Finite element analysis of miniscrew placement in mandibular alveolar bone with varied angulations

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Summary

Background: Titanium miniscrews are increasingly used as orthodontic anchorage. Various factors are known to affect the stability of miniscrew. Placement angle is one of the most controversial issues in this area. Thus, the aim of this finite element study was to evaluate the influence of placement angle and direction of force on the stability of miniscrews.

Materials and methods: Finite element analysis was performed using miniscrews inserted into 1 mm of cortical bone and 10 mm of trabecular bone at angles of 30, 60, 90, 120, and 150 degrees to the alveolar bone. Force of 2 Newton (N) was applied to the heads of the miniscrews in two directions of 0 and 30 degrees.

Results: The finite element analysis showed that inserting miniscrews at 90 degree angle would provide better anchorage than 30, 60, 120, and 150 degree angles at either direction of force. The least trabecular bone von Mises stress was 5.6 MPa at 90 degrees at both directions of force and the least cortical bone stress was 31.2 MPa at 90 degrees at both directions of force.

Conclusions: Insertion of miniscrews at angles less than or greater than 90 degrees to the alveolar process bone might decrease the anchorage stability of the miniscrew.

Introduction

Miniscrews have become an accepted and reliable method for providing temporary additional anchorage during orthodontic and orthopaedic treatment (1–4). These miniscrews have several advantages over the conventional methods of skeletal anchorage. Miniscrews are easier to place, can be placed in more varied locations, are smaller and more cost effective, and have the possibility of immediate or early loading (3, 5, 6). However, the clinical behaviour of miniscrews is still unclear. Various authors have reported loosening and failure during clinical orthodontic treatment (7, 8). Various factors have been reported to influence the stability of miniscrews such as implant type and dimensions (9, 10), the design and shape of the screw thread (11), implant surface characteristics (12), the amount of orthodontic force (13), soft-tissue characteristics (14), cortical bone thickness (15), and insertion angle (16, 17). Miniscrews have been placed in virtually every bony location in the mouth; however, the angle of insertion reported in the literature varies from 30 to 90 degrees relative to the alveolar bone (5, 18). Zhao et al. (17) suggested that a placement angle between 50 and 70 degrees might be advisable in order to achieve better stability of loaded microscrews. Similarly, Wilmes et al. (19) suggested an insertion angle ranging from 60 to 70 degrees as advisable. However, Woodall et al. (16) found that placing orthodontic miniscrews at angles less than 90 degrees to the alveolar process bone surface does not offer force anchorage resistance advantages.

Finite element analysis is a computer-based numerical simulation technique that is widely used for predicting the mechanical
behaviour of engineering structures. It can be used to calculate deflection, stress, vibration, buckling behaviour, and many other phenomena. Finite element analysis is a useful tool to evaluate the biomechanical performance of miniscrews at varying angulations and the potential for angulation to contribute failure.

Considering the discrepant results in the literature, the aim of this study was to do a finite element analysis of placement angle on the stability of titanium miniscrews at varying angulations and the potential for angulation to contribute failure.

Materials and methods

Three-dimensional finite element models were created to represent screw placement angles of 30, 60, 90, 120, and 150 degrees. The bone block and screw models were meshed using ABAQUS 6.10 software. The bone block, consisting of cortical and trabecular bones, was simplified to dimensions of 20 mm in length and width, and 15 mm in height for evaluation (Table 1). The screws were modelled as a titanium alloy miniscrew (1.6 mm diameter, 8 mm long, 0.2 mm thread ridge, and 0.6 mm thread pitch; ISA orthodontic implant; Biodent, Tokyo, Japan) (15) with an elastic modulus of 110 gigapascals (GPa) and Poisson’s ratio of 0.34 (Figure 1).

A section of mandibular bone was considered. The cortical layer measured 1 mm thick and was assigned an elastic modulus of 14 GPa, and the trabecular bone layer measured 10 mm with an elastic modulus of 3 GPa. The bone was assumed to be homogenous and isotropic with a Poisson’s ratio of 0.3. The screws were inserted to a depth of 8 mm up to the collar of the miniscrew. The contact between the bone and the screw was defined as a frictional interface with a coefficient of friction of 0.37. The superior, inferior, and lingual nodes of the bony elements were fixed completely, and the screw was displaced to 0.6 mm at a distance of 2.0 mm from the bone surface.

Two directions of traction were defined in each model. In one group the direction of traction was considered as parallel to the bone surface (0 degree group) and in the other group it was considered as 30 degrees to the bone surface (30 degree group; Figure 2). In this study, the directions of force was constant for all angles in each group. The interface between the miniscrew and the bone elements was fixed and the traction force was fixed at 2 N, which is the approximate orthodontic force applied to a miniscrew (15). Two Newton force is the maximum magnitude in the generally accepted range, according to the reported clinically safe limit for immediate loading without causing damage to the bone (20, 21).

von Mises stresses were evaluated for miniscrew insertions into bone model at 30, 60, and 90 degree angles. The evaluations were done for two directions of traction of 0 and 30 degrees parallel to the bone surface.

Results

The von Mises stress distributions in cortical and trabecular bones are shown in Figures 3 and 4. The finite element analysis showed cortical bone stress in both 0 and 30 degree directions of force was greatest for screws placed at 120 and 60 degree angles and least for 90 degree angle (Table 2; Figures 5 and 6). Trabecular bone stresses were 35 and 35.1 MPa for 60 and 120 degree angles, respectively, at 0 degree direction of force, and 33.4 and 34 MPa for 60 and 120 degree angles, respectively, at 30 degree direction of force. The trabecular bone stress for 90 degree angle was 5.6 MPa at both directions of force.

Discussion

In this finite element study, miniscrews were inserted in a bone model at 30, 60, 90, 120, and 150 degree angles to the alveolar process bone. The stress distribution was calculated for both cortical and trabecular bones at 0 and 30 degree different directions of force. Cortical and trabecular

Table 1. The number of nodes and elements of models

<table>
<thead>
<tr>
<th></th>
<th>Nodes</th>
<th>Elements</th>
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<tbody>
<tr>
<td>Cortical bone</td>
<td>2601</td>
<td>12485</td>
</tr>
<tr>
<td>Trabecular bone</td>
<td>16802</td>
<td>84010</td>
</tr>
<tr>
<td>Screw</td>
<td>85896</td>
<td>433655</td>
</tr>
</tbody>
</table>

Figure 1. Screw model meshed by software.

Figure 2. Zero and 30 degree directions of pull for all angles of insertion.

Figure 3. von Mises stress distributions in cortical and trabecular bones for 0 degree direction of pull.
bone stress was least for screws placed at 90 degrees to the alveolar process bone, regardless of the direction of the force.

These results appear to support the clinical finding of Woodall et al. (16) that in a finite element model, the anchorage resistance of screws placed at 90 degrees to the alveolar process bone was dramatically greater than that of screws placed at either 60 or 30 degrees. However, in the same study, they did not find any difference related to insertion angle of miniscrew in cadaver bone samples. Zhao et al. (17) and Wilmes et al. (19) also suggested that oblique insertion of miniscrews leads to slightly greater stability. The different results might be due to the fact that these two studies were conducted on beagles and pigs, respectively, which have different nature with human bone. Moreover, in a recent review, it was stated that all associations between specific maximum insertion torque values and success were based on literature rated as having low quality (22).

Various other factors have been mentioned to affect the success rate of miniscrew anchorage. Manni et al. (23) did a retrospective study on 300 miniscrews and found that the success rate was better in male patients. They also found that the 1.3 mm wide and 11 mm length miniscrews had a better success rate. Kim et al. (24) found that patient’s age (older than 15 years) and operator’s skill influenced the clinical success of orthodontic miniscrews in the palate.

Gracco et al. (25) analysed the stress distribution developing around an orthodontic miniscrew inserted into the maxilla and the stress changes for different screw lengths. Their finite element analysis showed that critical conditions occur for screws 14 mm long with an orthodontic load of 2 N and the optimal screw length seems to be 9 mm. Lin et al. (21) incorporated a finite element approach and factorial analysis to determine the biomechanical effects of exposure length of the miniscrew, the insertion angle, and the direction of orthodontic force and found that increased exposure lengths resulted in higher bone stresses adjacent to the miniscrew and the direction of orthodontic force had no significant effect on cortical bone stress.

In a recent systematic review, Papageorgiou et al. (26) summarized the knowledge from published clinical trials regarding the failure rates of miniscrews used for orthodontic anchorage purposes and identified the factors that possibly affect them. They found that orthodontic miniscrews have a modest small mean failure rate, which indicates their usefulness in clinical practice. They also emphasized that although many factors seem to affect their failure rates, the majority of them still need additional evidence to support any possible associations.

One of the limitations of this study is the simplified geometry of the bone model. Even though the strength of a bone block is similar to that of jaw bone, the strain patterns might vary with the bone geometry. Therefore, further in vivo studies are required to achieve more precise results.

Conclusions

In a finite element model, the cortical and trabecular bone stress created by loading screws placed at 90 degree angle was less than the bone stress created by inserting screws at either 30, 60, 120, or 150 degree angles. Thus, based on the results of this study placing miniscrews at angles less or more than 90 degrees would not offer any anchorage advantages at 0 or 30 degree directions of force.

References