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Effect of cortical bone thickness, insertion angle and force direction variations on miniscrew and surrounding bone: A Finite Element Study

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Abstract:
Introduction: *To evaluate the effect of different cortical bone thicknesses (0.5, 1, 1.5, 2 mm), miniscrew insertion angles (30^o, 60^o and 90^o) and force directions (horizontal and oblique) on stress distribution on miniscrew and surrounding bone using finite element analysis.* ***Materials and Methods:*** *Twenty-four three-dimensional assemblies of miniscrew models placed in alveolar bone blocks were constructed using Inventor professional version 8 software. The models simulated miniscrews inserted in bone of different cortical bone thicknesses with different insertion angles. A load of 2 N was applied to the miniscrew head in two directions. The resultant deformations and stresses of the applied load were collected from the output of ANSYS program.* ***Results:****The results demonstrated that increasing the cortical bone thickness (C.B.T) reduced the exerted microstrain on bone. 60^o inserted miniscrews generated much more strains on cortical bone than 90^o and 30^o inserted miniscrews. In 60^o inserted miniscrew, horizontal force generates about 45% more strains on cortical bone than oblique one. Force direction has minor effect on bone strains, but horizontal force slightly generates more strains on cortical bone than oblique one.* ***Conclusion:*** *It can be concluded that increasing C.B.T reduces the exerted microstrain on bone. Moreover, inserting miniscrew at 60^o to the bone surface generates much more strains on cortical bone especially when a force parallel to the bone surface is applied that may affect miniscrew success rate.*

Keywords: *Miniscrew, Finite Element Method, Cortical bone, Insertion angle, Force direction.*

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I. Introduction

Anchorage control plays an important role in orthodontic treatment and significantly affect treatment outcome as it can minify undesired movements[1].

Although numerous and different devices have been developed and used for anchorage, none of them has been capable to assure absolute anchorage in all cases. Currently, Miniscrews have been extensively applied in orthodontic treatment as a stationary absolute anchorage device on account of their various advantages over the traditional methods of skeletal anchorage. Their success rate in general is considered to range from 80% to 90% [1].

Even so, the behavior of miniscrews clinically is not clear yet. Loosening and failure of miniscrews throughout orthodontic treatment have been reported by several authors[2, 3]. There are many factors that can affect miniscrew stability which have been reported by authors like miniscrew type, length and diameter[4], thread design and shape[5], surface characteristics[6] and the magnitude and direction of orthodontic force applied[7].Although different factors may affect miniscrew placement sites such as nearby anatomical landmarks, access and biomechanics used in treatment, adequate stability is shown to be provided when C.B.T is more than 1 mm[8], while failure and looseness of orthodontic miniscrew are associated with thinner cortical bone[7].

It's impossible to measure stresses accurately on miniscrew and surrounding bone in vivo. However, most of the suggested ways to increase miniscrew stability and to decrease stress concentration on miniscrew and strain concentration on bone were provided without the support of mechanical reasoning. These outcomes could depend on the model or method and should be applied with caution. No reliable guidelines can be provided for its clinical usage without a thorough understanding of the biomechanical rationale of the orthodontic miniscrew.

Finite Element Method (FEM) is significantly utilized to predict the mechanical behavior of different engineering structures[1] and can be applied to solids of irregular geometries that contain different material properties[9]. FEM has high sensitivity and enables the observation of deformation/strain distribution. So, it is an effective tool in evaluating the biomechanical performance of miniscrews at different situations[2].

The actual impact of various insertion angles in relation to various force directions on stress and strain distribution on bone and miniscrew is still unknown. So, this study was conducted to investigate the roles of C.B.T, insertion angle and force direction on stress distribution on miniscrew and strain distribution in the surrounding cortical bone using finite element analysis.

The null hypothesis was that, the relationship between various insertion angles and force directions will affect stress and strain distribution. Also, it was supposed that when C.B.T is increased, the stress and strain concentration will be decreased.

II. MATERIALS AND METHODS

Geometric modeling

Three dimensional solid modeling software (Autodesk Inventor Professional version 8) was used for modeling miniscrew with diameters of 1.8 mm and length of 8 mm. The selected miniscrew type was 3M Unitek™ Temporary Anchorage Device (TAD) System (Fig.1) as it provides the following advantages:

1. Multifaceted uses ranging from conventional anchorage to skeletal malocclusions.
2. The threaded body is self-tapping and self-drilling, therefore there is no need to make a predrilled hole.
3. The apical 4 mm is tapered from 0.3 mm to 1.8 mm, thus the bone is compressed in and around the miniscrew threads rather than cutting and removing bone.

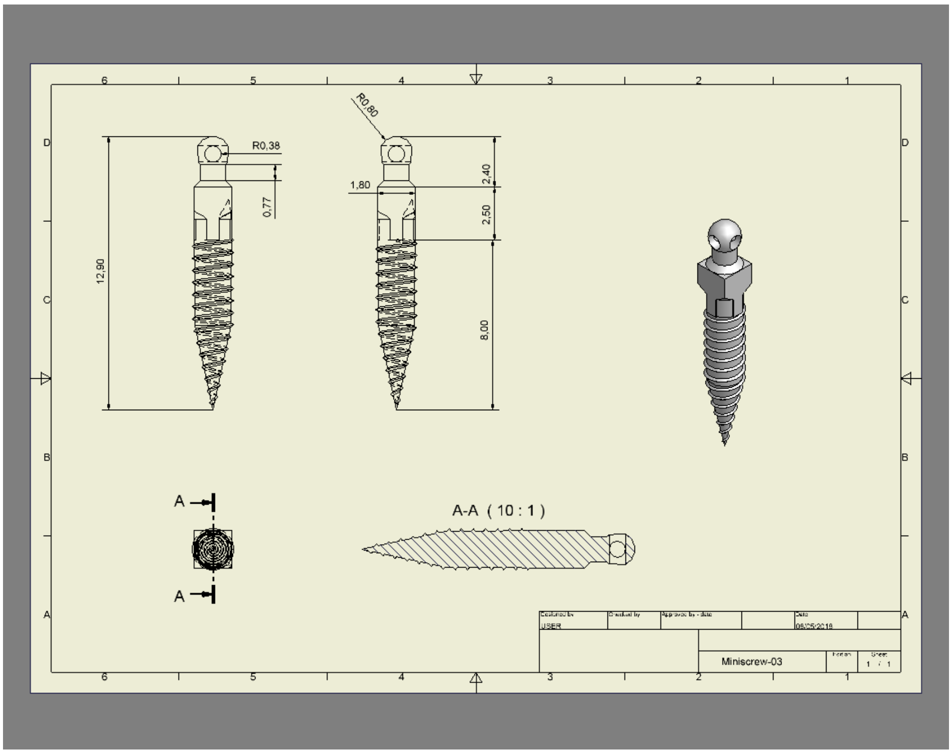


Figure 1: Miniscrew design on Autodesk Inventor screen based on manufacturer dimensions.

The cortical and spongy bones were modeled in the finite element package. The bone geometry was simplified and simulated as a parallelogram representing cortical bone (20 mm length x 20 mm width x 0.5, 1.0, 1.5, and 2 mm height), the spongy bone (20 mm length x 20 mm width x 14.5, 14.0, 13.5, and 13 mm height). Finally, these components were assembled in ANSYS environment and complete osseointegration was assumed.

Suitable element type selection:

Finite element simulations started with selecting the suitable element type according to the structural mass. There were several options available for structure mass types (beam, pipe, shell and solid). In our study, the bone model was considered a solid type. Therefore, the element types chosen were the Tetrahedral and Brick.

Defining the material properties:

All model materials were homogeneous, isotropic and linearly elastic. The miniscrew was assumed to be pure titanium with a Young's modulus of 110 GPa and a Poisson's ratio of 0.35[10]. For healthy bone quality, the Young's moduli of the cortical and spongy bones were 14 GPa[10] and 1.3 GPa[11] respectively, and the Poisson's ratios were 0.3 for both[10, 11].

Mesh generation

The accuracy obtained from any FEA model was directly related to the finite element meshing process. In our study, the mesh generation process involved dividing the previous constructed geometrical model (miniscrew and bone) into small tetrahedral and brick finite elements (Fig.2). The solution functions obtained from these elements were combined together to calculate a solution to the whole body. The smaller these elements were made, the more the mesh was refined and the more accurate the results.

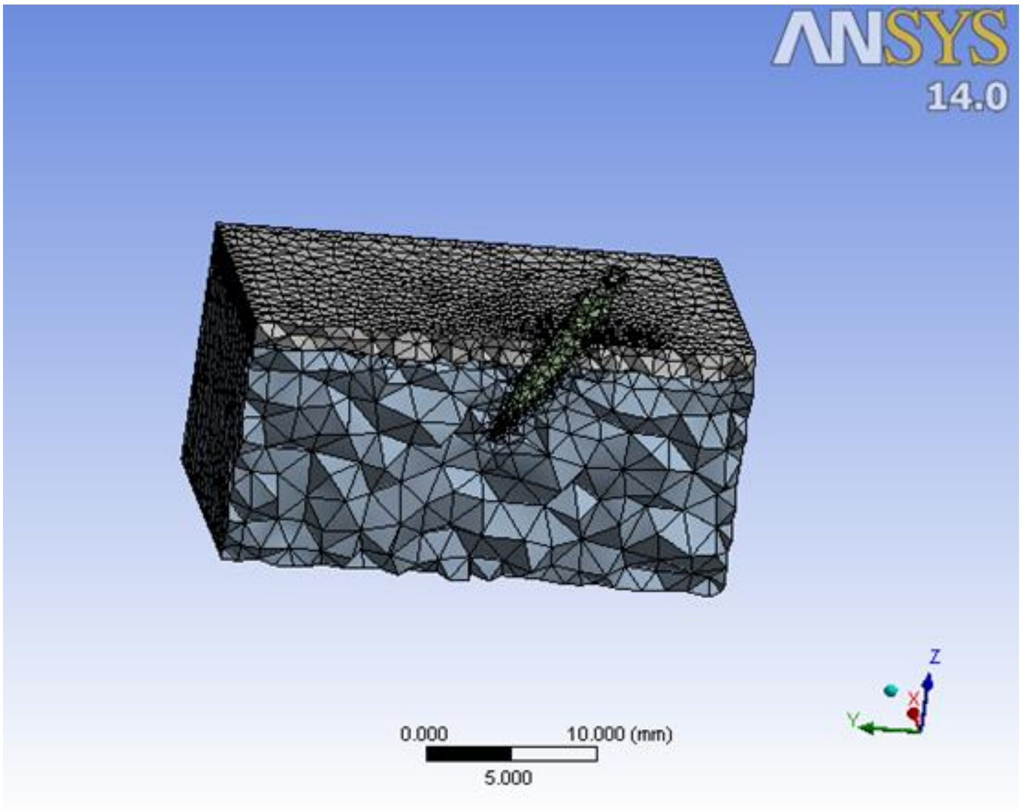


Figure 2: Complete longitudinal cut section in 60° inserted miniscrew.

Loading and boundary conditions:

After meshing the model, the next step was to apply structural load and constraints. The restriction of the boundary condition was mandatory to prevent the body from floating, translating and rotating. The contouring lines of the cortical and spongy bone geometries were set to be fixed in place as a boundary condition. Then a load of 2 N was applied to the miniscrew head in two directions:

(1) Parallel to bone.
(2) Oblique by 30º up-word to the horizontal plane (Fig.3).

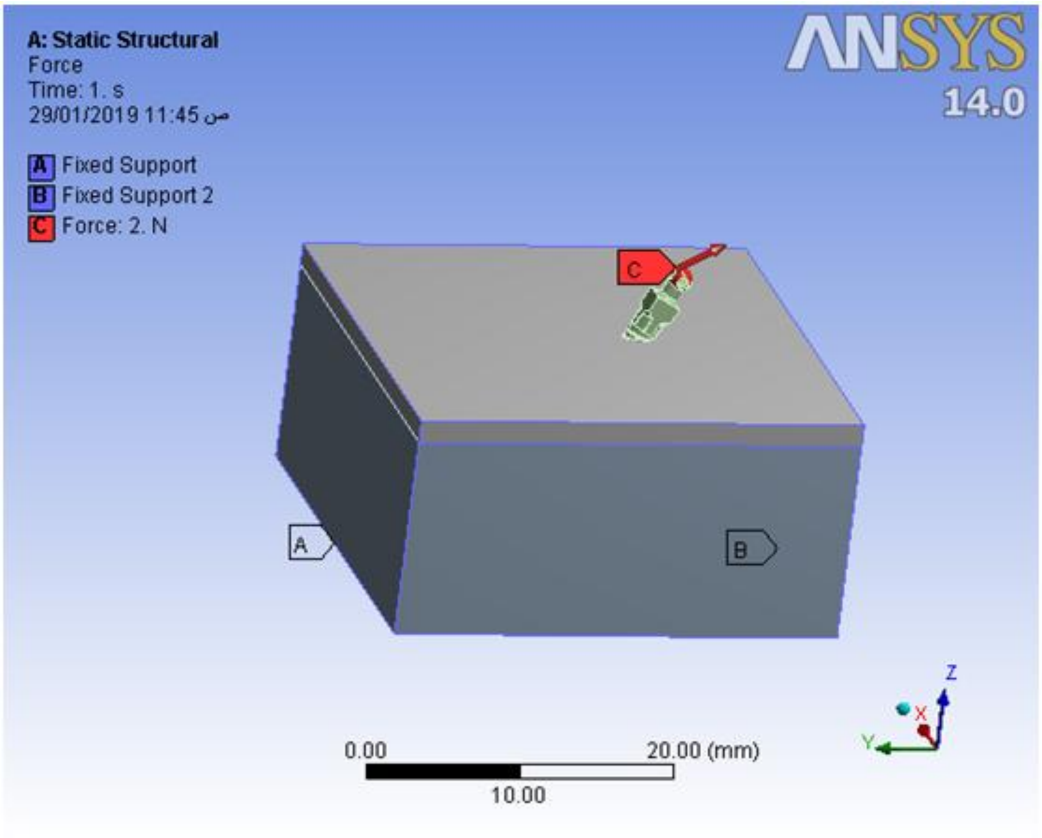


Figure 3: Finite element model showing oblique force applied on 60° inserted miniscrew.

Obtaining the solution functions of resultant stresses:

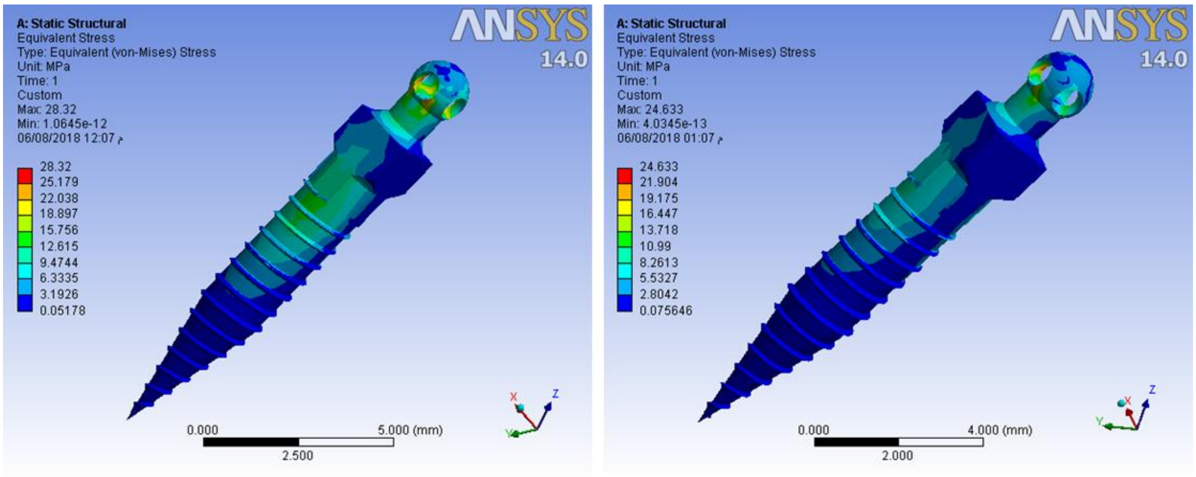
Linear static analysis was carried out using commercial multipurpose finite element software package (ANSYS version 14.0).The resultant deformations and stresses of the applied load were collected from the output of ANSYS program, and they were collected in tables and figures according to maximum values of total deformations and Von Mises stress. In the present work, the results were based on the total deformation (Usum) and the Von Mises stress (Svon) values. In order to calculate the microstrain in cortical bone, the maximum compressive stress (S3) was used.

This finite element study simulated clinical situations where miniscrew was inserted with various insertion angles (30º, 60º and 90º) in different cortical bone thicknesses (0.5, 1.0, 1.5 and 2.0 mm) and 2 N orthodontic force were applied in different directions on all twelve meshed models.

Statistical significance analyses were not carried out since the results of FEA are individual values without any statistical spread[12].

III. Results

Results showed that stress distribution on miniscrew and strain distribution on bone would be changed if C.B.T, insertion angle or force direction was changed. For different C.B.T, horizontal force generated more stresses on miniscrew body than oblique one (Fig.4). For all miniscrew insertion angles, miniscrew stresses were insensitive to bone thickness.



(A) **(B)**

Figure 4: Von mises stresses on miniscrew inserted at 60^o in bone when C.B.T was 0.5 mm (A), Horizontal force (B), Oblique force.

60^o inserted miniscrews generated much more strains on cortical bone than 90^o and 30^o inserted miniscrews. In 60^o, horizontal force generated about 45% more microstrains on cortical bone than oblique one (Fig.5) with the greatest microstrain generated when C.B.T was 0.5 mm (Fig.6).

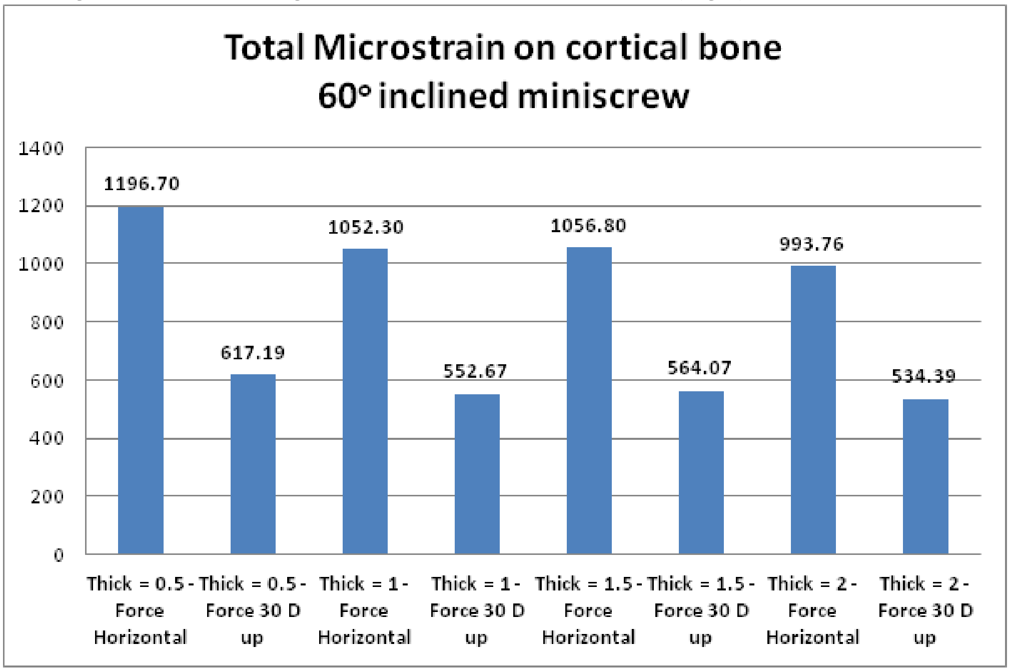


Figure 5: Bar chart showing microstrains on cortical bone of different thicknesses when insertion angle was 60^o to bone surface and 2 N force applied in two directions.

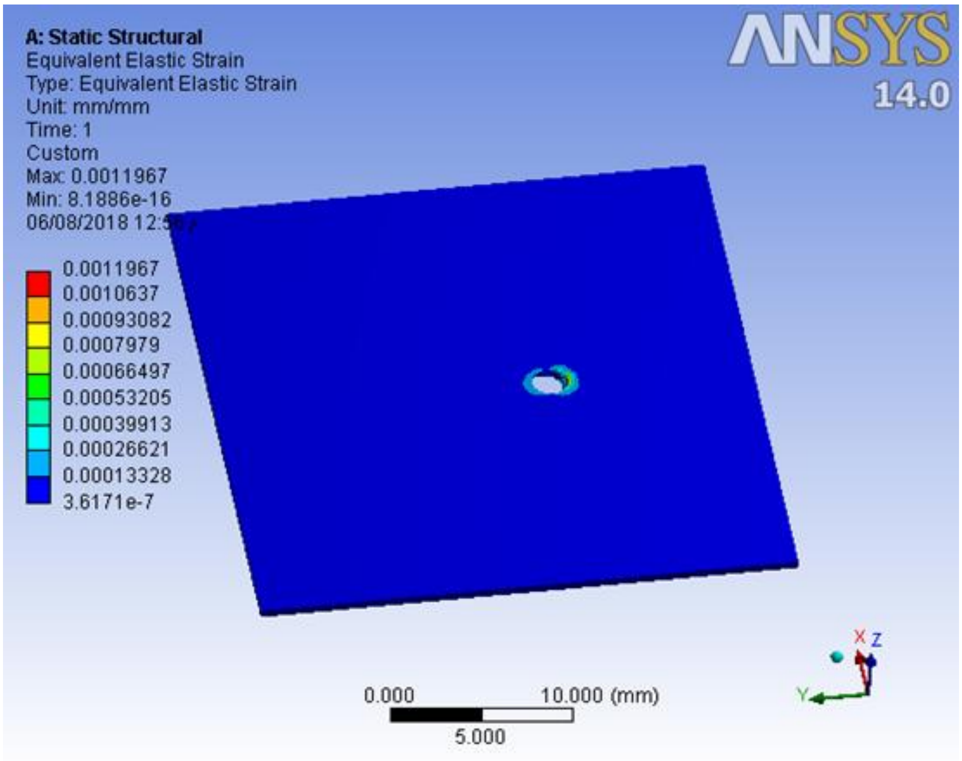


Figure 6: Microstrain on cortical bone when horizontal force was applied on 60^o inserted miniscrew and C.B.T was 0.5 mm.

Force direction had minor effect on bone strains, but horizontal force generated more strains on cortical bone than oblique one (Table 1).

insertion Angle	Bone thickness	Force Direction	Uy	Usum	Svon	Strain Von
			Micron	Micron	M.Pa	Micro-Strain
Vertical	1.5	Horizontal	0.223	0.312	6.761	488.33
Vertical	1.5	30 D up	0.193	0.338	6.254	451.50
30 D oblique	1.5	Horizontal	0.004	0.277	4.216	379.67
30 D oblique	1.5	30 D up	0.000	0.118	0.511	308.70
60 D oblique	1.5	Horizontal	0.004	0.374	13.276	1056.80
60 D oblique	1.5	30 D up	0.001	0.211	7.057	564.07

Table 1: Microstrain on cortical bone of all modeled insertion angles and force directions with 2 N force when C.B.T was 1.5 mm.

In general, under horizontal force, regardless the miniscrew angulation, increasing the bone thickness slightly reduced the exerted microstain on bone (Fig.5). Under oblique force (30º up-word to the horizontal plane), using vertical miniscrews, bone strains were insensitive to cortical bone thickness. On the other hand, when inclined miniscrews were used, increasing the bone thickness reduced the exerted microstrains on bone.
Anyway, the maximum Von Mises stresses generated in the miniscrew and cortical bone were below the yield stress of pure titanium and cortical bone. Therefore, the miniscrews and cortical bone had sufficient strength to withstand force magnitudes up to 2 N. Also, the maximum value of calculated microstrain on the cortical bone was well below the physiologic limit of bone integrity (200 MPa)[12].

IV. Discussion

Recently, miniscrews have been implemented in most of orthodontic treatments and its success is influenced by miniscrew insertion angle, force direction and C.B.T in addition to other factors[13].

In order to maximize the benefits of miniscrews, understanding its mechanical variables is necessary. However, within the clinical environment it is unachievable to detect the underlying biomechanical mechanisms of miniscrews due to the restricted mechanical indices that can be measured and inaccurate parameters control. Hence, FEA could be considered a suitable method to estimate stresses and deformations exerted in orthodontic miniscrews simulating real clinical situations[14].

The objective of this study was to analyze stress distribution on miniscrew and surrounding bone in situations of different C.B.T, miniscrew insertion angles and force directions using FEA.

The results of this study revealed that increasing the C.B.T slightly reduced the exerted microstrains on bone except when applying oblique force (30^o up) on vertically inserted miniscrews in which bone strains were insensitive to C.B.T.

This supported the outcomes of other studies which found that C.B.T is directly proportional to the miniscrews success rate. Considerably, greater miniscrew success rate was accompanied with C.B.T more than 1 mm[15 16].

Our findings were also in agreement with **Okumura et al.[17] 2010** who found that stresses increased with the decrease of C.B.T. They concluded that from a biomechanical point of view, to enhance miniscrew success rates in the posterior maxillary segment, accurate preoperative assessment of the cortical bone at the miniscrew placement location is necessary.

Other studies, however, found that C.B.T did not influence the stresses concentrated in cortical bone surrounding miniscrew. This may be due to the differences in miniscrew design, geometry and study model[12].

In the present work, the insertion angles of the miniscrews were 30^o, 60^o and 90^o to the cortical bone surface. In case of 60^o inserted miniscrews, Horizontal force generated 45 % more strain on cortical bone than oblique force, while 90^o and 30^o inserted miniscrews generated much less strains on the cortical bone than the 60^o insertion angle.

Similar results were also obtained in other studies which reported that the cortical and spongy bone stresses generated by force application to the miniscrews inserted at 90^o were less than those generated at both 30^o and 60^o [13, 18].

Similar results were also obtained from the study of **Choi et al.[19] 2016** except for the 30^o insertion angle. They found that the maximum von Mises stresses increased as the angle of insertion decreased. They detected that miniscrew insertion at 90^o to the bone surface is preferable to minimize stresses concentrated on the supporting bone.

Also, previous studies found that the created stresses on the cortical bone in 60^o inserted miniscrews were more than those created with 30^o inserted miniscrew [20].

On the other hand, other studies concluded that the miniscrew insertion angle had a considerable effect on the primary stability with the best results gained with an insertion angle ranging from 60^o to 70^o [21].

Also, **Raji et al. [22] 2014** and **Zhao et al. [23] 2011** concluded that oblique insertion angle of the miniscrews was preferred as it offered more primary stability compared to the vertical insertion. These distinctions with our findings might be imputed to the differences in miniscrew design, geometry, length, diameter and study model.

The force magnitude in our study was 2 N, which is the optimum force that approximates the force applied to a miniscrew during orthodontic treatment as reported by previous studies which concluded that orthodontists can apply loads to miniscrews immediately, as longer healing time did not offer more stability at forces up to 2 N [15 24].

In the present work, for all different C.B.T, we found that force direction has minor effect on bone strains, but horizontal force generated slightly more strains on the cortical bone than oblique one for all insertion angles especially in the 60^o inserted miniscrews in which horizontal force generated about 45% more strains on the cortical bone than oblique one.

These results were consistent with those of Marimuthu et al.[25] 2015 who suggested that force direction had statistically insignificant influence on stress distribution in bone surrounding miniscrews and concluded that the force direction has insignificant influence on miniscrew stability.

In accordance with our findings, **Lin et al.[26] 2013** reported that orthodontic force direction had insignificant impact on cortical bone stresses.

However, In contrary to our results, Fattahi et al.[27] 2015 observed that the maximum stresses on bone at force directions 0°, 45°, and 90° were 38.90, 30.57 and 6.62 MPa, respectively. They concluded that von Mises stresses concentrated on bone and miniscrew could be affected by different force directions.

In the current work, the maximum Von Mises stresses concentrated in the miniscrew and cortical bone in all models were 33.68 and 14.43 MPa respectively. Both values were much lower than the known yield stress of titanium (692 MPa) and cortical bone (200 MPa) respectively [12].

V. Conclusions

- Increasing the C.B.T reduces the exerted microstrain on bone.
- Inserting miniscrews at 60^o to the bone surface should be avoided as it generates much more strains on cortical bone than 90^o and 30^o. Especially when a force parallel to the bone surface is applied.
- Force direction has minor effect on bone strains, but horizontal force generates slightly more strains on cortical bone than oblique one.

- Titanium miniscrews and cortical bone had sufficient strength to withstand force magnitudes up to 2 N.

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