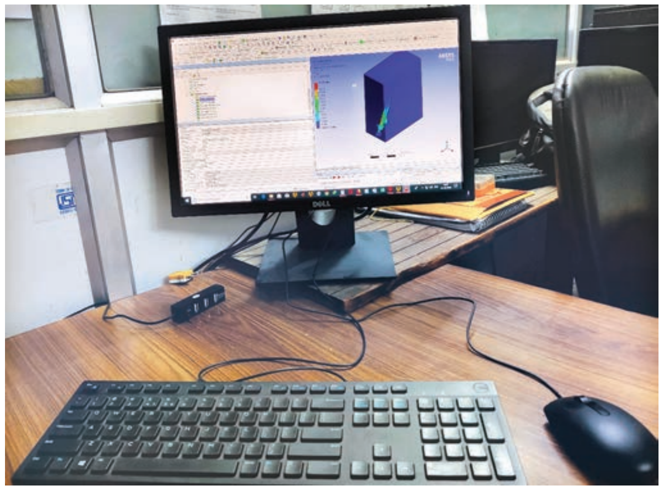
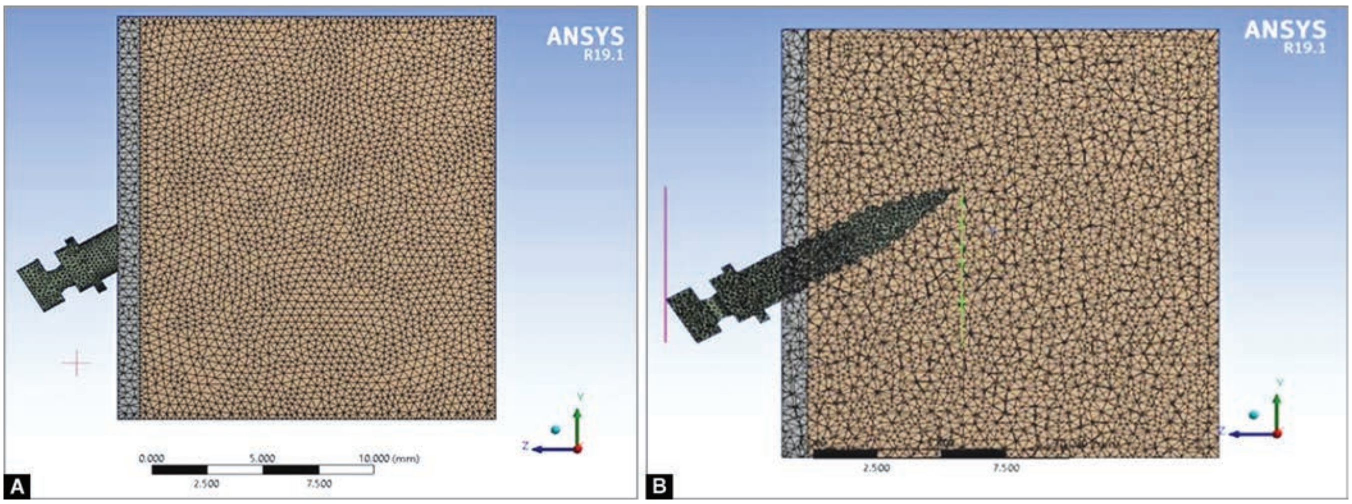
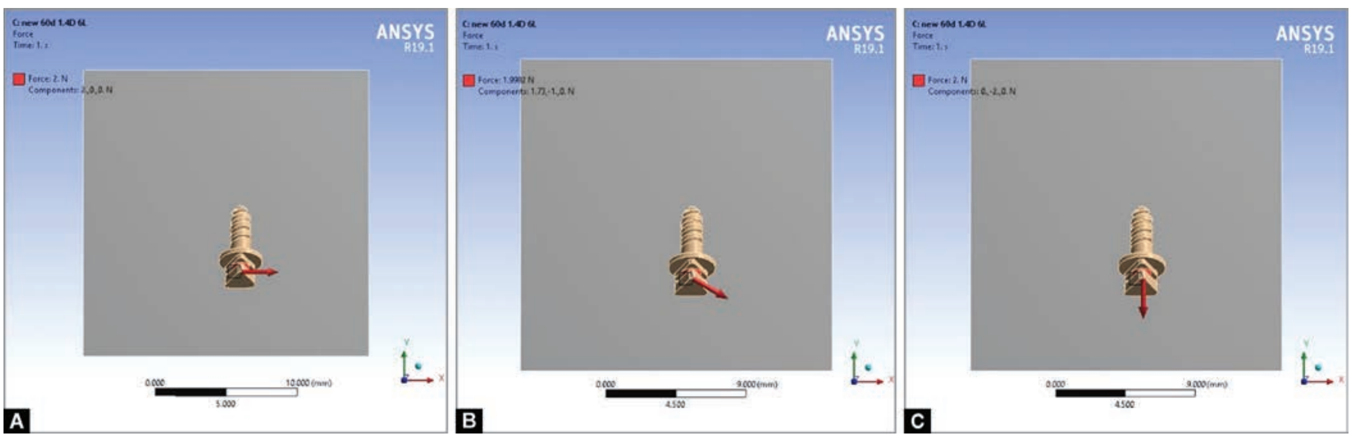


Fig. 3: Computer workstation used for meshing of FE models and carrying out postprocessing analysis



Figs 2A and B: Generate a hexahedral mesh of individual elements: (A) for posterior maxillary bone; (B) for single self-drilling titanium MI



Figs 4A to C: The direction of orthodontic force (2 N) corresponding to the head of MI. (A) Applied at 90° to the vertical plane of the MI (simulating anterior retraction); (B) Applied at 30° to the vertical plane of the MI (simulating anterior intrusion and retraction); (C) Applied at 90° to the horizontal plane of the MI (simulating molar intrusion) *post hoc* test after ascertaining normality by Shapiro–Wilk's test and homogeneity of variance between groups by Levene's test. A two-tailed ($\alpha = 2$) $p < 0.05$ was considered statistically significant. Analysis was performed on Statistical Package for the Social Sciences software (Windows version 17.0) (Flowchart 1).

Results and Observations

The present three-dimensional FE study evaluated and compared the stress and strain distribution around OMIs of varying geometry, based on the von Mises stress hypothesis, utilizing MPa units. A quantitative evaluation of the stress distribution in both cortical and cancellous bones, as well as the MI, was conducted using a color scale. The stress scale ranges from blue to red, with blue representing no stress (0 MPa) and red indicating the highest stress area. The outcome measure of the study was maximum von Mises stress (or stress). Stress was assessed on three variables *viz* MIs, cortical bone and cancellous bone and for each variable, it was assessed on three different directions/angles (° or degree) of forces *viz* simulating anterior retraction (i.e., line of force at 90° to the vertical plane of MIs), simulating anterior intrusion and retraction (i.e., line of force at 30° to the vertical plane of MIs), and simulating molar intrusion (i.e., line of force at 90° to the horizontal plane of MIs). The stress was measured in MPa units (Figs 5 to 7).

Table 1A: List of FE groups and models

Group	*Description of the groups (Models)*
Group 1a	Mini implant model 1.4 x 6 mm at 30 insertion
Group 1b	Mini implant model 1.4 x 6 mm at 60 insertion
Group 2a	Mini implant model 1.4 x 8 mm at 30 insertion
Group 2b	Mini implant model 1.4 x 8 mm at 60 insertion
Group 3a	Mini implant model 2 x 10 mm at 30 insertion
Group 3b	Mini implant model 2 x 10 mm at 60 insertion
Group 4a	Mini implant model 2 x 12 mm at 30 insertion
Group 4b	Mini implant model 2 x 12 mm at 60 insertion

Maximum von Mises Stress in MIs at Different Directions of Forces

The maximum stress in MIs at different directions of forces is summarized in Table 1B and depicted in Figure 8A). The maximum stress at force 90° to the vertical plane of MIs was highest in group 1a and least in group 4b. Similarly, at 30° to the vertical plane of MIs, it was highest in group 2a and least in group 4b. Further, at 90° to the horizontal plane of MIs, it was also highest in group 2a and least in group 4b. Overall, among three different directions of forces, it was highest in group 1a (90° to the vertical plane of MIs) and least in group 4b (90° to the horizontal plane of MIs).

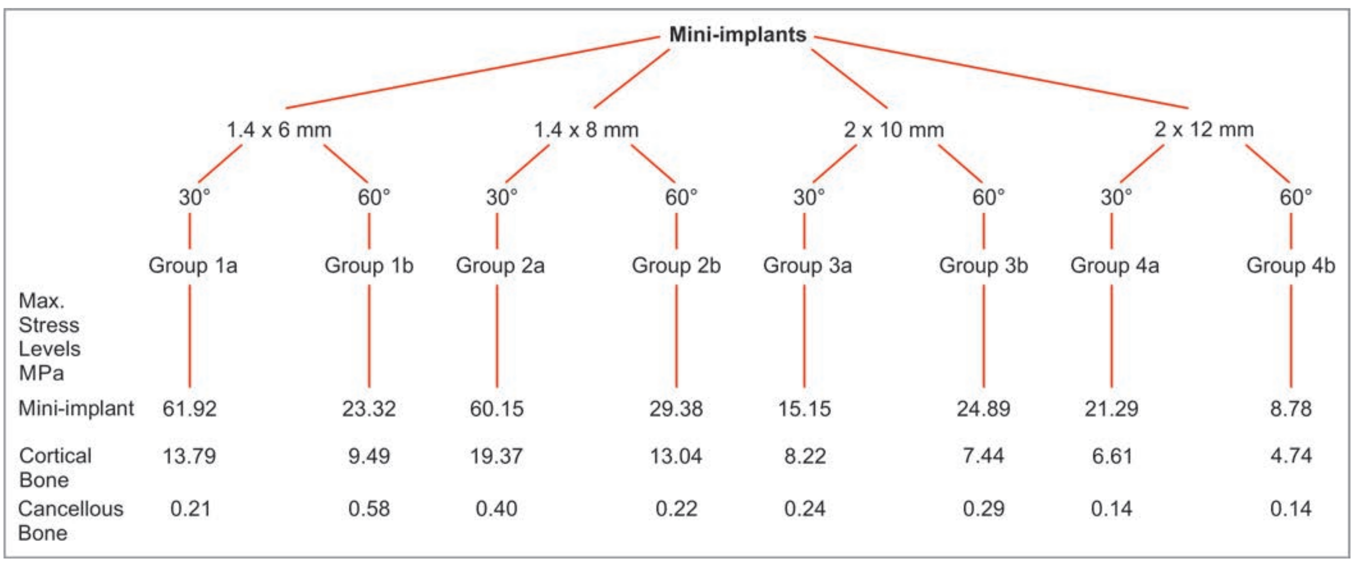
Maximum von Mises stress in the Cortical Bone at the Different Directions of Forces

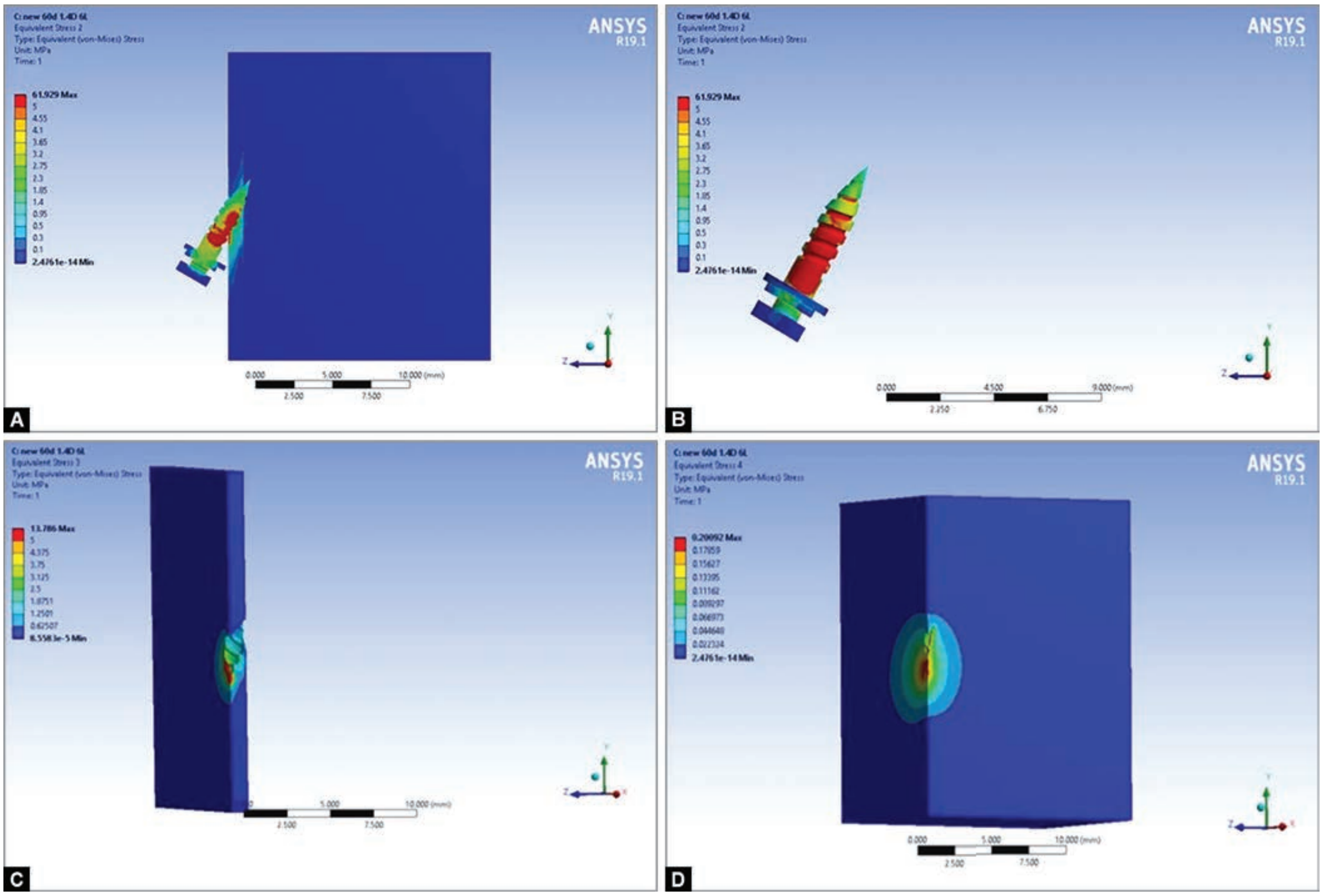
The maximum stress in the cortical bone at different directions of forces is summarized in Table 1C and depicted in Figure 8B. The maximum stress at force 90° to the vertical plane of cortical bone was highest in group 2a and least in group 4b. Similarly, at 30° to the vertical plane of cortical bone, it was highest in group 2a and least in group 4b. In contrast, at 90° to the horizontal plane of cortical bone, it was also highest in group 2b and least in group 4a. Overall, among three different directions of forces, it was highest in group 2a (90° to the vertical plane of cortical bone) and least in group 4a (90° to the horizontal plane of cortical bone).

Maximum von Mises stress in the Cancellous Bone at Different Directions of Forces

The maximum stress in the cancellous bone at different directions of forces is summarized in Table 1D and also depicted in Figure 8C. The maximum stress at force 90° to the vertical plane of cancellous bone was highest in group 1b and least in group 4a. In contrast, at 30° to the vertical plane of cancellous bone, it was highest in group 1b and least in group 4b. Conversely, at 90° to the horizontal plane of cancellous bone, it was also highest in group 1b and least in group 4a. Overall, among three different directions of

Flowchart 1: Flow diagram for ease of understanding





Figs 5A to D: von Mises stress distribution for MI group 1a (anterior retraction). (A and B) Stress distribution is seen at the bone-implant interface and in the MI alone. Maximum stress seen in the MI was at 61.92 MPa; (C and D) Stress distribution was seen at the cortical bone and in the cancellous alone. Maximum stress seen in the cortical bone was 13.786 (≈13.79) and 0.20 MPa in cancellous bone

forces, it was highest in group 1b (30° to the vertical plane of cancellous bone) and least in group 4a (90° to the horizontal plane of cancellous bone).

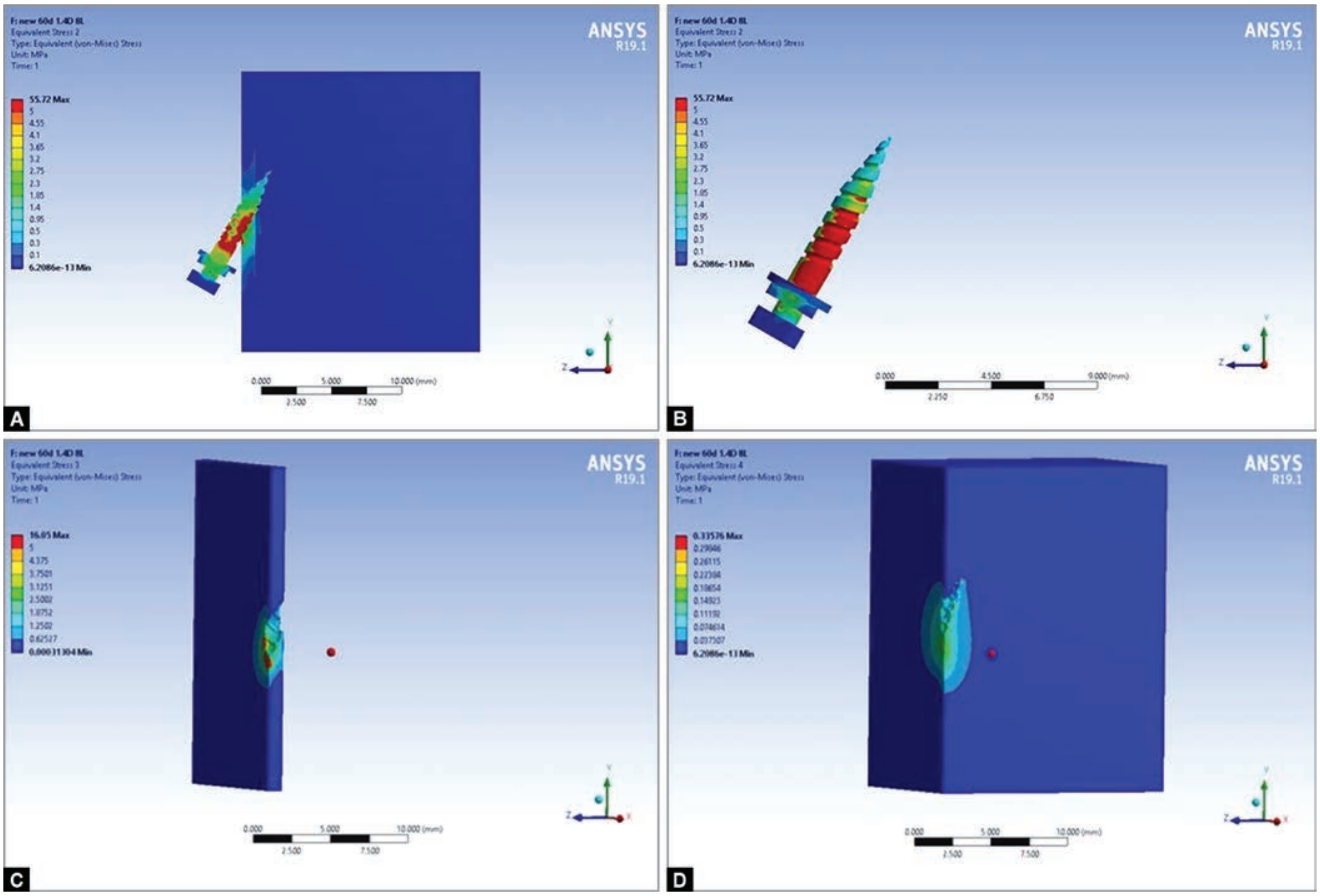
The findings indicate that the stress distribution was primarily localized in the collar of the MI, with the cortical bone experiencing greater stress levels in comparison to the cancellous bone. Notably, the stress estimates were observed to be higher in instances where the MI was placed at a 30° angle, as opposed to a 60° insertion angle.

Discussion

The present research aimed to identify the most dependable von Mises stress factors in FE models that are specific, with the purpose of predicting the efficacy or inefficacy of OMIs. The von Mises stress, which signifies the highest distortion energy, was the focus of the investigation. The present study employs the FE method (FEM) to investigate alterations in stress distribution at the supporting bone and miniscrew resulting from variations in the angle and geometry of the miniscrew, as well as the direction of force. The FEM has been an established tool for identifying optimal design parameters and facilitating the development of improved MI designs. Numerous authors have utilized mechanical analysis through FEM to gain insight into the biomechanical behavior surrounding dental implants. According to Chatzigianni et al.,[7] a comparative examination of numerical and experimental data pertaining to OMIs revealed a tendency toward FEA as a potentially advantageous substitute for experimental methodologies.

In 1983, Creekmore and Eklund[8] were the pioneers in introducing screws for orthodontic anchorage in clinical practice. This marked the beginning of a new era in orthodontic treatment, where various types of MIs have been utilized for anchorage reinforcement. Kanomi[9] recommended the use of titanium MIs as intraoral anchorage devices. This development has significantly improved the efficacy and precision of orthodontic treatment.

The primary stability of MIs is a critical determinant, given that the majority of failures in OMIs transpire during the initial phases of treatment. Due to the limitations in the diameter and length of OMIs, it is imperative to design an optimal shape that can provide sufficient primary stability. The biomechanical influences on bone structure are significant in determining the longevity of bone around implants. The phenomenon of bone tissue remodeling in response to mechanical stress has been documented in scientific literature. Insufficient levels of stress in the vicinity of an implant may result in suboptimal bone integration or even bone atrophy. Conversely, excessive stress accumulation in the adjacent bone can lead to pressure necrosis and, ultimately, implant loss.[10] Hence,

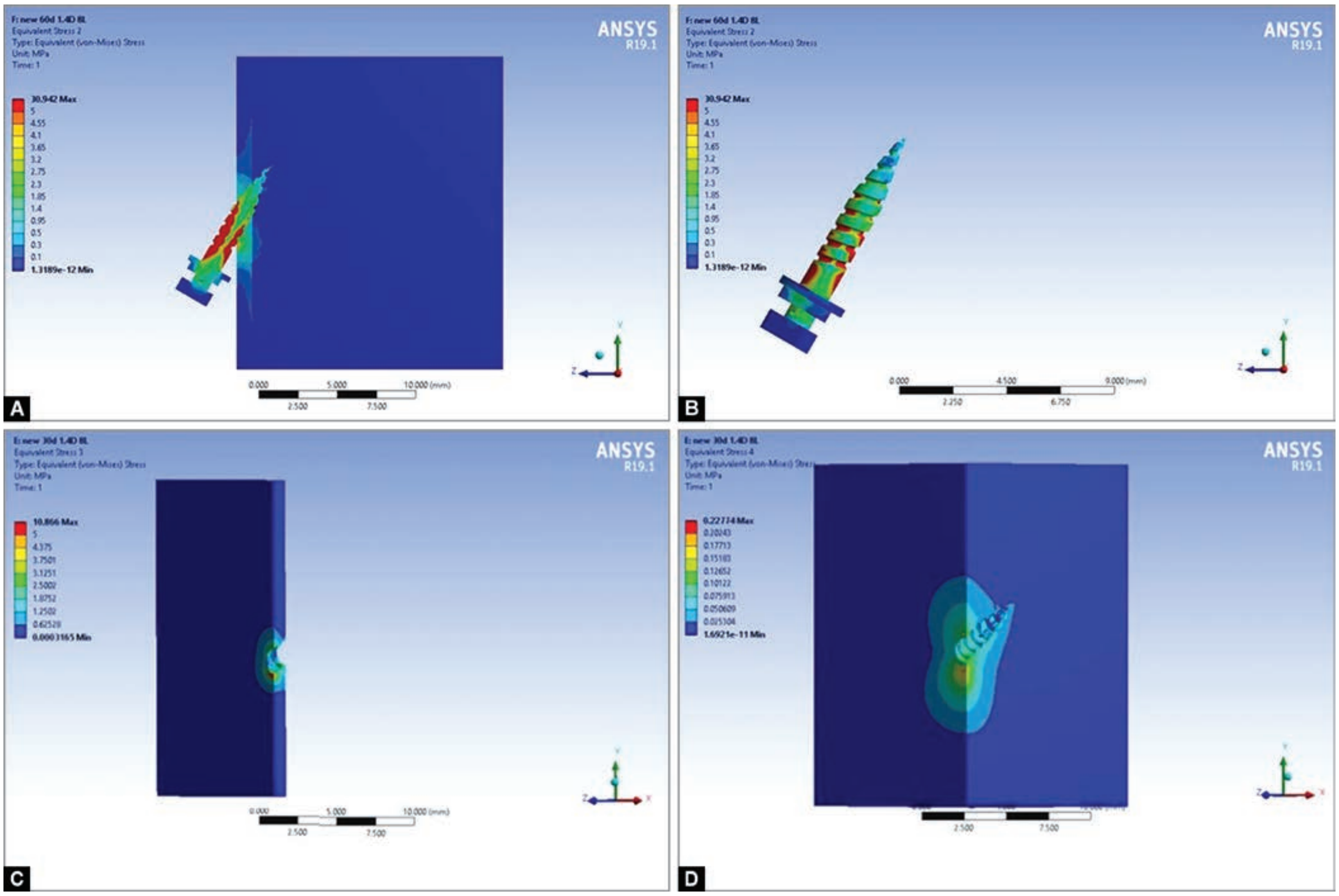


Figs 6A to D: von Mises stress distribution for MI group 2a (anterior intrusion and retraction). (A and B) Stress distribution is seen at the bone-implant interface and in the MI alone. Maximum stress seen in the MI was at 55.72 MPa; (C and D) Stress distribution was seen at the cortical bone and in the cancellous alone. Maximum stress seen in the cortical bone was 16.05 and 0.33 MPa in cancellous bone

it is imperative to conduct a comparative analysis of the stress generated in both metal and bone tissues among MIs of diverse geometric configurations and insertion angles when exposed to force application and directions, in accordance with clinical requirements such as retraction force, intrusion and retraction, and extrusive force.[6]

The maintenance of physiological homeostasis necessitates that both the implant and bone are exposed to a specific range of mechanical stress, as has been widely recognized. This stress induces strain in the bone tissue, which is characterized by a relative change in length, either elongation or contraction. The extent of strain is directly proportional to the stress and the mechanical properties of the bone. Frost[11] has proposed that the measure of strain can be classified into various ranges, which allows us to anticipate the influences on the bone. The lower threshold of bone equilibrium, defined as the range of load that maintains a balance between bone tissue formation and resorption through ongoing remodeling processes, is estimated to be between 50 and 100 µstrain (1–2 MPa). Bone resorption occurs as a consequence of underutilization when the mechanical stimulus falls below a certain threshold. The upper boundary of this range is estimated to be within the range of 1000–1500 µstrain (20 MPa), beyond which bone formation is the primary reaction. The imposition of further stress on bone tissue results in the formation of microfissures and microfractures. These fractures occur at a threshold of approximately 3000 µstrain (60 MPa), which exceeds the capacity of the ongoing repair mechanisms, leading to bone resorption. Hence, exceeding the physiological limit of MI displacement may cause bone trabecula microfracture, leading to tissue absorption and implant failure. It is, therefore, crucial to consider these physiological limits when designing and placing MIs to ensure their long-term success and prevent adverse effects on the surrounding bone tissue.

The present study investigated the stress values observed on MIs with dimensions of 1.4 × 6 and 1.4 × 8 mm, inserted at angles of 30 and 60°. The results indicated that the minimum stress value was 20.26 MPa, while the maximum stress value was 61.92 MPa. These values were found to be within the standard fatigue limit of titanium, which is 193 MPa.[12] The findings of this study are coherent with those of the previous FEM studies conducted by Zhang et al.,[13] which also reported a reduction in stress value of 22 MPa with a 30° insertion angle of MIs. The authors of the previous study also concluded that a tilted angle of 30° would result in a doubling of the length of the MI, allowing it to permeate the cortical bone. Consequently, decreasing the angle would increase the contact area between the microimplant and



Figs 7A to D: von Mises stress distribution for MI group 2a (molar intrusion). (A and B) Stress distribution is seen at the bone-implant interface and in the MI alone. Maximum stress seen in the MI was at 30.94 MPa; (C and D) von Mises stress distribution for MI group 2b (molar intrusion)—stress distribution seen at the cortical bone and in the cancellous alone. Maximum stress seen in the cortical bone was 10.866 (≈10.87 MPa) and 0.22 MPa in cancellous bone

Table 1B: Maximum stress (MPa) in MIs at different directions of forces

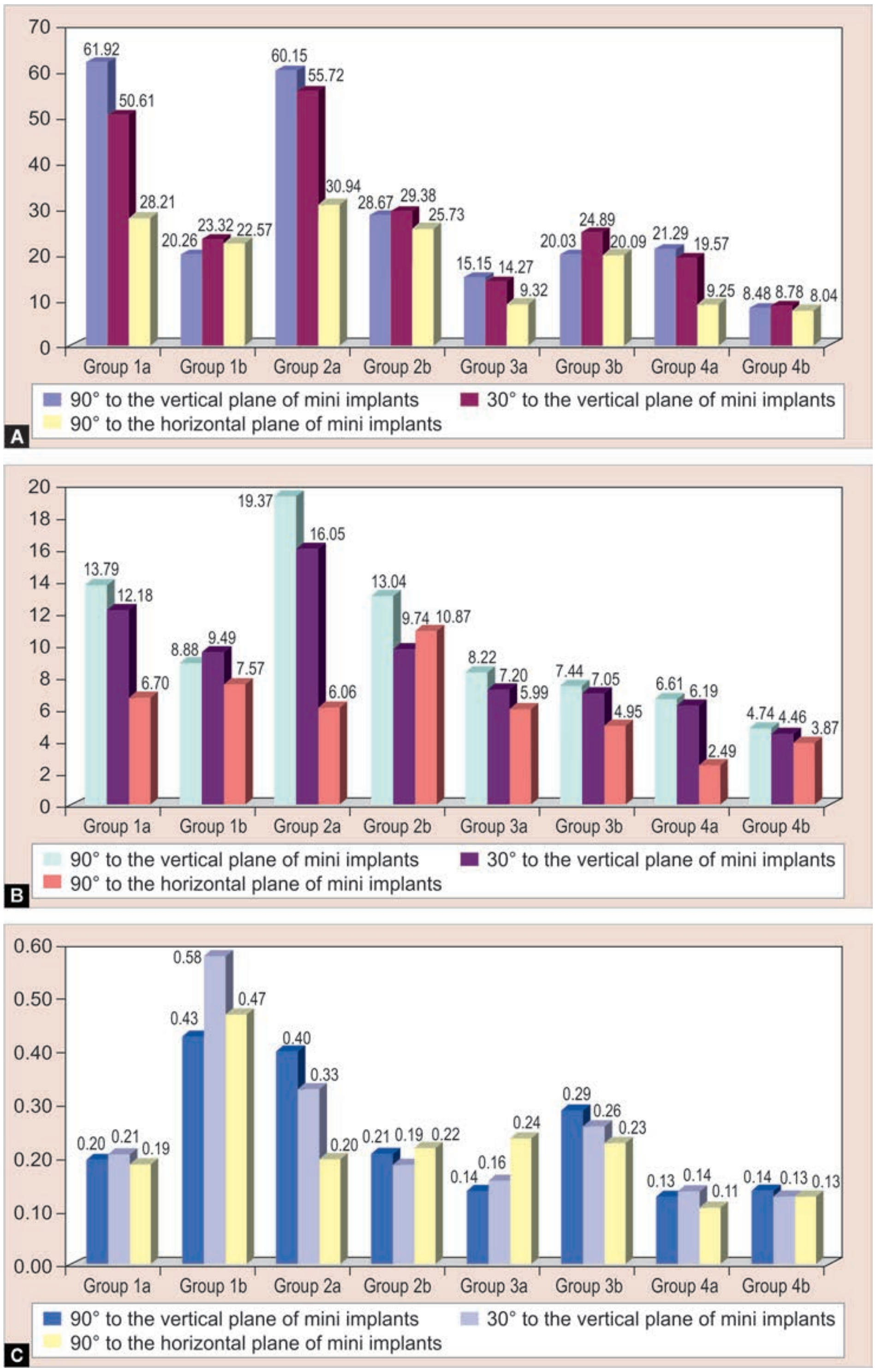
	Maximum stress in mini-implants (MPa)		
FE model/ Group	*90 degrees to the vertical plane of mini-implants*	*30 degrees to the vertical plane of mini-implants*	*90 degrees to the horizontal plane of mini-implants*
Group 1a	61.92	50.61	28.21
Group 1b	20.26	23.32	22.57
Group 2a	60.15	55.72	30.94
Group 2b	28.67	29.38	25.73
Group 3a	15.15	14.27	9.32
Group 3b	20.03	24.89	20.09
Group 4a	21.29	19.57	9.25
Group 4b	8.48	8.78	8.04

Table 1C: Maximum stress (MPa) in the cortical bone at different directions of forces

	Maximum stress in cortical bone (MPa)		
FE model/ Group	*90 degrees to the vertical plane of mini-implants*	*30 degrees to the vertical plane of mini-implants*	*90 degrees to the horizontal plane of mini-implants*
Group 1a	13.79	12.18	6.70
Group 1b	8.88	9.49	7.57
Group 2a	19.37	16.05	6.06
Group 2b	13.04	9.74	10.87
Group 3a	8.22	7.20	5.99
Group 3b	7.44	7.05	4.95
Group 4a	6.61	6.19	2.49
Group 4b	4.74	4.46	3.87

Table 1D: Maximum stress (MPa) in the cancellous bone at different direction of forces

	Maximum stress in cancellous bone (MPa)		
FE model/Group	*90 degrees to the vertical plane of mini-implants*	*30 degrees to the vertical plane of mini-implants*	*90 degrees to the horizontal plane of mini-implants*
Group 1a	0.20	0.21	0.19
Group 1b	0.43	0.58	0.47
Group 2a	0.40	0.33	0.20
Group 2b	0.21	0.19	0.22
Group 3a	0.14	0.16	0.24
Group 3b	0.29	0.26	0.23
Group 4a	0.13	0.14	0.11
Group 4b	0.14	0.13	0.13



Figs 8A to C: (A) Maximum stress in MIs (MPa) at different directions of forces; (B) Maximum stress in cortical bone (MPa) at different directions of forces; (C) Maximum stress in cancellous bone (MPa) at different direction of forces

cortical bone, thereby enhancing the firmness of microimplants. The stress values observed on MI dimensions of 2 × 10 and 2 × 12 mm, with a 30° insertion angulation, and 2 × 10 mm, with a 60° insertion angulation, were found to fall within the tolerable fatigue limits of titanium, ranging from 9.25 to 24.89 MPa. However, molar intrusion simulation for MI model 2 × 12 mm at a 60° angle showed a lower range between 8.04 and 8.78 MPa, which was also within the appropriate fatigue limits of titanium. Miyawaki et al.[14] reported a better success rate for MIs with diameters of 1.2 and 1.3 mm compared to those with a diameter of 1.6 mm. Furthermore, the use of MIs with a diameter of 1 mm resulted in a 0% success rate, as they were found to have a higher chance of fracture. Therefore, Miyawaki et al. advocated that MIs with a diameter of 1 mm were not suitable for clinical use.

This study also investigated the stress distribution patterns in cortical bone upon the insertion of an MI with a dimension of 1.4 mm (either 6 or 8 mm length) at two different angulations, namely 30 and 60°. The results revealed that the stress distribution in the cortical bone was noticeably elevated for the 30° insertion angulation compared to the 60° insertion angulation. The lowest stress distribution values obtained for the 30° insertion angulation were 6.61, 6.19, and 2.49 MPa for the three directions of force application reviewed. These values were consistent with the findings of previous studies conducted by Motoyoshi et al.[15] On the contrary, the highest stress values were observed for the 60° insertion angulation, with values of 13.04, 9.74, and 10.87 MPa, in all three directions of force application. However, it is noteworthy that the difference between the minimal and maximal stress values was negligible and well within the mechanostat values proposed by Frost.[11] Also, the stress values were monitored in the cortical bone for both 30 and 60° insertion angles of a 2 mm diameter MI. The results indicated that the stress values ranged between 2.49 and 8.22 MPa, which was within the mechanostat values proposed by Frost. Furthermore, the maximum von Mises stresses intensified as the insertion angle was decreased during miniscrew placement, and horizontal force application was applied to inserted miniscrews in both diameter groups. However, if the insertion angle is small, the contact area between the miniscrew and cortical bone increases, leading to an increase in stress between the screw and cortical bone, irrespective of miniscrew length and width. The stress distributions in cortical and cancellous bone showed that the stress was primarily endured by cortical bone, with little transmission to cancellous bone.

The investigation of stress distribution in cancellous bone under different directions of forces revealed stress values ranging from 0.11 to 0.58 MPa, indicating minimal stress induced during simulated orthodontic tooth movement. Similar findings were reported by Zhang et al.,[13] where stress values in cancellous bone ranged from 0.63 to 0.56 MPa. Notably, the maximum stress value in cancellous bone was significantly lower than that in cortical bone due to the higher Young's modulus of cortical bone contrasted to cancellous bone. This observation is consistent with the results of a study by Huang et al.,[16] which demonstrated that bone density is related to the modulus of elasticity and can significantly impact biomechanical responses. The stress patterns observed in both cortical and cancellous bone were within standard limits for all measurements of MIs experimented in the present study, as well as in the metal. Furthermore, the results of the study by Jiang et al.[17] indicated that increases in diameter and length reduced the maximum equivalent stresses in cortical and cancellous bones and MIs, which is in agreement with our study findings.

This study has confirmed the noteworthy impact of diameter and length on primary stability. Additionally, it has been noted that the diameter exerts a greater influence than the length in mitigating stress and displacement. These findings are consistent with other *in vivo* investigations that have reported positive effects of both length and diameter on survival rates.[18]

Limitations of the Study

The study's limitations include the simplified geometry of the bone model, which may result in varying strain patterns despite the bone block's strength being similar to that of the maxillary bone. The selection of cortical bone thickness for the maxilla model was based on prior research, with a thickness of 1.5 mm being employed to streamline model fabrication. Anatomical considerations are crucial during MI insertion due to variations in root curvatures and cortical bone appearances. The peri-MI region displays heterogeneity and anisotropy in physiological conditions. However, this study utilized a uniform and isotropic model that solely accounted for physical characteristics. Our findings should be applied in clinical practice following further investigations. Additionally, auxiliary research is required to ascertain the impact of alterations in cortical bone thickness and/or cancellous bone density.

Conclusion

- The MIs utilized in the current investigation effectively withstood the orthodontic loading, which emulated the retraction of the anterior teeth, intrusion, and molar intrusion. Loads of about 200 gm generated strains in the optimal range of bone preservation.
- The FE models of all kinds indicated that the region with the greatest stress and strain was near the implant's neck and the cervical margin of the surrounding bone.
- Varied insertion angles of orthodontic MI significantly impact stress values and distribution in bone and implant.
- The analysis revealed that the 1.4 mm MI generated greater von Mises stress, particularly when inserted at a 30° angle. The MI exhibited stress concentration at its neck and head, irrespective of its length (6 or 8 mm), as per the findings.
- The analysis of cortical bone stresses under horizontal loading revealed moderate stress levels for 1.4 mm MIs. Increasing the insertion angle from 30 to 60° resulted in decreased stress concentration around the implant threads.
- The insignificance of the comparison of von Mises stress in cancellous bone was due to low-stress transmission.
- The MIs measuring 2 × 12 mm are recommended for the anterior segment retraction, anterior intrusion and retraction, and molar intrusion, provided the insertion site anatomy permits. The optimal insertion angle is 60° for improved stability and reduced stress.
- Horizontal force caused significant increases in stress on cortical bone and MIs compared to vertical loading.

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