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ORIGINAL ARTICLE

Effects of orthodontic miniscrew placement angle and structure on the stress distribution at the bone miniscrew interface – A 3D finite element analysis

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KEYWORDS

Finite element model analysis;
Miniscrew;
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Abstract *Aims:* The study was conducted to evaluate the effects of orthodontic miniscrew placement angle and structure in terms of length and diameter on stress distribution at the bone miniscrew interface.

Methods: 10 FE models were created representing miniscrews inserted in the buccal alveolar bone between the maxillary first molar and second premolar to simulate varying angulations of miniscrew placement (90°, 60°, 45°, 30°) to the long axis of the maxillary first molar, varying length (6mm, 8mm, 10mm, 12mm) and varying diameter (1.2mm, 1.3mm, 1.4mm, 1.5mm). In order to simulate retraction forces an identical force of 200 g was applied perpendicular to the long axis of the miniscrew in all the models. Finite Element Modeling Analysis was used to analyze the stress distribution at the bone miniscrew interface.

Results: Minimum and maximum stress in the miniscrew was generated at placement angles of 30° and 90° respectively. In the bone minimum and maximum stress was found at placement angles of 90° and 30° respectively. On increasing the miniscrew diameter stress in both the miniscrew and the bone decreased. There was no difference found in the stress distribution patterns with varying miniscrew length.

Conclusion: Based on stress patterns, biomechanical stability of the miniscrew is enhanced by a placement angle of 90° to the long axis of the first maxillary molar and a diameter of 1.5 mm for the site selected in this study while miniscrew length has no implication on its stability.

1. Introduction

Successful orthodontic treatment largely requires intraoral anchorage with a high resistance to displacement. Adequate anchorage may become difficult, if not impossible, to obtain when teeth are missing.[1] Skeletal anchorage such as miniscrews

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have increasingly been used for orthodontic anchorage because of their ability to provide absolute anchorage, ease of placement and removal, and relatively low cost. Several kinds of titanium miniscrews have recently attracted a great deal of attention.[2–4]

With more patients being treated with miniscrews as anchorage units their clinical stability requires more attention. The clinical success of an implant is largely determined by the manner in which the mechanical stresses are transferred from the miniscrew to the surrounding bone.[5]

Finite element analysis, an effective computational tool adapted from the engineering arena offers a viable and non-invasive alternative for predicting the stress distribution in the contact area of the miniscrew with the cortical bone and the trabecular bone which is a key factor in the success or failure of the miniscrew.[6]

Conflicting opinions based on clinical studies[7–9] have been reported regarding the effect of miniscrew length, diameter and placement angle on miniscrew success, hence this study was undertaken to evaluate the effects these parameters on stress distribution at the bone miniscrew interface and thus establish a scientific basis for selection of a miniscrew to be used for orthodontic anchorage between the maxillary second premolar and first molar with adequate stability under orthodontic loading.

2. Materials and methods

In this study a finite element model was used to determine the stress distribution along the bone miniscrew interface based on the miniscrew placement angle, length and diameter. The area of simulation was the interdental region between the maxillary second premolar and first permanent molar.[4] The placement of the miniscrew was 5 mm gingival from the intercrestal bone level between the two teeth.

In this study the analytical model was developed based on the following information:

(1) C.T. scan image of the maxilla: Earlier studies[10] used histological sections of animals to evaluate the bone thickness. However this study used a C.T scan image of the human maxilla[11] along with average bone thickness values obtained in radiological studies reported previously in literature[12,13] to evaluate cortical bone thickness in the interdental region between the maxillary second premolar and first permanent molar. The average thickness of bone was estimated to be 14.5 mm bucco-lingually of which cortical bone thickness was 2.5 mm.
(2) Miniscrew Dimensions and Morphology: The miniscrew model was based on the Abso Anchor (Dentos, Daegu, Korea). Miniscrew profile and morphology was evaluated using a stereo microscope (Olympus-SZX 12), at 20× magnification (Fig. 1).

The purpose of the geometric modeling phase is to represent a geometry in terms of points (grids), lines, surfaces (patches) and volume (hyperpatches).

Once the dimensions of bone and miniscrew were obtained these values were fed as input in both x and y dimensions into the modeling software (Hypermesh FE modeling package).

Figure 1 Abso anchor at 20×.

The digitized points of the x and y coordinates were joined by lines to create the 2D cross section of the miniscrew and bone (Fig. 2). This cross section was rotated 360° to get a three dimensional model of the bone and miniscrew. A total of 10 geometric models were generated with varying miniscrew morphologies as pertaining to the aim of the study. The study was carried out in a stepwise manner in which one variable was investigated at a time, while all other variables were controlled. The control variables are presented in Table 1. The models were created to simulate varying angulations of miniscrew placement (90°, 60°, 45°, 30°) to the long axis of the maxillary first molar, varying length (6, 8, 10, and 12 mm) and varying diameter (1.2, 1.3, 1.4, and 1.5 mm). In order to represent the placement angle the entire geometric model was rotated about the Z axis, so that the long axis of the miniscrew was at varying angles to the long axis of the maxillary first permanent molar.[13]

The geometric models thus generated were converted to finite element models. The completed 3D geometric model was converted into a MSC Nastran input file and imported into MSC Patran.[14] The element shape described was hexahedral in form. The finite element model consisted of 57,041 elements and 60,077 nodes (Fig. 3).

The assumption was made that the materials were homogenous and linear and that they had elastic material behavior characterized by two material constants viz. Elastic Modulus and Poisson's ratio. For an isotropic material the properties are the same in all directions. The following values of Elastic Modulus and Poisson's Ratio were used[6] (Table 2).

Boundary conditions were applied and since the miniscrew was assumed to be rigidly anchored in bone the entire outer surface of the bone was restrained from translation along all three axes and restrained from rotations around all three axes. The surface of insertion of miniscrew was left free (Fig. 3).

In order to simulate retraction forces an identical force of 200 g was applied 3 mm from the point of insertion of the miniscrew into bone and was directed perpendicular to the long axis of the miniscrew along the Z axis (Fig. 3).

The Von Mises stress generated in the bone and the miniscrew were measured individually for each of the simulated models. The displacement was evaluated for the miniscrew model simulated at a length of 8 mm, 1.3 mm diameter and 30° placement angulation. The results obtained are tabulated and represented as stress contour diagrams and graphs.

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

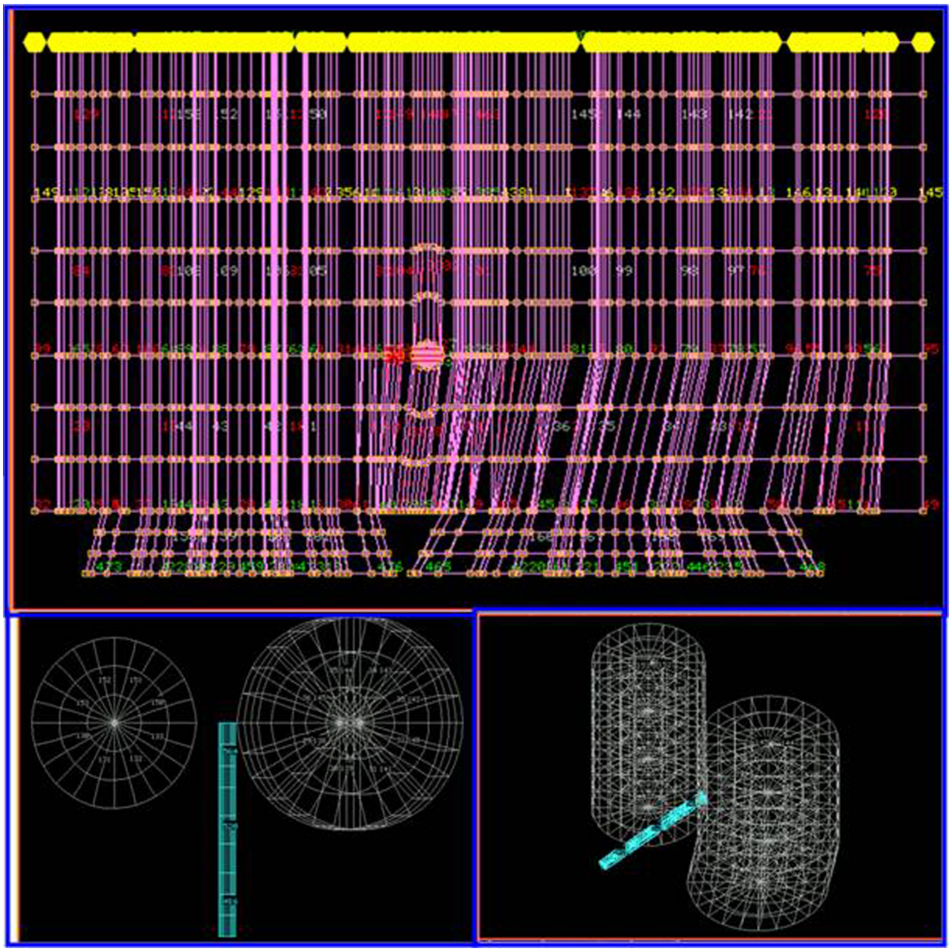

Figure 2 2D geometric model showing miniscrew placement between first molar and second premolar.

Table 1 Control variables.

Variable	Control value
Miniscrew placement angle	30°
Miniscrew diameter	1.3 mm
Miniscrew length	8 mm

3. Results

The Von Mises stress evaluated for miniscrew placement angles at 30°, 45°, 60° and 90° at constant miniscrew length and diameter showed that with increasing placement angle, stress values in the bone decreased while stress values in the miniscrew increased. (Table 3, Fig. 4). The maximum stress in the bone was observed at 30° and minimum at 90°. The maximum stress in the miniscrew was observed at 90° and minimum at 30°. The areas of maximum stress concentration were located at the neck of the miniscrew.

The Von Mises stress decreased in both the bone and miniscrew for increasing miniscrew diameters while keeping miniscrew length and placement angle constant (Table 4, Fig. 5).

There was no difference in the stress values either in the bone or miniscrew at varying miniscrew lengths. At all lengths evaluated, a constant stress value of 20.41 and 20.44 MPa in the bone and miniscrew respectively was observed (Fig. 6).

The displacement was 1.63234 μm for the miniscrew simulated at 8 mm length, 1.3 mm diameter and 30° placement angulation with a maximum displacement noted at the head of the miniscrew. There was no displacement observed at the tip of the miniscrew (Fig. 7).

4. Discussion

The concept of 'Absolute Anchorage' involving the use of miniscrews as anchorage devices has expanded orthodontic treatment horizons to a great extent due to their ease and versatility of placement and wide application.[15]

The clinical success of a miniscrew is largely determined by the manner in which the mechanical stresses are transferred from the miniscrew to the surrounding bone without generating forces of a magnitude that would jeopardize the longevity of the miniscrew.[5] Very low stress levels around a miniscrew may result in poor connection with bone or bone atrophy. On the other hand, abnormally high stress concentrations in the supporting tissues can result in pressure necrosis and subsequently miniscrew failure.[10,16]

The present study was undertaken to obtain a mathematical simulation of the stress distribution around a miniscrew used

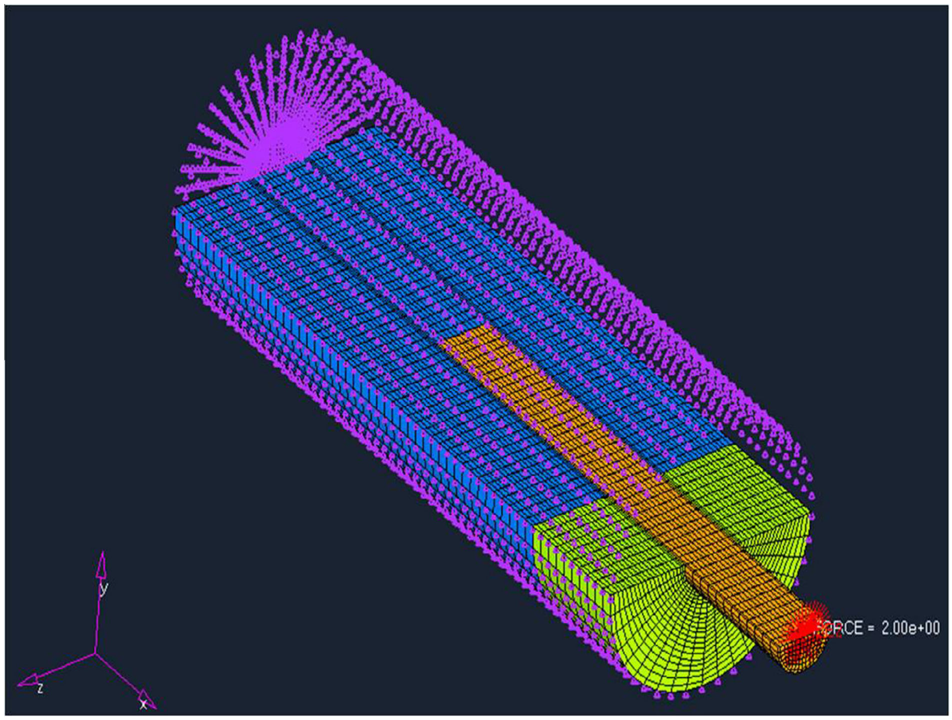

Figure 3 3D geometric model of bone and miniscrew showing boundary conditions and force application.

Table 2 Material properties used in the analysis.

Material	Elastic modulus (MPa)	Poisson's ratio
Cortical bone	15,000	0.3
Trabecular bone	1,500	0.3
Miniscrew (Titanium)	1,10,000	0.35

Table 3 Stress values for varying miniscrew placement angulation.

Placement angle (°)	Stress (MPa)	
	Bone	Miniscrew
30	20.41	20.44
45	19.01	24.87
60	14.41	26.01
90	9.134	27.41

for orthodontic anchorage between the maxillary first permanent molar and second premolar which is a commonly preferred placement site because of the large space and easy accessibility for various orthodontic mechanics. The degree of contribution of the miniscrew length, diameter and placement angle on stress dissipation at the bone miniscrew interface was studied.

For angle measuring methods some authors used the tooth axis[13,17] or the bone surface as the criterion.[18,19] In this study we used the long axis of the maxillary first molar as a reference for angle measurement. This study showed that a placement angle of 90° generated the least stress in the bone surrounding the implant suggesting that a perpendicular placement angle is more favorable for miniscrew stability, which is corroborated by the findings in previous studies.[19–21] The results of this study however conflict with the suggestions made by several authors who advise placing orthodontic miniscrews at an angle to the alveolar process bone.[7,13,22] With an oblique insertion angle, screw to cortical bone area contact increases which might favor stability but cantilever load arm concomitantly lengthens which adversely affects miniscrew stability even at orthodontic force levels.[21] Based on the results of this study and those of previous studies a miniscrew placement angle of 90° is recommended as long as root damage can be avoided to take advantage of improved biomechanical stability.

When evaluating the effect of varying miniscrew diameter, the results of the study showed that progressively increasing the diameter of the miniscrew decreased the Von Mises stress generated in both the miniscrew and the bone (Table 4, Fig. 5). This was due to the increased bone contact area available with larger diameter allowing dissipation of stresses over a larger surface area.

The results were in accordance with those reported from clinical studies evaluating factors affecting success of miniscrews.[7,8,23] A decrease in miniscrew diameter will both increase the number of potential insertion sites and facilitate the surgical removal.[24] However a too small diameter also increases the risk of screw fracture. Buchter et al.[25] experienced 3 times more fracture during placement of 1.1 mm screw rather than a 1.6 mm diameter screw. Miyawaki et al. in 2003[7] in a clinical study suggested a 1.5 mm diameter screw for stability in the maxilla.

The proximity of miniscrews to the adjacent tooth root is a major risk factor for failure of screw anchorage.[9] There is at least 1.5 mm of distance between the first molar and second premolar roots in the maxilla.[13] Thus screws with diameters up to 1.5 mm can be safely used without the possibility of root damage.

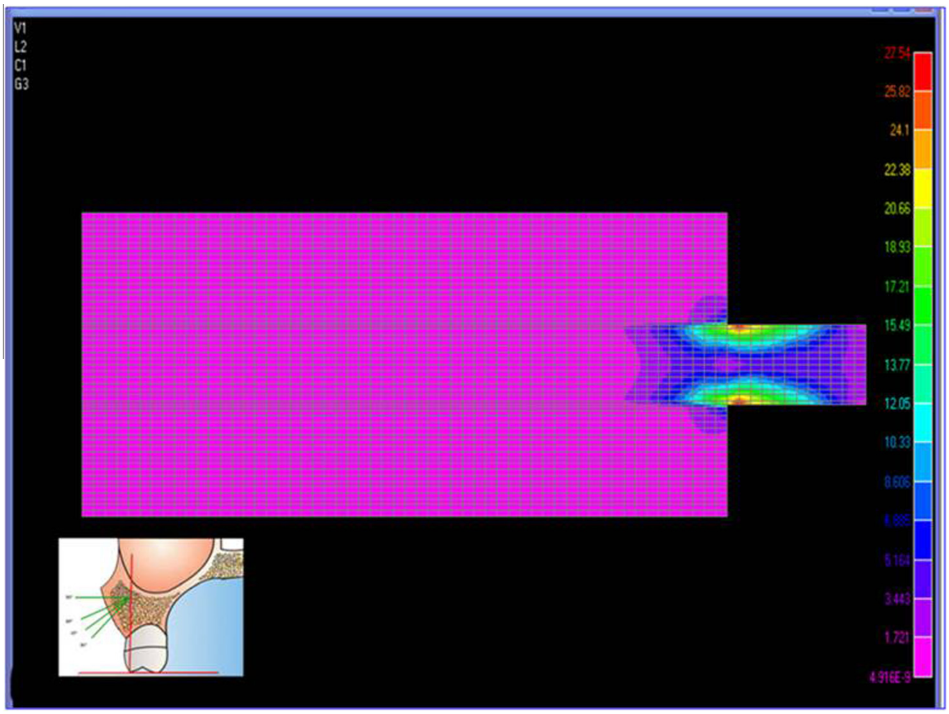

Figure 4 Stress contour picture at miniscrew placement angle of 90°.

Table 4 Stress values for varying miniscrew diameter.

Miniscrew diameter (mm)	Stress (MPa)	
	Bone	Miniscrew
1.2	20.32	25.81
1.3	20.41	20.44
1.4	15.32	15.15
1.5	10.75	12.18

The importance of miniscrew length has been investigated in several studies most of which have concluded that it does not significantly affect miniscrew stability.[7,9,22,23] Some studies, however have found some differences in stability between miniscrews of different lengths.[26] The results of this study showed that varying the length of the miniscrew had no effect on the stress distribution patterns. Von Mises stress values obtained at the bone – miniscrew interface were similar for all four lengths simulated at a constant angulation and diameter (Fig. 6). The length of the miniscrew used should be decided based on the surrounding structures and location of placement.

Stress contour pictures revealed (Fig. 4) that the stress was limited to the initial 1.5 to 1.75 mm of bone thickness surrounding the miniscrew indicating that stress was limited to cortical bone thickness as cortical bone thickness was simu-

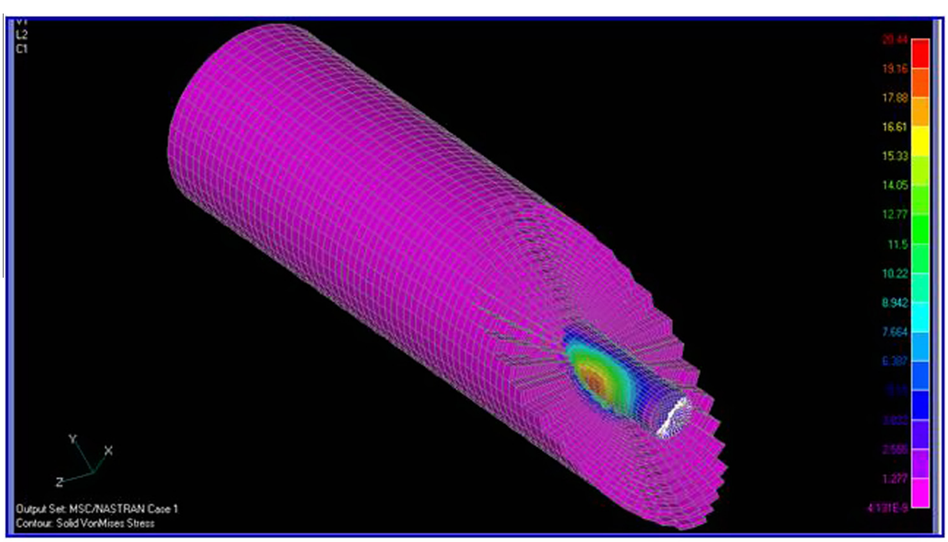

Figure 5 Stress contour picture at miniscrew diameter of 1.3 mm.

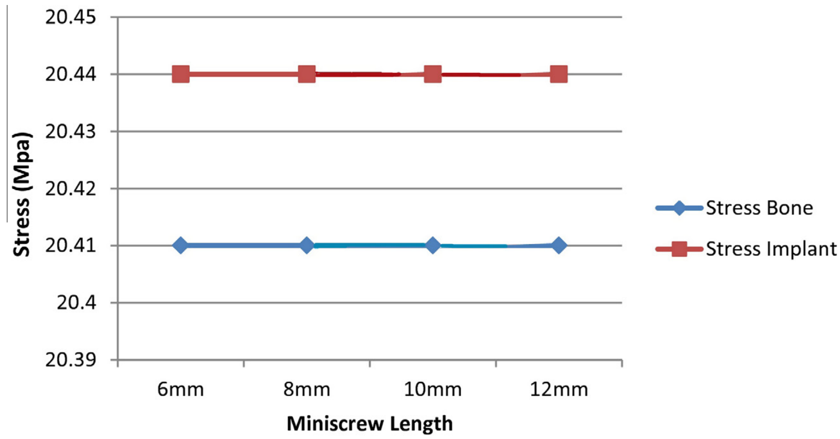

Figure 6 Graph showing stress values for varying miniscrew length.

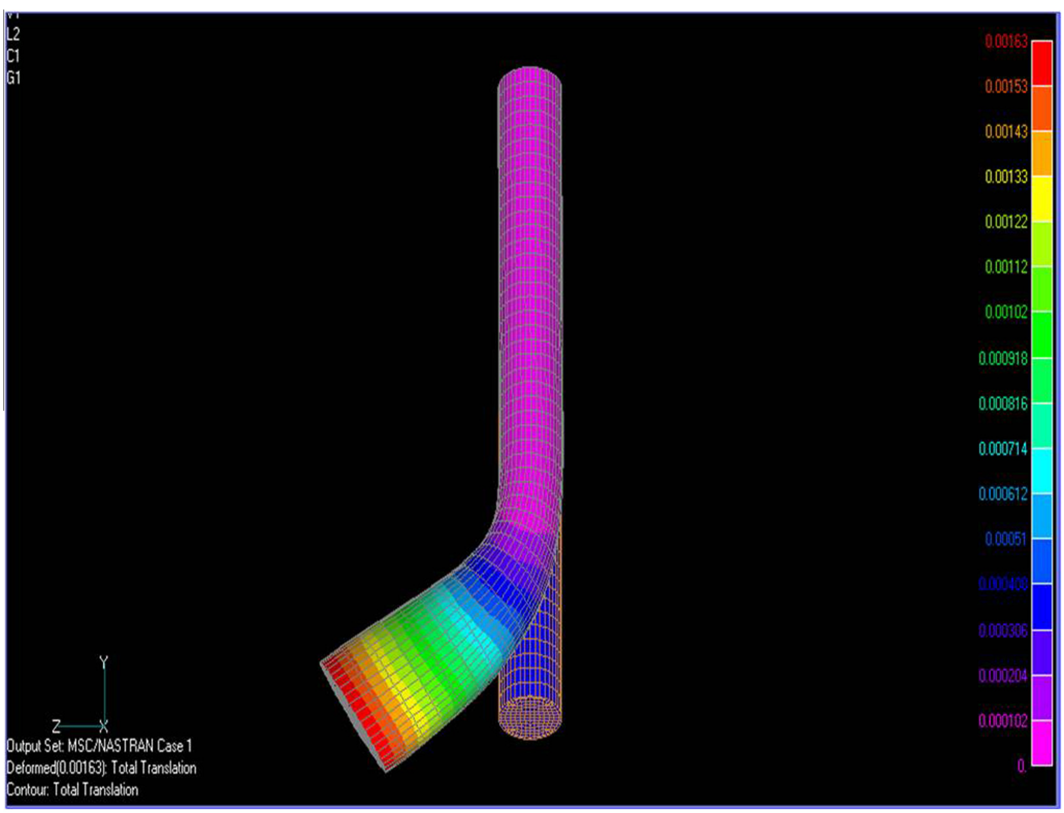

Figure 7 Displacement of the miniscrew.

lated at 2.5 mm in our study. This was in compliance with results obtained by Melsen et al.,[27] who stated that stress levels were higher in the cortical bone.

In agreement with previous FEM studies[28–30] the critical stress point in the miniscrew in this study was 2.75 mm from the point of force application indicating that it was located at the neck of the miniscrew. This suggests that the miniscrew should be strongest at its neck to withstand fracture under loading.

The maximum stress generated in the bone and miniscrew in all the simulated finite element models in this study was 20.41 and 27.51 MPa respectively. Both these values were well below the yield stress of bone (200 MPa)[31] and titanium (692 MPa)[32] indicating that both bone and the miniscrew have sufficient strength to resist forces during orthodontic loading.

The displacement was 1.63234 μm for the miniscrew simulated at 8 mm length, 1.3 mm diameter and 30° angulation (Fig. 7) with maximum displacement at the head of the miniscrew and no displacement observed at the tip indicating that there was no probability of impingement of the tip of the miniscrew on the roots of the teeth after orthodontic loading if the initial placement was correct. However, extrusion and tipping of miniscrew implants up to 1.5 mm during en-masse retraction and intrusion of anterior teeth have been reported which did not correlate with the displacement of a few micrometers obtained in our study implying that miniscrew implant displacement under an orthodontic load could be a progressive process.

FEM studies have inherent technical difficulties which involves the construction of accurate models. In paucity of current literature involving the precise material properties of bone and in line with majority of the finite element studies[21,23,26,28,30] it was assumed that cortical and cancellous bone were isotropic, homogenous and linearly elastic. These assumptions need to be taken into account when interpreting the results of this study.

5. Conclusion

The present study derived the following conclusions:

(1) To achieve better biomechanical stability of loaded miniscrews in the selected site of the study, a miniscrew placement angle of 90° in relation to the long axis of the first maxillary molar is recommended.
(2) A selection of larger diameter miniscrews within anatomical boundaries will ensure better stability under orthodontic loads.
(3) Miniscrew length has no effect on miniscrew stability and selection should be based on clinical anatomy of the site of placement.
(4) The displacement of the head of the miniscrew was clinically insignificant under orthodontic loading and there was no displacement of the tip of the miniscrew.
(5) A conical miniscrew with a thicker neck would be more efficient in resisting forces.

6. Ethical declaration

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional or regional) and with the Helsinki Declaration of 1975, as revised in 1983.

Conflict of interest statement

None declared.

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