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# Effect of bite force on orthodontic mini-implants in the molar region: Finite element analysis

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**Objective:** To examine the effect of bite force on the displacement and stress distribution of orthodontic mini-implants (OMIs) in the molar region according to placement site, insertion angle, and loading direction. **Methods:** Five finite element models were created using micro-computed tomography (microCT) images of the maxilla and mandible. OMIs were placed at one maxillary and two mandibular positions: between the maxillary second premolar and first molar, between the mandibular second premolar and first molar, and between the mandibular first and second molars. The OMIs were inserted at angles of 45° and 90° to the buccal surface of the cortical bone. A bite force of 25 kg was applied to the 10 occlusal contact points of the second premolar, first molar, and second molar. The loading directions were 0°, 5°, and 10° to the long axis of the tooth. **Results:** With regard to placement site, the displacement and stress were greatest for the OMI placed between the mandibular first molar and second molar, and smallest for the OMI placed between the maxillary second premolar and first molar. In the mandibular molar region, the angled OMI showed slightly less displacement than the OMI placed at 90°. The maximum Von Mises stress increased with the inclination of the loading direction. **Conclusions:** These results suggest that placement of OMIs between the second premolar and first molar at 45° to the cortical bone reduces the effect of bite force on OMIs.
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**Key words:** Bite force, Orthodontic mini-implant, Finite element analysis, Stability

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## INTRODUCTION

Orthodontic mini-implants (OMIs) are now frequently used in orthodontics, owing to their small size, placement versatility, and biocompatibility.[1,2] However, stability is a prerequisite for the successful use of OMIs in clinical practice. In this regard, many studies have reported less than 90% success rates with OMIs.[3-5] Moreover, OMIs placed in the mandible reportedly exhibit a lower success rate than those placed in the maxilla.[4-8]

The lower success rate of OMIs in the mandible is associated with irritation, inflammation, and overtorquing.[4,9] Kuroda et al.[10] surmised that the occlusal force transmitted through the tooth to the screws in proximity could affect the stability of mandibular OMIs. While many authors have investigated these risk factors, the results of these studies have often proved inconclusive or contradictory. Therefore, predicting the stability of OMIs in the mandible remains difficult.

The maxilla and mandible are dominated by the attachments of the muscles of mastication; therefore, varying amounts of masticatory force are transferred to the teeth and supporting bone. Bite forces exerted on the alveolar bone are transferred directly to OMIs without mediators, such as the periodontal ligament. Thus, the internal stress and strain exerted on OMIs is unclear.

Finite element (FE) analysis can measure the distribution of strain and stress of internal as well as external structures. This technique has therefore been used in orthodontic research to investigate the biomechanics of orthopedic and orthodontic forces.[11,12] Furthermore, as FE analysis is based on element density and material properties, microCT may be useful for determining the trabecular structure of cancellous bone at high

**Table 1.** Properties of relevant materials

| | Elastic modulus (g/mm$^2$) | Poisson's ratio |
|---|---|---|
| Teeth | 2.00E + 06 | 0.30 |
| Cortical bone | 1.75 E + 06 | 0.30 |
| Cancellous bone | 5.00 E + 05 | 0.30 |
| Periodontal ligament | 4.40 E + 00 | 0.45 |
| Orthodontic mini-implant | 1.10 E + 07 | 0.33 |

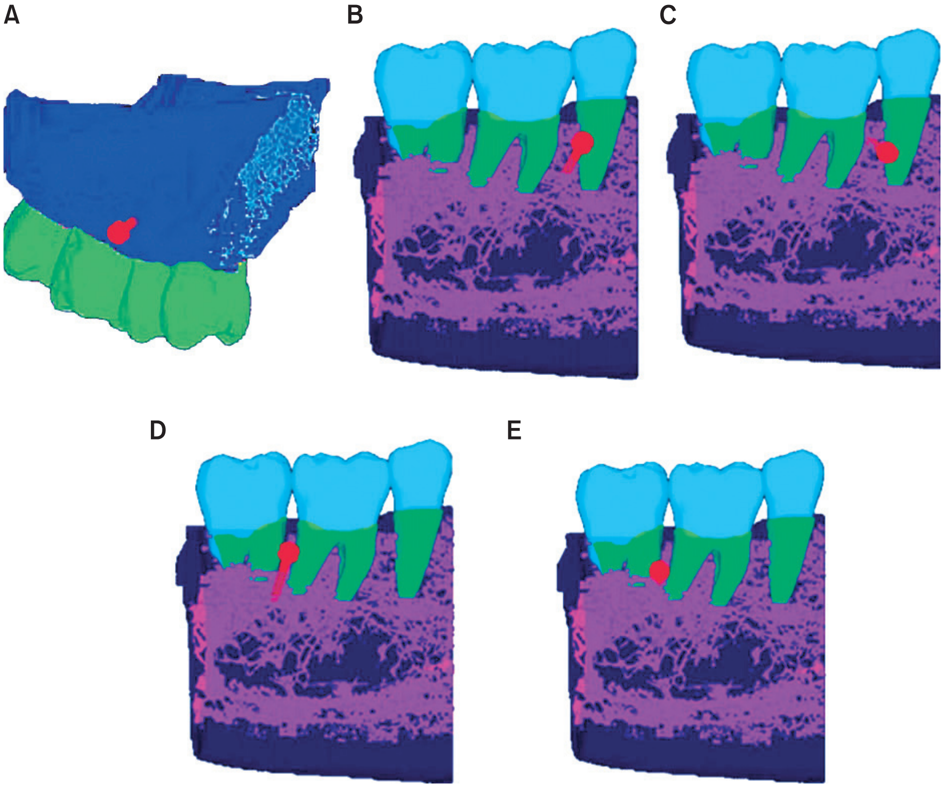

**Figure 1.** The five finite element models. A, Orthodontic mini-implant (OMI) placed between the maxillary second premolar and first molar at 45°; B, OMI placed between the mandibular second premolar and first molar at 45°; C, OMI placed between the mandibular second premolar and first molar at 90°; D, OMI placed between the mandibular first and second molars at 45°; E, OMI placed between the mandibular first and second molars at 90°.

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resolution.

Therefore, we used FE analysis to evaluate the effect of bite force on the stress distribution and displacement of OMIs according to the placement site, insertion angle, and loading direction.

## MATERIALS AND METHODS

The maxillary and mandibular right quadrants of an adult female (aged 28 at the time of death) were obtained from a cadaver at the Department of Anatomy, Ewha Womans University School of Medicine. Quadrants including the second premolar, first molar, and second molar were scanned using a microCT scanner (SKYSCAN 1172®; SkyScan, Kontich, Belgium) at a spatial resolution of 34.6 μm and 963 × 606 pixel matrices. The scanned images were transferred to Bionix Body Builder software (version 3.0; CANTIBio Inc., Suwon, Korea). HyperMesh software (version 8.0; Altair Engineering, Troy, MI, USA) was used to mesh the inside of the 3-dimensional surface with the tetrahedron element, with the options set for normal mesh generation. The dimensions and thread design of the OMIs used were based on the ARC T1207 (2.2 mm in diameter and 7.0 mm in length; BioMaterials Korea Inc., Seoul, Korea), which was assumed to be made of Ti-6Al-4V titanium alloy. The teeth, alveolar bone, periodontal ligament, and implant elements were also assumed to be homogeneous, isotropic, and linearly elastic (Table 1).

Five different FE models were created according to the OMI placement site and insertion angle. In model A, the OMI was placed between the maxillary second premolar and first molar at an angle of 45° to the cortical bone surface. In models B and C, the OMIs were placed between the mandibular second premolar and first molar and inclined at 45° and 90°, respectively. In models D and E, the OMIs were placed between the mandibular first and second molars at angles of 45° and 90°, respectively (Figure 1). Model A was composed of 1,129,504 elements and 5,259,789 nodes (Table 2).

To simulate bite force, a load of 25 kg was applied to the occlusal contact points.[13] Ten occlusal contact points were selected on the second premolar, first molar, and second molar, and 2.5 kg was loaded to each of these points (Figure 2). Forces were applied in 3 directions (0°, 5°, and 10° distal to the long axis of the tooth) to simulate different mandibular plane angles. For the boundary conditions, the bottom edge of the bone segments was fixed in 3 dimensions.

The displacement and Von Mises stress of the OMIs were measured at 8 nodes situated sequentially and numbered from the tip to the head of the OMI (Figure 3). The seventh node from the OMI tip was located at the outer surface of the cortical bone at a similar height in all models. Because occlusogingival movement, in particular, poses clinical problems related to the stability of OMIs, only the amounts of displacement along the occlusogingival axis were evaluated in this study. The Von Mises stress during loading was also measured to analyze the distribution of stress of the OMIs. The displacement and stress distribution of each OMI were analyzed using ANSYS software version 11.0 (ANSYS Inc., Canonsburg, PA, USA) and processed on an HP XW 6400 workstation (Hewlett-Packard Co., Palo Alto, CA, USA).

**Table 2.** The number of nodes and elements used in model A

| Component model | Number of nodes | Number of elements |
|---|---|---|
| Teeth | 425,742 | 1,997,826 |
| Cortical bone | 561,676 | 2,338,812 |
| Cancellous bone | 190,747 | 455,608 |
| Periodontal ligament | 123,580 | 422,641 |
| Orthodontic mini-implant | 10,633 | 44,902 |

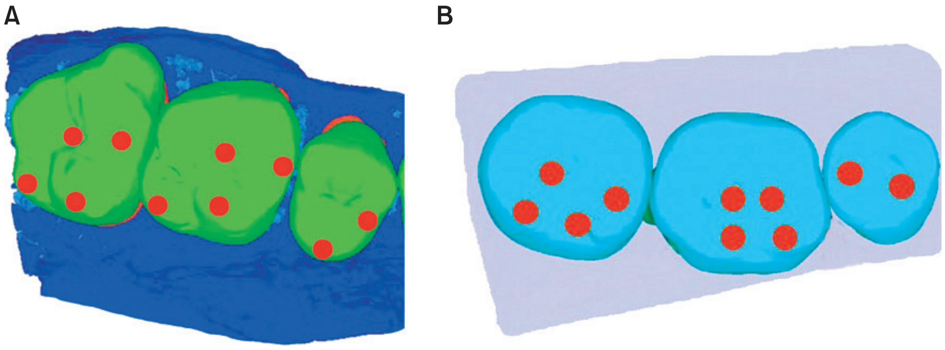

**Figure 2.** The 10 occlusal contact points used in the current study. **A**, Maxilla; **B**, mandible.

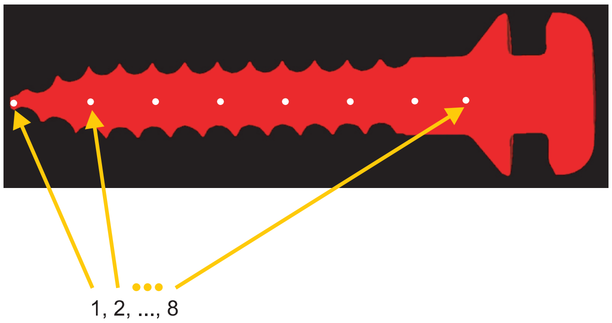

**Figure 3.** The eight reference nodes of the orthodontic mini-implant.

## RESULTS

To evaluate the differences between placement sites, models A, B, and D were compared. In all 3 models, the apices of the OMIs exhibited apical displacement. The head of the OMI showed occlusal movement in model A, while the heads of the OMIs moved apically in models B and D. The displacement and Von Mises stress were highest in model D and lowest in model A (Figure 4).

Of models B, C, D, and E, those with the OMI angled at 45° (B and D) were displaced slightly less than those angled at 90° (C and E). Additionally, while model E exhibited significantly greater stress distribution than model D, when comparing models B and C, slightly greater stress was observed with the OMI placed at 45°.

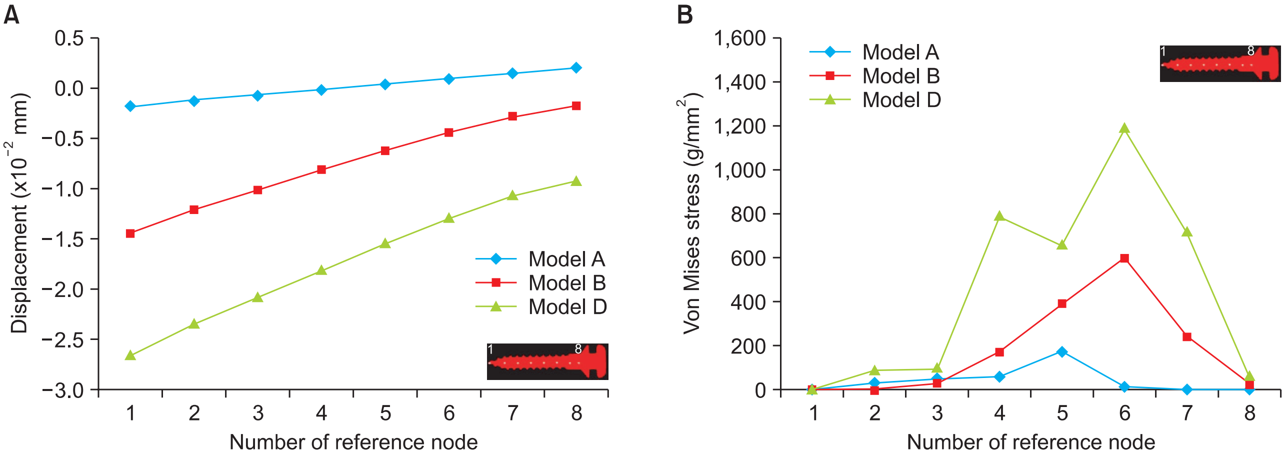

**Figure 4.** Displacements (A) and Von Mises stress distributions (B) of orthodontic mini-implants (OMIs) in models A, B, and D. The X-axis indicates sequential points along the OMI from the tip to the head. A, Positive Y-axis values indicate occlusal movement of the OMI, and negative Y-axis values indicate apical movement.

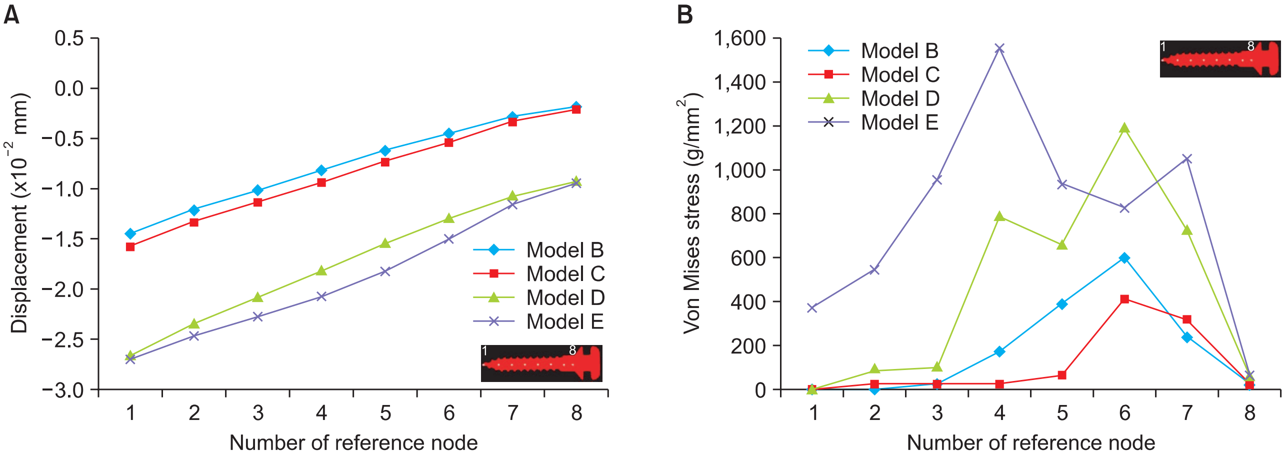

**Figure 5.** Displacements (A) and Von Mises stress distributions (B) of orthodontic mini-implants (OMIs) in models B, C, D, and E. The X-axis indicates sequential points along the OMI from the tip to the head. A, Positive Y-axis values indicate occlusal movements of the OMI, and negative Y-axis values indicate apical movements.

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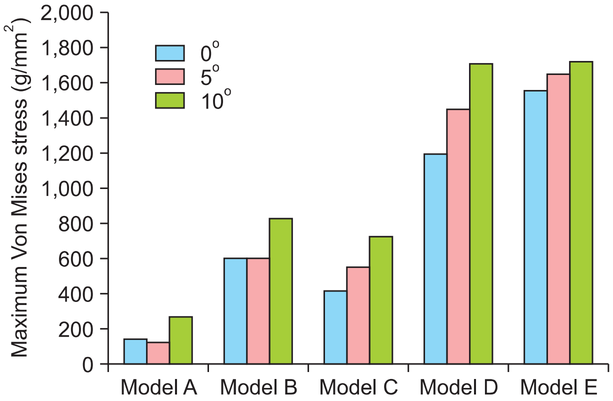

**Figure 6.** Maximum Von Mises stress of the orthodontic mini-implants in the five models according to different loading directions.

The magnitude of the difference in Von Mises stress between OMIs placed at 45° and 90° was relatively smaller in the anterior mandibular molar region (Figure 5).

The maximum Von Mises stresses resulting from different loading directions in all models are shown in Figure 6. The OMI loaded with 0° angulation exhibited lower maximum Von Mises stress than any of the other models, except model A. The maximum stress increased as the loading direction increased in inclination (Figure 6).

## DISCUSSION

The stability of an OMI depends on the absence of mobility in the bone bed after placement.[14,15] Stability is achieved by mechanical interlocking between the OMI surface and bone. However, micromotion of the OMI may result in microfracture, bone resorption, and subsequent formation of a fibrous capsule around the OMI. A lack of proper bone support can eventually result in OMI failure. Many studies have examined factors associated with the stability of skeletal anchorage. However, thus far, relatively few studies have evaluated the relationship between bite force and OMI stability. Thus, the present study assessed the effect of bite force on OMIs, with regard to variations in placement site, insertion angle, and loading direction.

The use of FE analysis in dental biomechanical research has facilitated the analysis of internal stress and strain in the alveolar support structure.[16-18] Since the structure of teeth and bones cannot be simulated via simplified geometric representation, the patient's specific geometry from a CT scan is often used to generate a model of the teeth and bones. MicroCT can generate images of small structures, including those of bone, vessels, and soft tissues, with a resolution higher than that generated by conventional CT. Therefore, microCT-based analysis allows the creation of a much more precise FE model, and was thus used in this study.

To evaluate the effect of bite force on OMIs according to placement site, models A, B, and D were compared. The OMI placed between the mandibular first and second molars (model D) exhibited the highest displacement and stress, while the OMI placed between the maxillary second premolar and first molar (model A) exhibited the least displacement and stress. Farnsworth et al.[19] measured the cortical bone thickness of commonly used maxillary and mandibular OMI placement sites using cone-beam CT images and reported that the average thickness in adults was 1.45 mm at the maxillary buccal 5 - 6 site, 1.91 mm at the mandibular buccal 5 - 6 site, and 2.49 mm at the mandibular buccal 6 - 7 site. Motoyoshi et al.[20] reported higher stress distribution of implants placed where the cortical bone thickness was 2 mm when compared to placement in cortical bone with a thickness of 1 mm. They suggested that the thicker cancellous bone supporting the OMI body absorbed a higher proportion of the load, reducing the load to the thin cortical bone. This phenomenon may be related to the lower success rate of OMIs in the mandible than those placed in the maxilla, and to the relative success of OMIs placed in the posterior mandibular area as compared to those placed in the anterior mandibular area.[4-6]

Many studies have reported that the angle of insertion has a significant impact on the primary stability of OMIs.[21-23] As the insertion angle relative to the bone decreases, the contact area with cortical bone, which is closely associated with mechanical retention, increases. As expected, angled OMIs showed slightly lower displacement than non-angled OMIs in this current study. However, the difference was not statistically significant, and angled OMIs showed higher stress distribution in models B and C (Figure 5). We hypothesize that the additional thickness of the cortical bone could have influenced the placement site-related differences in stress distribution in angled OMIs. While thicker cortical bone may provide more mechanical retention, it may also transfer more stress to the OMI. However, the amount of additional stress imparted by thicker cortical bone may be too small to affect the OMI; this issue thus requires further investigation.

Miyawaki et al.[3] reported that a high mandibular plane angle was a risk factor for OMI mobility. They suggested that the lower success rate in patients with a high mandibular plane angle was due to thinner buccal cortical bone. In the current study, all models had the same cortical bone thickness; only loading conditions were experimentally manipulated. Nevertheless, when more strongly inclined loading was applied, greater stress was observed (Figure 6). Thus, the vector of the bite force could affect the OMIs in long-faced subjects. However, manipulating the force direction alone is not sufficient to accurately simulate the biomechanical influences of different skeletal patterns. Adjustments of the tooth axis, masticatory force, and cortical bone thickness in conjunction with the mandibular plane angle should be considered. In addition, since the human mandible deforms parasagittally and transversely during function, the pattern of mandibular deformation may differ according to skeletal pattern. Therefore, modeling that includes jaw deformation should be investigated in future studies.

Sugiura et al.[24] reported that cortical bone resorption occurred around screws in regions of high compressive stress (exceeding 50 MPa). Meanwhile, Li et al.[25] developed critical stress curves for overload and underload resorption. According to the relevant stress curve, when bone density was 1.8 g/cm$^3$, overload resorption was observed in areas with a Von Mises stress of over 28 MPa. While the stresses observed in the present study did not exceed this critical threshold, stress may increase in the actual oral environment. Maximum bite force varies considerably depending on skeletal pattern. Moreover, due to the comparatively greater deformation in the more posterior areas of the mandibular arch,[26-28] the strain and stress in the more posterior mandibular areas may be higher than the results predicted in the present study.

FE analysis only calculates initial-moment differences and does not assess long-term reactions or effects;[29] in reality, mastication occurs intermittently and repetitively. Furthermore, evaluating orthodontic forces was not within the scope of the present study. Rather, the focus of this study was on the initial stability of OMIs. Therefore, to fully elucidate the effects of bite force on the stability of OMIs, further studies incorporating fatigue tests, different bite forces, and orthodontic traction forces should be conducted.

## CONCLUSION

Placing OMIs in an angulation and more anteriorly may be optimal for reducing the effects of bite force on mandibular OMIs, particularly in subjects with a high mandibular plane angle. This may help to increase the stability of OMIs.

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