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Effect of changing various parameters on stress distribution in mini-screws and surrounding alveolar bone :A three-dimensional finite element analysis

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Aim: *The purpose of the study was to clarify and evaluate the effects of various force magnitudes and mini-screw length, diameter and insertion angle on the stress distribution of the mini-screw and the surrounding bone utilizing a three dimensional finite element analysis.* ***Methods:*** *We created a three dimensional finite element model simulating various clinical situations where mini-screws with different diameters (1.5 and 2 mm), lengths (9, 11 and 13 mm) and insertion angles (45º and 90º) were utilized under various force magnitudes (200 and 250gm). The resultant deformations and stresses from the applied loading were analyzed with a 3D FEM according to maximum values of total deformations and Von Mises stress.* ***Results:*** *The Von Mises stresses in both the mini-screw and the cortical bone in obliquely inserted 1.5 mm diameter screws with 200 gm and 250gm force were higher than those with 2 mm diameter screws. The Von Mises stresses in the spongy bone in both the vertically and obliquely inserted 1.5 and 2 mm diameter screws with 200gm and 250gm force were higher with the 2 mm diameter screws. The maximum compressive stress and equivalent micro-strain in cortical bone was evident with screw dimensions 13mm length and 2mm diameter under an oblique force magnitude of 250 gm. The Von Mises stresses in the spongy bone in obliquely inserted 1.5 and 2 mm diameter screws with 200gm and 250gm force were higher with the 2 mm diameter screws The maximum stress (Von Mises) generated in the mini-screw and cortical bone in all the simulated finite element models was 72.77 and 13.52 MPa respectively.* ***Conclusion:*** *Increase in the mini-screw diameter with both vertical and oblique insertion reduced the deformations and stresses within the mini-screw and cortical bone but increased the deformations and stresses within the spongy bone. Increase in the mini-screw length with vertical insertion had negligible effect. The deformation and stress values within the cortical bone were higher in oblique insertion than vertical insertion with both (200 and 250 gm) force.*

Introduction

Orthodontic mini-screws are increasingly used by orthodontists to provide temporary skeletal anchorage during orthodontic treatment this is because they offer additional advantages over conventional types of anchorage. In traditional orthodontic treatment, extraoral appliances such as headgear and various intraoral appliances are utilized to prevent anchorage loss. However lack of patient compliance in case of extraoral anchorage, and in some situations of missing or periodontal affected teeth that are strategic for intraoral anchorage, the utilization of these appliances is compromised.

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The orthodontic mini-screws offers several advantages, including small size, easy surgical procedure, minimal anatomic limitations which enable them to be placed in various sites without damaging any anatomical structures, easy insertion and removal with minimal trauma, and the ability of immediate loading after implantation, in addition to their relatively low cost.[1,2]

However, the mini-screw success rate in clinical practice has been reported to range from 83.9% to 93.3%[3,4].It was found that several factors influence their success and stability like mini-screw length, diameter[5], design (tapered or cylindrical)[6] and surface treatment in addition to force magnitude[7,8], insertion angle and torque[9,10], implantation location, root proximity, soft-tissue characteristics.

On the other hand, factors identified as causing failure include inflammation, infection, nonkeratinized implant sites, and small size mini-screws, in addition to reliance on patient compliance in hygiene measures and application of intermaxillary elastics when needed.[6]

Kyung et al. [11] recommended mini-screw insertion at angles of 30^o to 40^o in-order to avoid root injury, rather than perpendicular to the bone surface. Whereas previous studies suggested an insertion angle between 50^o and 70^o to achieve greater mini-screw stability under various loading conditions.[12,13] Other researches, reported that inserting mini-screws at a 90^o angle to the bone surface decreases the stress concentration, whereas mini-screws at angles less than 90^o to the alveolar surface did not provide advantages as regard to anchorage resistance force.[9,10,14]

Finite element analysis (FEA) is a noninvasive computer-based numerical simulation technique that is widely used for analyze, predicting, and forecast the biomechanical behavior of object movements. FEA provides the optimal assessment for the physical response to a mechanical stimulus and permits the study of different loading conditions.

The successful use of mini-screws in various applications demands a full understanding of their biomechanical performance in conjunction to their surrounding bone. Therefore, the FEA was utilized to better understand the stresses generated with different combinations of mini-screws sizes and angles of insertion.

The purpose of the study was to clarify and evaluate the effects of various force magnitudes and mini-screw length, diameter and insertion angle on the stress distribution of the mini-screw and the surrounding bone utilizing a three dimensional finite element analysis.

Materials and Methods

This finite element study simulated clinical situations where mini-screws with different diameters (1.5 and 2 mm), lengths (9, 11 and 13 mm) and insertion angles (45^o and 90^o) were utilized under various force magnitudes (200 and 250gm).

I. Materials:

The standard MONDEAL LOMAS (Medical Systems, Muhlheim, Germany)mini-screw type was chosen for this study due to the following advantages; (i) The denser pitch design and increased thread depth that ensured maximum anchorage. (ii) The self-drilling tip of the screw with its sharp threaded flanks provided easy cutting within the bone. In addition, to special surface treatment for the screw called anodization process (Anodurit®) to provide a higher bending fatigue strength and lessen surface contamination for screw.

A three dimensional solid modeling software (Inventor professional version 8) was utilized for modeling the mini-screw with its various diameters and lengths (1.5 and 2.0mm) (9.0, 11.0, and 13.0mm) respectively. Whereas a three dimensional finite element analysis (FEA) software (Ansys version 14.0Inc., Canonsburg, PA, USA) was utilized for modeling the cortical and spongy bone assembly.The server upon which these programs were ran was, Workstation HP (ProLaint ML150, with Intel Xeon 3.2 GHz processors with 1 MB L2 cache, 8 GB RAM).

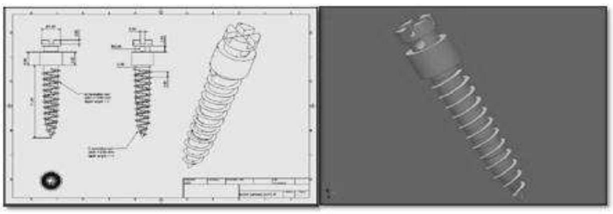


Figure 1: Sample of screw on the Inventor screen

II. Method:

*Construction of geometrical test model incorporated the miniscrew model which was created on Autodesk Inventor Version (8) (Autodesk Inc., San Rafael, CA, USA) according to the manufacturers dimensions and design as illustrated in figure 1.

The cortical and spongy bone model were simulated as a parallelogram where the cortical bone dimensions were (20 mm length, 20 mm width, and 2 mm height), whereas the spongy bone dimensions were (20 mm length, 20 mm width, and 13 mm height).

The assembly of the mini-screw within the bone model was founded on subtracting the volume of the minis-crew model from both the cortical and spongy bone models according to the Boolean operation. The mini-screw model was then incorporated into the bone model in ANSYS* environment on the assumption of complete osseointegration. In this study the bone model was considered a solid type therefore the selected element types were the tetrahedral and brick. In this study both the mini-screw and bone (cortical and spongy) were assumed to be linearly elastic,homogeneous, and isotropic (thus having identical properties in all three dimensional directions) materials. For easier prediction of material behavior all loadings were in a linear range under static loading. The material properties of each different component representing the model were then assigned into the program. The linear static stress/strain analysis needed the definition of two essential parameters the Elastic

(Young's) modulus and Poisson's Ratio for each component incorporated within the assembly which are shown in table 1. All interfaces between the mini-screws and bone (cortical and spongy) were assumed to be bonded due to complete ossteoinegration

Table 1: Material properties

Material	Young's Modulus [MPa]	Poisson's ratio
Screw (Titanium)	110,000	0.34
Spongy bone	13,700	0.35
Cortical bone	1300	0.35

In this study the mesh generation involved dividing the constructed geometrical model (mini-screw and bone) into numerous small tetrahedral and brick finite elements. The smaller the elements the more precise, refined and accurate are the results. The solution functions obtained from all the elements compromising the mesh were combined together to calculate a solution to the whole body.

Twelve meshed models were required in order to test all the possible combinations of the mini-screws (length, diameter and insertion angle) under the various loading (200 and 250gms), which are listed in table 2. The following step was applying the structural load and constraints. A full constraint was used to simulate the boundary condition. Restriction of the boundary condition was mandatory in order to prevent the body from floating, rotating, and translating. This was performed by fixing the contouring lines of the cortical and spongy bone geometries figure.

All the various model combinations incorporating the screw and bone were subjected to loads of 200 and 250 gms with a 30^o angle to the horizontal plane table 3. In order to mimic the solution functions for the resultant stresses a linear static analysis was made on a work station* using commercial multipurpose finite element software package (ANSYS version 14.0). The resultant deformations and stresses from the applied loading were collected in tables and figures according to maximum values of total deformations and Von Mises stress.

In our study the results were based on the total deformation (U_{sum}) and the Von Mises stress (S_{von}) values. In order to calculate the microstrain in cortical bone the maximum compressive stress (S_3) was used. This was calculated in accordance to the formula (microstrain = $S_3 \times 72$).

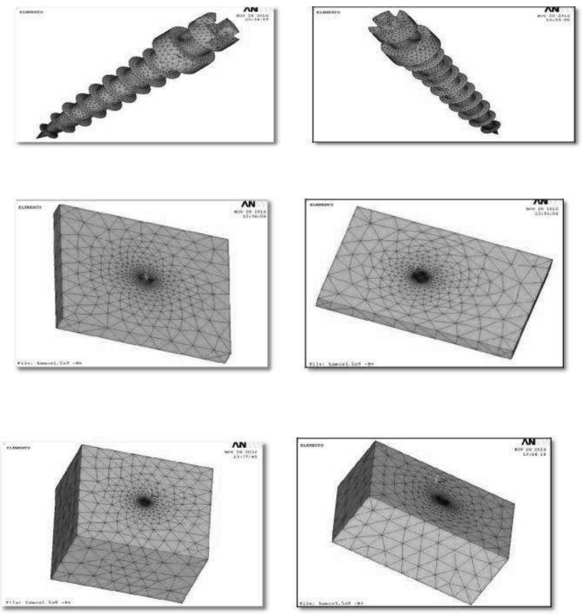


Figure 2: Model components after meshing (a) screw 1.5x9.0, (b) screw 2.0x11.0, (c) cortical bone with vertical screw hole, (d) cortical bone with oblique screw hole, (e) spongy bone with vertical screw hole, (f) spongy bone with oblique screw hole.

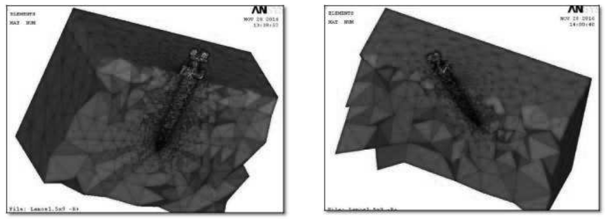


Figure 3: Sample of a complete longitudinal cut section in finite element models for the (a) vertical and (b) oblique screw.

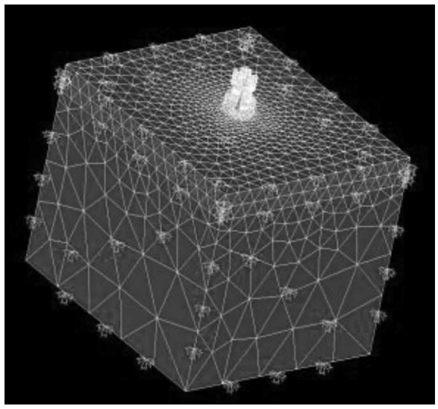


Figure 4: Finite element mesh assembly illustrating boundary constraints.

Table 2 Mesh density

Volume	Number of Nodes	Number of Elements
Model #1: 1.5x9.0 - vertical		
Cortical bone	887	8,729
Cancellous bone	8,408	59,043
Screw	5,712	45,794
Model #2: 1.5x11.0 - vertical		
Cortical bone	1,347	12,119
Cancellous bone	9,784	69,192
Screw	7,007	55,954
Model #3: 1.5x13.0 - vertical		
Cortical bone	938	9,140
Cancellous bone	9,976	72,097
Screw	7,652	61,094
Model #4: 2.0x9.0 - vertical		
Cortical bone	819	8,242
Cancellous bone	7,782	55,196
Screw	5,353	43,266
Model #5: 2.0x11.0 - vertical		

Cortical bone	773	8,036
Cancellous bone	7,793	56,769
Screw	6,149	49,433
Model #6: 2.0x13.0 - vertical		
Cortical bone	777	8,050
Cancellous bone	7,848	58,959
Screw	7,165	57,435
Model #7: 1.5x9.0 - Oblique		
Cortical bone	1,599	15,039
Cancellous bone	5,086	37,418
Screw	7,357	57,449
Model #8: 1.5x11.0 - Oblique		
Cortical bone	1,903	17,354
Cancellous bone	9,491	67,683
Screw	8,761	68,322
Model #9: 1.5x13.0 - Oblique		
Cortical bone	1,942	18,777
Cancellous bone	9,724	74,606

Screw	10,138	78,361
Model #10: 2.0x9.0 - Oblique		
Cortical bone	2,102	19,554
Cancellous bone	9,965	76,587
Screw	11,002	79,023
Model #11: 2.0x11.0 - Oblique		
Cortical bone	2,189	19,775
Cancellous bone	10,461	81,146
Screw	11,095	85,268
Model #12: 2.0x13.0 - Oblique		
Cortical bone	2,304	20,087
Cancellous bone	10,723	82,214
Screw	11,134	88,573

		Miniscrew						Miniscrew		
Runs	**Load (gm)**	**Position 90°**	**Diameter**	**Length**		**Runs**	**Load (gm)**	**Position 45°**	**Diameter**	**Length**
1	200	Vertically	1.5	9		13	200	Oblique	1.5	9
2	250	Vertically	1.5	9		14	250	Oblique	1.5	9
3	200	Vertically	1.5	11		15	200	Oblique	1.5	11
4	250	Vertically	1.5	11		16	250	Oblique	1.5	11
5	200	Vertically	1.5	13		17	200	Oblique	1.5	13
6	250	Vertically	1.5	13		18	250	Oblique	1.5	13
7	200	Vertically	2	9		19	200	Oblique	2	9
8	250	Vertically	2	9		20	250	Oblique	2	9
9	200	Vertically	2	11		21	200	Oblique	2	11
10	250	Vertically	2	11		22	250	Oblique	2	11
11	200	Vertically	2	13		23	200	Oblique	2	13
12	250	Vertically	2	13		24	250	Oblique	2	13

Table 3: The twenty four finite element runs.

RESULTS

The Von Mises stresses in vertically inserted 1.5mm diameter screws with 200gm and 250gm force were higher than those with 2 mm diameter screws as illustrated in figure 5 (a-b) respectively.

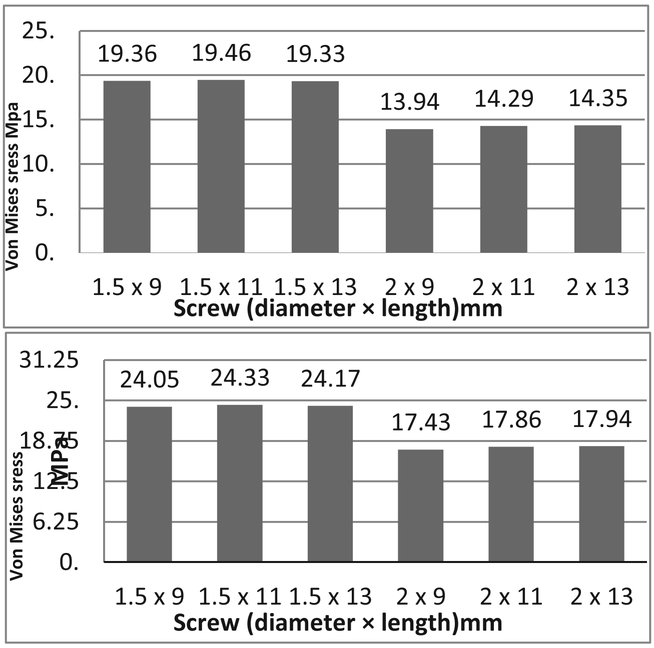


Figure 5(a-b) Vertically inserted screws with 200 and 250 gm force (Von Mises stresses) in mini-screws

The Von Mises stresses in obliquely inserted 1.5 mm diameter screws with 250 gm force were higher than those with 2 mm diameter screws as illustrated in figure 6 (a-b) respectively.

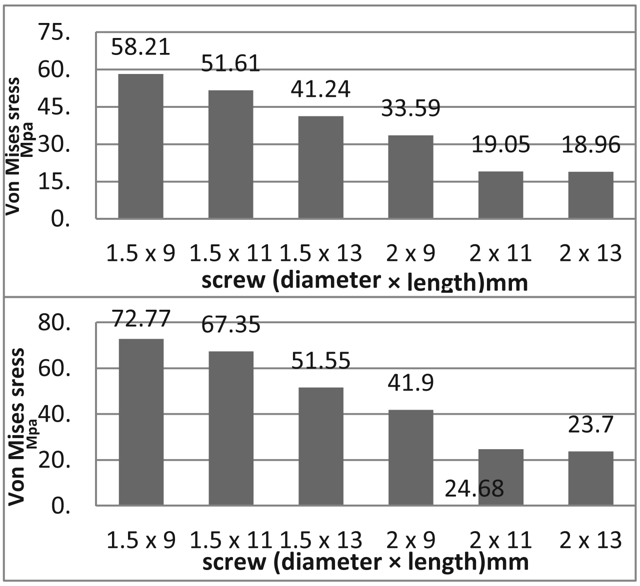


Figure 6(a-b) Obliquely inserted screws with 200 and 250 gm force (Von Mises stress) in mini-screws

The Von Mises stresses in cortical bone in vertically inserted 2mm diameter screws with 200 gm and 250gm force were nearly the same as those with 1.5 mm diameter screws as illustrated in figure 7 (a-b) respec-

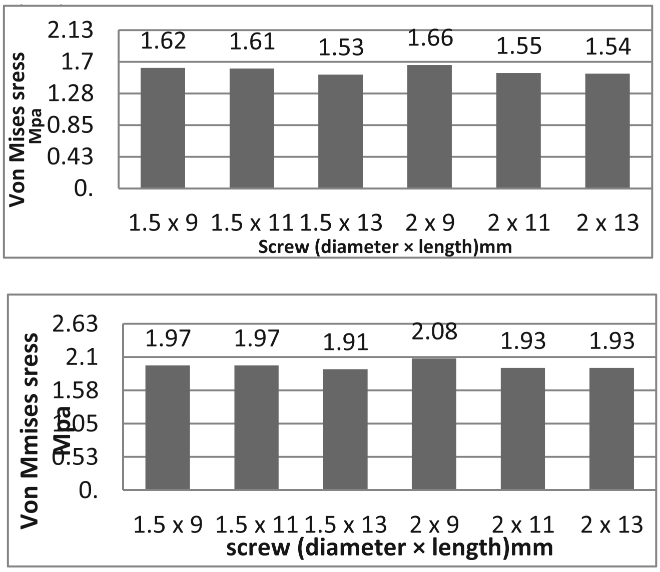
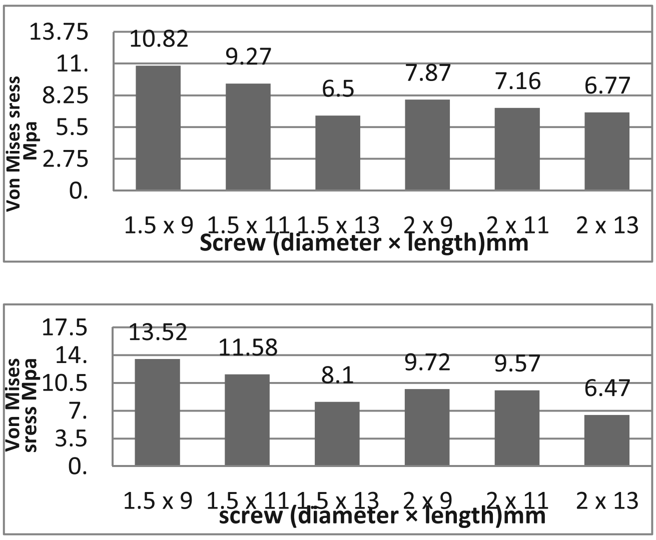
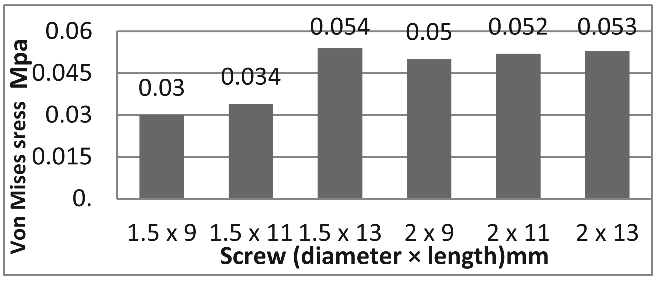


Figure 7(a-b) Vertically inserted screws with 200 and 250 gm force (Von Mises stresses) in cortical bone

The Von Mises stresses in the cortical bone in obliquely inserted 1.5 mm diameter screws with 200 gm and 250gm force were higher than those with 2 mm diameter screws as illustrated in figure 8 (a-b) respectively.



The Von Mises stresses in spongy bone in vertically inserted 2mm diameter screws with 200gm and 250gm force were higher than those with 1.5 mm diameter screws as illustrated in figure 9 (a-b) respectively.



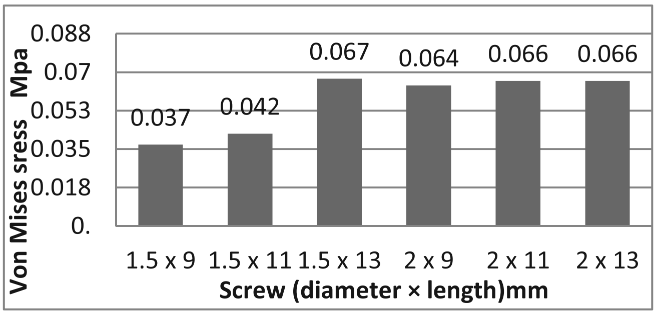
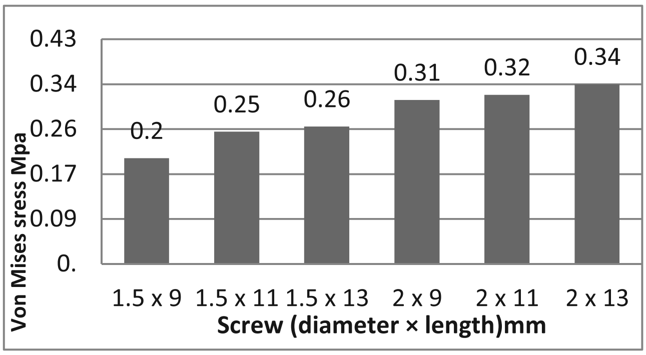


Figure 9(a-b) Vertically inserted screws with 200 and 250 gm force (Von Mises stresses) in spongy bone

The Von Mises stresses in the spongy bone in obliquely inserted 1.5 and 2 mm diameter screws with 200gm and 250gm force were higher with the 2 mm diameter screws as illustrated in figure 10 (a-b) for Von Mises respectively.



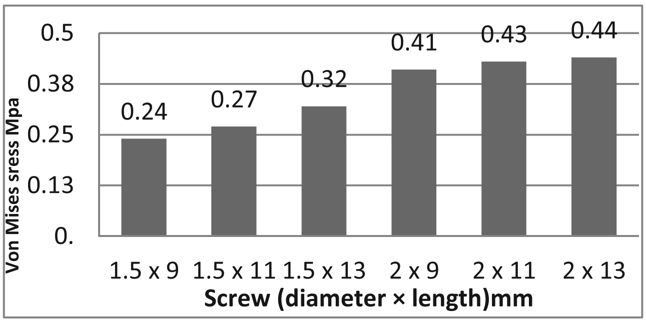


Figure 10(a-b) Obliquely inserted screws with 200 and 250 gm force (Von Mises stress) in spongy bone

The maximum compressive stress and equivalent micro-strain in cortical bone was evident in run 23 with screw dimensions 13mm length and 2mm diameter under an oblique force magnitude of 250 gm as shown in table 4.

Table 4: The Maximum compressive stress and equivalent micro-strain in the cortical bone in oblique insertion both 200 and 250 gm force magnitudes

Oblique		200 gm	S3	S3	Oblique		250 gm	S3	S3
Diameter	Length		MPa	με	Diameter	Length		MPa	με
1.5	9.0	R14	13.06	940.3	1.5	9.0	R13	16.33	1175.7
1.5	11.0	R16	12.81	921.6	1.5	11.0	R15	15.29	1100.8
1.5	13.0	R18	7.4	532.8	1.5	13.0	R17	9.39	676.1
2.0	9.0	R20	8.51	612	2.0	9.0	R19	10.63	765.4
2.0	11.0	R22	32.19	2317.6	2.0	11.0	R21	40.16	2887.2
2.0	13.0	R24	35.29	2534.4	2.0	13.0	R23	44.11	3175.2

Discussion

The success of mini-screws is influenced by factors; length, diameter and surface characteristics in addition to insertion angle and torque, force magnitude, anatomic location, soft-tissue characteristics, root proximity, and primary stability.

Increasing the diameter of mini-screws increases their primary stability more effectively than increasing their lengths.[5] However, larger mini-screw diameter can limit the placement options due to root proximity. Thus, various tapered mini-screw designs have been proposed to solve this problem. A tapered mini-screw increases primary stability through induction of a controlled compressive force in the cortical bone.[15] However, excessive insertion torque might lead to deformations of the surrounding bone that would cause congestion and necrosis at the bone interface.[16] Increased deformation from excessive stress may increase inflammatory mediators to the site and result in bone resorption and remodeling, which in turn might cause mini-screw failure.[9]

In order to maximize the benefit of mini-screws applications, it is thus important that their mechanical variables become fully understood. However, the clinical environment proposes difficulty in determining the underlying biomechanical mechanisms for mini-screws via an experimental approach because of the limited measureable mechanical indices and imprecise parameter control. Hence, FEA can be a suitable method for estimating stresses and deformations exerted on mini-screws simulating real clinical situations.

FEA is a computer-based numerical simulation technique that is widely utilized for predicting the mechanical behavior of engineering structures, in addition to solving solutions for engineering problems. Based on their numeric origin, the investigated parameters can be controlled more specifically, and many mechanical indices can also be examined at any site on the model to reflect the rationale of a mechanical response.

The validity of three dimensional FEA is mainly dependent upon: 1) Similarity of the finite element model to the real structure to be analyzed since excessive simplifications in the geometry would inevitably lead to considerable inaccuracy. 2) Accurate and precise modeling of the material properties utilized in the case model. 3) Effectiveness of modeling to the boundary conditions.

In our study the model consisted of the following components: mini-screw, cortical and spongy bone. The dimensions of the mini-screws in our study were 1.5 mm and 2 mm in diameter, which were the most preferred and widely used diameters. [14,17,19] According to Miyawaki et al [3] the success rate of mini-screws increased from 0.0% to 83.9% with the diameter increase from 1.0 to 1.5mm.

The bone geometry in this study was simplified and simulated as a parallelogram composing both the cortical and spongy bone. The dimensions for the cortical bone were (20mm length x 20mm width x 2mm high) whereas the spongy bone dimensions were (20mm length x 20mm width x 13mm high). These dimensions were based on the recommendations of Liu et al.[20]

The mini-screw solid modelling was created at the Autodesk Inventor Version (8)[*]. This software program provided more accurate simulation the exact mini-screw design, while in previous studies the mini-screw design was simulated directly in the ANSYS[†] environment software which had limited options in accurate design simulation operations. The subsequent operations which involved Boolean, osseointegration and boundary constrains were in accordance to Perilloet al.[21]

Pickard et al [22]recommended a 45°insertion angle for the mini-screws to the bone surface to creat a larger contact area between the cortical bone and the mini-screw. This will increase the placement torque, resulting in a positive effect on the mini-screw stability during orthodontic forces application. However, Joseph et al [23] and Choi et al[24]suggested that the 90°insertion angle of mini-screws in order toavoid the setbacks of oblique insertion such as potentially creating longer lever arms and reducing the insertion depths inside the bone. Insertion at an oblique angle might cause slippage of the mini-screw during its first contact with the bone surface as well as microdamage of the cortical bone.

In our study the increase in length for all the vertical mini-screw insertions with both 200 and 250 gm of force magnitude had no effect on the deformation and Von Mises stress within the mini-screws. Similarly this was evident within the cortical and spongy bone. However, in case of oblique insertion the mini-screw length increase reduced Von Mises stresses generated within the mini-screw and cortical bone but increased the Von Mises stresses within the spongy bone. Therefore, the increase in mini-screw length can be considered more effective with oblique insertion this is concurrent with the findings of Choi et al. [24] who concluded that the maximum von Mises stresses increased as insertion angle decreased during mini-screw. The stresses in cortical and spongy bone were lowest for mini-screws placed at 90^o to the bone surface, irrelevant of mini-screw design. This finding is consistent with the results of previous studies [9,10] demonstrating that maximum von Mises stresses in mini-screws and cortical bone decreased as insertion angle increased. An analysis of stress distributions in cortical and spongy bone revealed that the stress was absorbed mostly by cortical bone, and small amount was transmitted to spongy bone.[9]

These finding were cited by Liu et al [20] in their FEA study. They reported that the exposed length (the level arm of the bending moment) was the real factor influencing stress and displacement not the total length of the mini-screw so longer mini-screw might not provide extra stability if it cannot be implanted deeply enough to reduce the lever arm. In addition Lin et al.[20] reported that the exposed lengths of mini-screws were significantly associated with cortical bone stress during force application. Neither orthodontic force direction nor the insertion angle affect cortical bone stress significantly.[20]

In our study the increase in mini-screw diameter from 1.5 to 2mm with both 200 and 250 gm force magnitudes in both vertical and oblique insertion of mini-screws decreased the deformations and stresses within the mini-screws and cortical bone. However, these mechanical properties increased in spongy bone. These findings were in agreement with Wilmes et al [13] and Liu et al[20]who reported that increasing the mini-screw diameter was the mosteffective way to reduce the stress, hence increasing the stability and decreasing the failure rate.

Finally, it could be concluded that with both vertical and oblique insertions the pattern of deformations and stresses within the screw and cortical bone decreased with increase in length and diameter with both force magnitudes (200 and 250 gm). However the stress values within the cortical bone were higher in oblique insertion.

Our results were consistent withPerillo et al [10] Woodall et al [14] and Lee et al [19] in their studies on cadaver and finite element model. They found that the anchorage resistance offered by screws inserted at 90^o to the alveolar process bone was greater than the anchorage resistance of screws inserted at 30^o or 60^o. In addition to the cortical bone stress created via loading mini-screws inserted at 90^{o} was less than the bone stress created via loading mini-screws at either 30^{o} or 60^{o}. They recommend insertion of the mini-screws perpendicular (90^{o}) to the cortical bone as long as it did not risk root damage in order to take advantage of the improved biological and biomechanical stability when applying heavy forces.

Our results also supported the outcomes of Choi et al [24] in which they designed a three-dimensional maxilla model of a dentition with extracted first premolars and used 2 types of mini-screws (tapered and cylindrical) with 1.45mm diameter and 8mm length inserted at 30^{o}, 60^{o}, and 90^{o} with respect to the bone surface. They concluded that both cylindrical and tapered mini-screw designs, perpendicular 90^{o} insertion to the bone surface is recommended to reduce stress in the surrounding bone and offer better anchorage.

The maximum stress (Von Mises) generated in the mini-screw and cortical bone in all the simulated finite element models in this study was 72.77 and 13.52 MPa respectively. Both of these values were well below the known yield stress of titanium (692 MPa) and cortical bone (200 MPa) respectively.[25] Therefore, it can be concluded that mini-screws and cortical bone had sufficient strength to withstand force magnitudes up to 250 mg.

Frost[26]noted that if the peak strain exceeded 4000 micro-strain,the structural integrity of the bone was threatened leading to pathologic overload and micro-damage accumulation with subsequent bone resorption and reduction of bone strength, resulting to mini-screws loosening.

In the current study the concept of micro-strain was considered. The maximum stress value at the cortical bone was observed with the oblique insertion of mini-screws. This value (44.1 MPa) was equivalent to 3175.2 micro-strain. This calculated value was well below the physiologic limit (4000 micro-strain) of bone integrity. Therefore, it can be concluded that the FEA utilized in our study is a useful tool to estimate the force effect on stress distribution and predict the tissue reaction against the orthodontic and orthopedic force.

There are limitations in this study that must be taken into consideration when interpreting the data.
The cortical bone thickness of model was selected according to previous studies.[20,27] A cortical bone. thickness of 1.5 mm was utilized to simplify model construction. Whereas the peri-screw area exhibits anisotropy and heterogeneity during physiological conditions, this study was performed with an isotropic and homogeneous model that considered physical features only.

Conclusions

- Increase in the miniscrew diameter with both vertical and oblique insertion reduced the deformations and stresses within the miniscrew and cortical bone but increased the deformations and stresses within the spongy bone.

- Increase in the miniscrew length with vertical insertion had negligible effect. However, in oblique insertion it reduced the deformations and stresses within the miniscrew and cortical bone but increased the deformations and stresses within the spongy bone.

- The deformation and stress values within the cortical bone were higher in oblique insertion than vertical insertion with both (200 and 250 gm) force.

- The maximum stress (Von Mises) 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 250 gm.

- The maximum value of calculated microstrain on the cortical bone was well below the physiologic limit of bone integrity.

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