Effect of the alveolar bone level and inclination of the tooth on periodontal stress for a maxillary central incisor

: Finite element analysis

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The Master's Thesis
Submitted to the Department of Dental Science
and the Graduate School of Yonsei University
in partial fulfillment of the
requirements for the degree of
Master of Dental Science

Younghoon Kim

June 2013

This certifies that the dissertation thesis of

Younghoon Kim is approved.

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The Graduate School
Yonsei University
June 2013

감사의 글

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연구의 진행을 위하여 많은 도움을 준 강다영 선생님과 후배 이미림, 류제성에게 깊은 감사의 마음을 전합니다. 또한 수련 생활에 큰 힘이 되어준 의국 동기들(고재민, 김성아, 배미주, 장지성, 정서연)에게도 감사의 마음을 전합니다.

항상 변함없는 사랑으로 저를 믿고 훌륭하게 길러주신 부모님과 한결 같은 믿음으로 응원해주시는 장인,장모님, 그리고 사랑하는 형님과 형수님에게도 이 자리를 빌어 깊은 감사의 마음을 전합니다.

마지막으로 늘 곁에서 힘이 되어주는 사랑하는 아내에게 고마운 마음을 전합니다.

2013년 6 월 저자 씀

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ABSTRACT

Effect of the alveolar bone level and inclination of the tooth on periodontal stress for a maxillary central incisor

: Finite element analysis

With increasing number of adult orthodontic patients, it has become necessary to understand movement of the tooth with alveolar bone loss. Numerous finite element analysis(FEA) studies have been conducted to analyze type of movement and stress patterns in orthodontic tooth movement. The purpose of this study was to determine the effect of alveolar bone loss together with inclination of the tooth on the magnitude and distribution of stresses within the PDL for a maxillary central incisor when controlled tipping was simulated with FEA.

Stress in the PDL and type of tooth movement were investigated using finite element analysis program. 20 three-dimensional models were created, representing a maxillary central incisor with facial inclination and alveolar bone loss. Each of the 20 models were subjected to three loads on the crown to simulate controlled tipping movement with varying M/f ratio from 0 to 10.

M/F ratio for controlled tipping(M/F_{cont}) at each alveolar bone level and incisor inclination was investigated. As incisor is more inclined, M/F_{cont} becomes smaller, while alveolar bone loss resulted in increased M/F_{cont} .

As more bone loss occurs the displacement of the apex($\varDelta$) becomes larger under the same inclination and M/F ratio, The variation of $\varDelta$ between each level of bone loss becomes smaller as M/F ratio get closer to the M/F_{cont} under the same inclination.

M/F ratio for uncontrolled tipping or root movement caused larger principal stress than M/F_{cont}. Also the variation of the stress value between each level of bone loss becomes larger when M/F ratio gets closer to 0 or 10. With more alveolar bone loss, the stress changes more sharply as M/F ratio varies under the same inclination.

When M/F ratio varies near the M/F_{cont}, compressive stresses dominate in the labial apical region(M/F below M/F_{cont})move to palatal apical area(M/F over the M/F_{cont}). Meanwhile, tensile stresses dominate in the labial area(M/F below M/F_{cont}) move from the cervical to midroot(M/F over the M/F_{cont}). These patterns were the similar for all the experimental conditions.

The results of this study will be the basis of further research examining the stress distribution process of PDL after orthodontic loading. When bone loss increases the displacement of the apex and maximum compressive and tensile stresses also increased. Also $\varDelta$ and stresses changed more sharply when M/F ratio varies. Which means inadequate force system causes larger displacement of apex and higher stress at the apical area in patients with alveolar bone loss and facial inclination of the incisor.

Key words: Finite element analysis, stress, alveolar bone loss, pathologic tooth migration, maxillary incisor

Effect of the alveolar bone level and inclination of the tooth on periodontal stress for a maxillary central incisor

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I. Introduction

Orthodontic treatment is no longer a contraindication to the patient with periodontal disease or to the maintenance of a healthy periodontal tissue(Re et al., 2000). Previous experimental and clinical studies have shown that a vertical alveolar bone loss is not a contraindication for orthodontic tooth movement(Lindskog-Stokland et al., 1993; Thilander, 1996). If periodontal disease is controlled, tooth movements in patients with alveolar bone loss occur under the same biological mechanism as in patients with normal periodontal support (Boyd et al., 1989).

Pathologic tooth migration (PTM) is a common complication of moderate to severe periodontitis and is often the motivation for patients to seek periodontal and orthodontic therapy. Periodontal bone loss appears to be a major factor in the etiology of PTM. Soft tissue forces of the tongue, cheeks, and lips are known to cause tooth movement and in some situations can cause PTM. Also considered important in the etiology of PTM is pressure produced from inflammatory tissues within periodontal pockets(Brunsvold, 2005). According to recent study, facial flaring was the most common type of pathologic migration in anterior tooth(Towfighi et al., 1997).

Orthodontic tooth movement is result of the reaction of the surrounding bone and periodontal ligament (PDL) to a mechanical stimulus(Atmaram and Mohammed, 1981; Melsen, 2001).After an orthodontic loading, a change in the strain-stress distribution in the periodontal ligament (PDL) and the surrounding alveolar bone occur(Cattaneo et al., 2008). Magnitude and direction of orthodontic loads determine the reaction of tissue as bone formation, bone resorption, and iatrogenic external apical root resorption (EARR)(Brezniak and Wasserstein, 2002a, 2002b). Recent studies using 3D imaging technology have suggested that higher forces or high PDL stress lead to more EARR(Cheng et al., 2009; Viecilli et al., 2007; Viecilli et al., 2008). Also analysis of recent data has related EARR to maximum absolute compressive stress in the PDL, providing the first translatable statistical estimations of stress- relationships(Viecilli et al., 2009).

There are several methods to analyze displacement and stress distribution of the tooth including strain gauge technique, photo elastic analysis and finite element analysis. As precise level of stress can not be determined with strain gauge technique and photo elastic analysis(Min, 1998), the finite element analysis (FEA) has proved to be a valid and reliable technique for the calculation of the local state of deformation and loading of complex structures(Cattaneo et al., 2005). In orthodontics, FEA has been used successfully to model the application of forces to single-tooth systems. Alveolar bone loss was shown to lower the center of resistance of the tooth and alter the stress patterns on the root in upright position(Cobo et al., 1996; Geramy, 2002; Tanne et al., 1987). Some studies showed that stresses are different according to loading condition. Stresses at the root apex are higher and distributed differently during intrusion compared with other movements, including extrusion(Rudolph et al., 2001; Shaw et al., 2004; Viecilli et al., 2008). With bodily movement, stress was distributed throughout the length of the tooth, but it was more concentrated at the alveolar crest(Rudolph et al., 2001). Previous studies found higher stresses in other areas than the apical region for teeth in an upright position, with the forces applied perpendicular to the occlusal plane(Bourauel et al., 1999; Cattaneo et al., 2005, 2008).One study showed that there are more compressive stresses concentrated at the apex of incisors with a high degree of inclination than in incisors that are more upright(Kanjanaouthai et al., 2012).

Some authors investigated stress distribution and movement pattern of teeth with different alveolar bone level in upright position(Cobo et al., 1996; Cobo et al., 1993; Geramy, 2000, 2002). However, in clinical situation upper central incisors are approximately 60° inclined to the occlusal plane(Bennett J, 2001). Moreover, the anterior tooth are often more proclined by PTM in adult patients with alveolar bone loss (Towfighi et al., 1997)and the force vector is rarely perpendicular to the long axis of an incisor.

The purpose of this study was therefore to determine the effect of alveolar bone loss together with inclination of the tooth on the magnitude and distribution of stresses within the PDL for a maxillary central incisor when controlled tipping was simulated with FEA.

II. Materials and methods

A. Construction of finite element models

Stress in the PDL and type of tooth movement were investigated using finite element analysis program(ANSYS Ver. 12.1, Swanson Analysis System, Canonburg, PA). 20 three-dimensional models were created, representing a maxillary central incisor with facial inclination and alveolar bone loss.

Tooth morphology was based on the 3D scanning of dental model produced by the sample survey of adults with normal occlusion(Model-i21D-400G, Nissin Dental Products, Kyoto, Japan). Bracket was modeled referring to micro-arch®(Tomy Co, Tokyo, Japan). The width of the periodontal ligament was 0.25mm and even around the root surface(Coolidge, 1937; Richardson, 1967). The morphology of the alveolar bone were modeled 1mm above cementoenamel junction (CEJ)following curvature of the CEJ in case of normal bone level(bone loss =0)(Fig 1.).

Tooth length, measured from incisal edge to root apex, was 24.2mm; The crown was 11mm from incisal edge to labial CEJ and the root 13.2mm. The middle of bracket slot was 4.5mm from incisal edge. Mesiodistal width of the bracket was 3.6mm and the bracket height was 1.5mm. Average alveolar bond thickness on the labial and lingual sides was determined from 3D scanning of the same dental model (Fig. 1.).

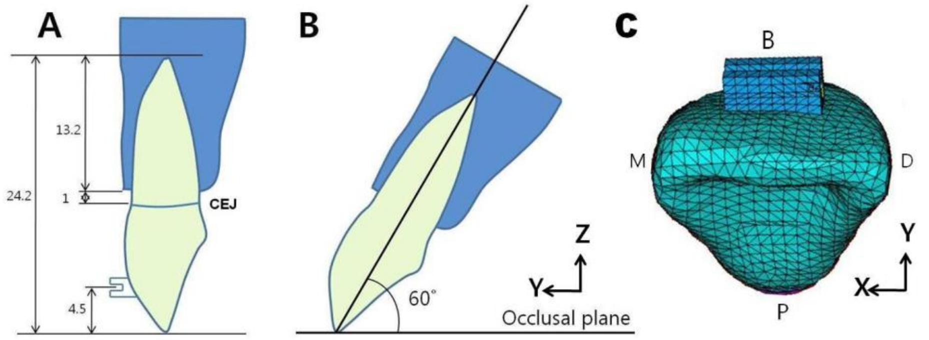


Fig. 1. Modeling of the incisor.

A: Tooth length and bracket position(mm)

B: Normal inclination of the incisor,60 ˚ to occlusal plane

C: Incisal view, M(mesial), D(distal), B(buccal), P(palatal)

Normal axis of the incisor was designed to be 60 ˚ inclined from the occlusal plane (Bennett J, 2001).The long axis of each incisor model was 0,5,10,15,20 degree inclined facially from the line of normal axis of incisor model. Also each model has 0,2,4,6mm of alveolar bone loss(Fig 2.).

Alveolar bone loss were assumed to be even in bucco-lingual and mesio-distal direction. In 2mm loss model, alveolar bone was 3 mm above CEJ, 4mm loss model was 5mm, 6mm loss model was 7mm respectively. Each of 20 models consisted of an incisor, PDL, and alveolar bone and subdivided into elements and nodes. A 3D brick tetrahedral element was chosen to construct the models(Fig 2.).

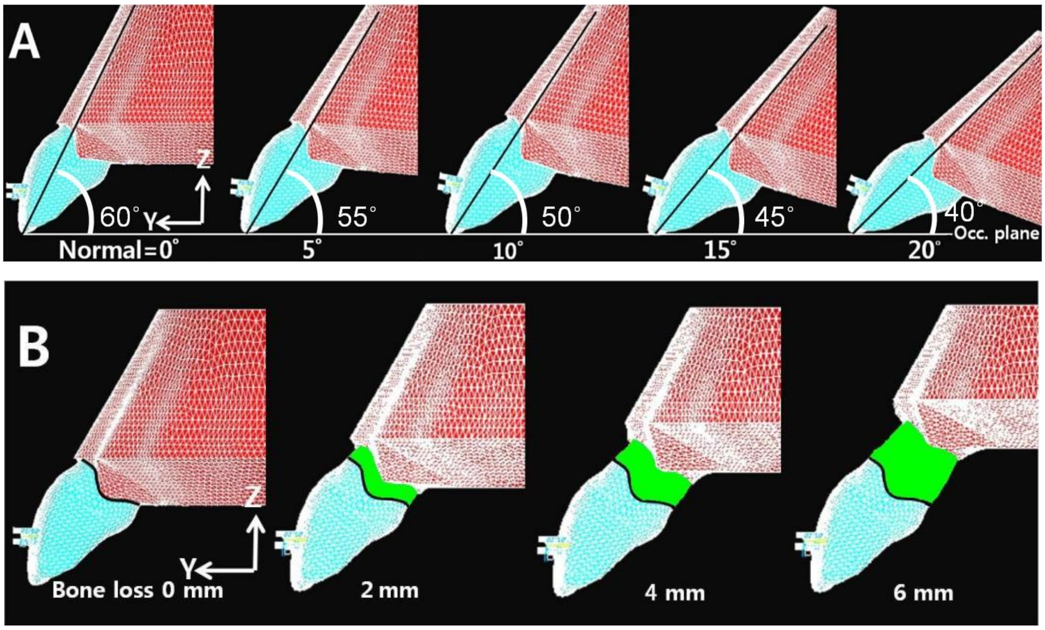


Fig. 2. Modeling of incisor with different axis and alveolar bone level. Total 20 models for each inclination and bone loss were created.

A: The long axis of each incisor model was 0,5,10,15,20 ° inclined facially from the line of normal axis of incisor model. Normal axis of the incisor was 60 ° inclined from the occlusal plane.

B : Each model has 0,2,4,6mm of alveolar bone loss, indicated with green color.

B. Mechanical properties of the materials

All materials were assumed to be homogeneous, isotropic, and linear-elastic. Applied properties for the each material were listed on Table1. These properties were selected from other studies(Cattaneo et al., 2005; Cobo et al., 1996; Cobo et al., 1993; Kanjanaouthai et al., 2012; Middleton et al., 1996).

Table 1. Mechanical properties of each material

	Young' s modulus(MPa)	Poisson' s ratio
Periodontal ligament	5.0E−02	0.49
Alveolar bone	2.0E+03	0.30
Teeth	2.0E+04	0.30
Stainless steel	2.0E+05	0.30

C. Loading conditions and boundary conditions

Each of the 20 models were subjected to three loads on the crown (Fig.3.).

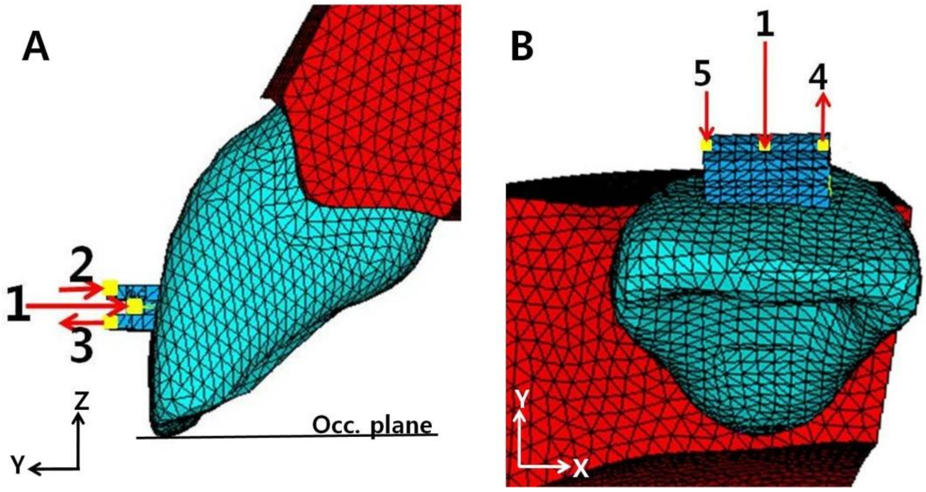


Fig. 3. Loading conditions.

A : 1−Retraction force(100gf) parallel to occlusal plane, 4.5mm apical from incisal edge at the midpoint of medisodistal width of the bracket.;

2,3−Force for counter tipping moment(M_t).

B : 4,5− Force for counter rotation moment(M_r).

1. Retraction force (F) of 100gf, placed at the midpoint of medisodistal width of the bracket, 4.5 mm apical to the incisal edge, parallel to the occlusal plane.
2. Counter tipping moment(M_t) caused labial crown movement. M_t was created by applying couple force(Fig. 3.). The length of moment arm was 1.5mm. The M_t/F ratio was varied from 0 to 10.
3. Counter rotation moment(M_r) that resulted in distolingual rotation counteracted the confounding moment generated by asymmetric form of the incisor. M_r was created by applying couple force(Fig. 3.). M_r was calculated to make the mesial and distal ends of incisal edge move an equal distance in the same direction. The length of moment arm was 3.6mm.

As a boundary condition, all nodes of the base of the model(bone) was fixed in all direction to constrain free body motion.

D. Calculation of Mt/F ratio for controlled tipping(M_t/F_{cont})

M_t/F ratio which created controlled tipping was calculated for the each 20 model respectively. Controlled tipping was assumed to happen when nodes at the apex moved to a minimum value by summing up the displacement in 3 dimension. The initial displacement of the apex in 3-dimension ($\varDelta = \sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}$)was calculated(Fig 4.). To investigate M_t/F ratio for controlled tipping(M_t/F_{cont}), M_t/F ratio for the smallest displacement was chosen.

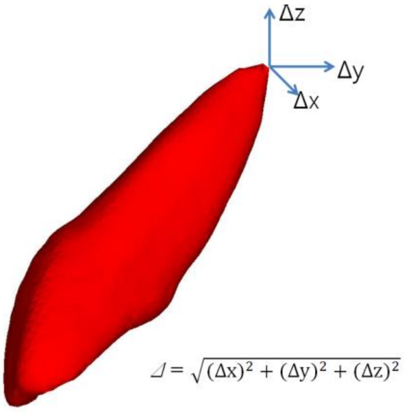


Fig. 4. Calculation of 3 dimensional displacement of the apex.

⊿ = $\sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}$

E. Analysis of stress distribution

The stress level of within the PDL was calculated in terms of principal stresses. The principal stresses can be found by asking whether or not there are planes on which the traction vector is purely normal, with no shear component.

In a three−dimensional stress field, there are three principal stress components, ranked in descending order. From all principal stresses calculated in the entire PDL, the maximum value of the first principal stress(S1, maximum tensile stress) and the minimum value of the third principal stress(S3, maximum compressive stress) were recorded for each model and each M/F ratio. In this study, these were named the maximum tensile stress and the maximum compressive stress, respectively.

III. Results

A. The relationship between the M_t/F ratio and the displacement of the apex

For each inclination and bone loss, the relationship between the M_t/F ratio and the displacement of the apex(Δ)was plotted in Fig. 5. To calculate M_t/F_{cont}, M_t/F for the smallest displacement was selected(Table 2.). As more bone loss occurs Δ becomes larger under the same M_t/F and inclination. The difference of Δ between each bone level becomes smaller as M_t/F get closer to M_t/F_{cont}(Fig. 6.). With more inclination of the incisor, M_t/F_{cont} becomes smaller (Fig. 7.).

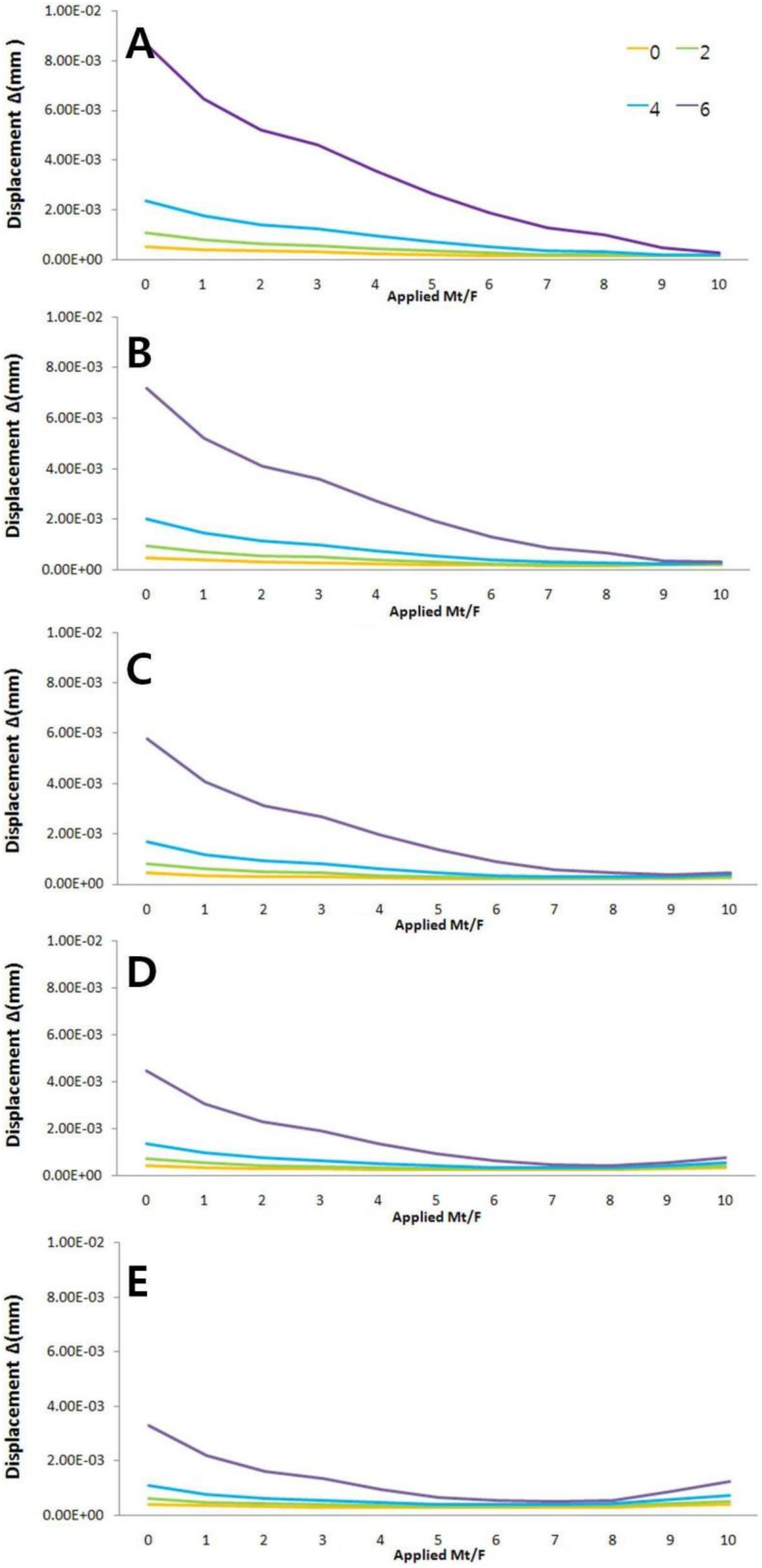

A
B
C
D
E
Displacement Δ(mm)
Displacement Δ(mm)
1.00E-02
8.00E-03
6.00E-03
4.00E-03
2.00E-03
0.00E+00
0
1
2
3
4
5
6
7
8
9
10
Applied Mt/F
0
2
4
6

Fig. 5.The relationship between the M_t/F ratio and the displacement(⊿) of the apex for alveolar bone loss 0,2,4,6mm and inclination of 0,5,10,15,20˚. To calculate M_t/F ratio for controlled tipping(M_t/F_{cont}), M_t/F for the smallest displacement was selected. A : facial inclination 0˚; B : facial inclination 5˚; C : facial inclination 10˚; D : facial inclination 15˚; E : facial inclination 20˚.

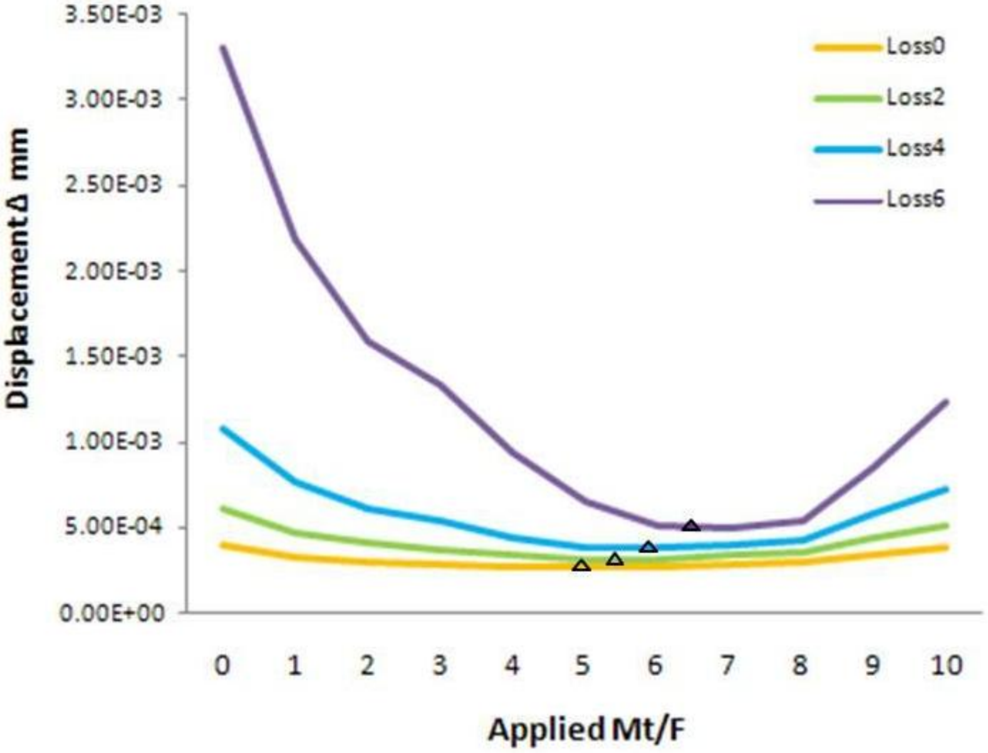


Fig. 6. The relationship between the M_t/F ratio and the displacement(⊿) with inclination of 20˚. The smallest displacement and M_t/F_{cont} were presented with triangular point on the graph. The variation of ⊿ between each bone level becomes smaller as M_t/F get closer to M_t/F_{cont}.

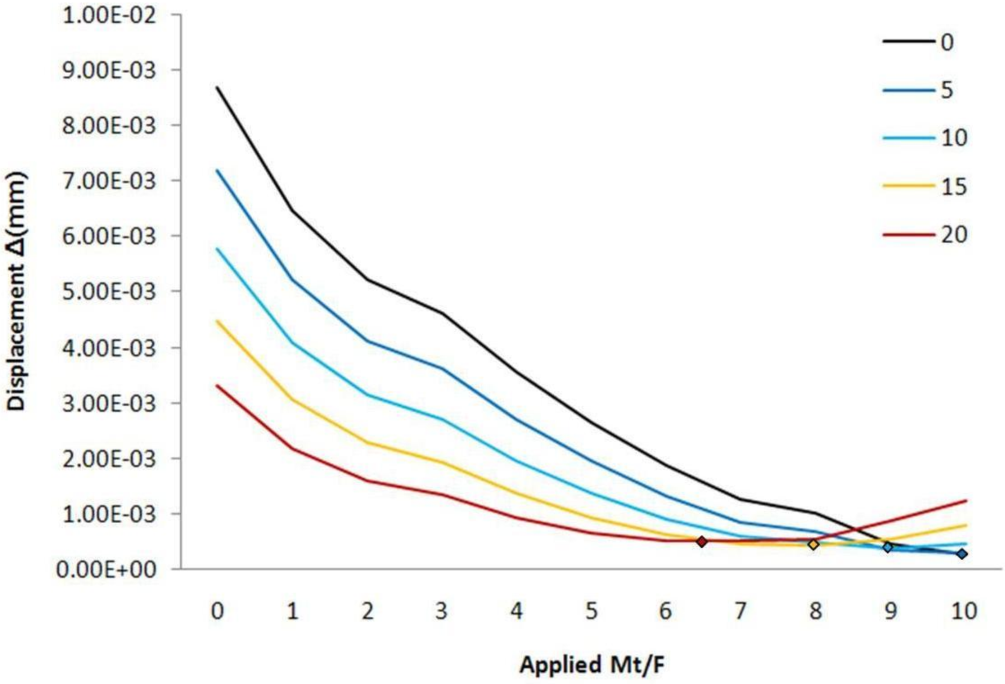


Fig. 7. The relationship between ⊿ and applied M_t/F ratio under the same alveolar bone loss(6mm) with various inclination(0,5,10,15,20 °). The smallest ⊿ for each inclination were represented with the rhombic point on the graph. As the incisor inclined more facially, M_t/F ratio for smallest ⊿(M_t/F_{cont}) becomes smaller. Note that M_t/F_{cont} for 0 ° was 11.0 , which is not represented on the graph.

B. M_t/F ratio for controlled tipping (M_t/F_{cont}) of the incisor

M_t/F_{cont} at each bone level and inclination were plotted in Fig 8. As incisor is more inclined facially, M_t/F_{cont} becomes smaller, while alveolar bone loss resulted in increased M_t/F_{cont} (Fig. 8.). For the incisor with aloveolar bone loss 0 and inclination 0 ˚, the M_t/F_{cont} was 8.5. For the incisor with bone loss 6 and inclination 20 ˚, M_t/F_{cont} was 6.5 (Table 2.).

Table 2. Mt/F for the smallest displacement of the apex.

Bone loss(mm)	Facial inclination of the incisor				
	0 ˚	5 ˚	10 ˚	15 ˚	20 ˚
0	8.5	8.0	7.0	6.0	5.0
2	9.0	8.5	7.5	6.5	5.5
4	9.5	9.0	8.0	7.0	6.0
6	11.0	10.0	9.0	8.0	6.5

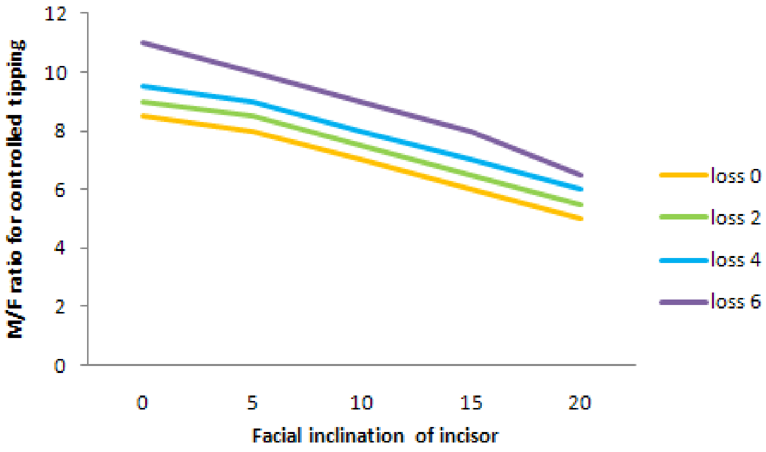


Fig. 8. M_t/F ratio for controlled tipping (M_t/F_{cont}). As incisor is more proclined, M_t/F_{cont} becomes smaller, while alveolar bone loss resulted in increased M_t/F_{cont} under the same incisor inclination.

C. The relationship between the M_t/F ratio and the principal stress

For each inclination and bone loss, the relationship between the M_t/F ratio and the principal stress (S1:Maximum tensile stress, S3:Maximum compressive stress) was plotted in Fig. 9.

Varying M_t/F ratio from M_t/F_{cont} towards 0 or 10, the maximum compressive stress becomes larger. With more alveolar bone loss, the stress changes more sharply when M_t/F ratio varies. Also the variation of the stress value between various bone levels becomes larger when M_t/F gets closer to 0 or 10 (Fig. 10.). As the incisor inclines more facially at the same alveolar bone loss level, M_t/F ratio for lowest principal stress gets smaller (Fig. 11.).

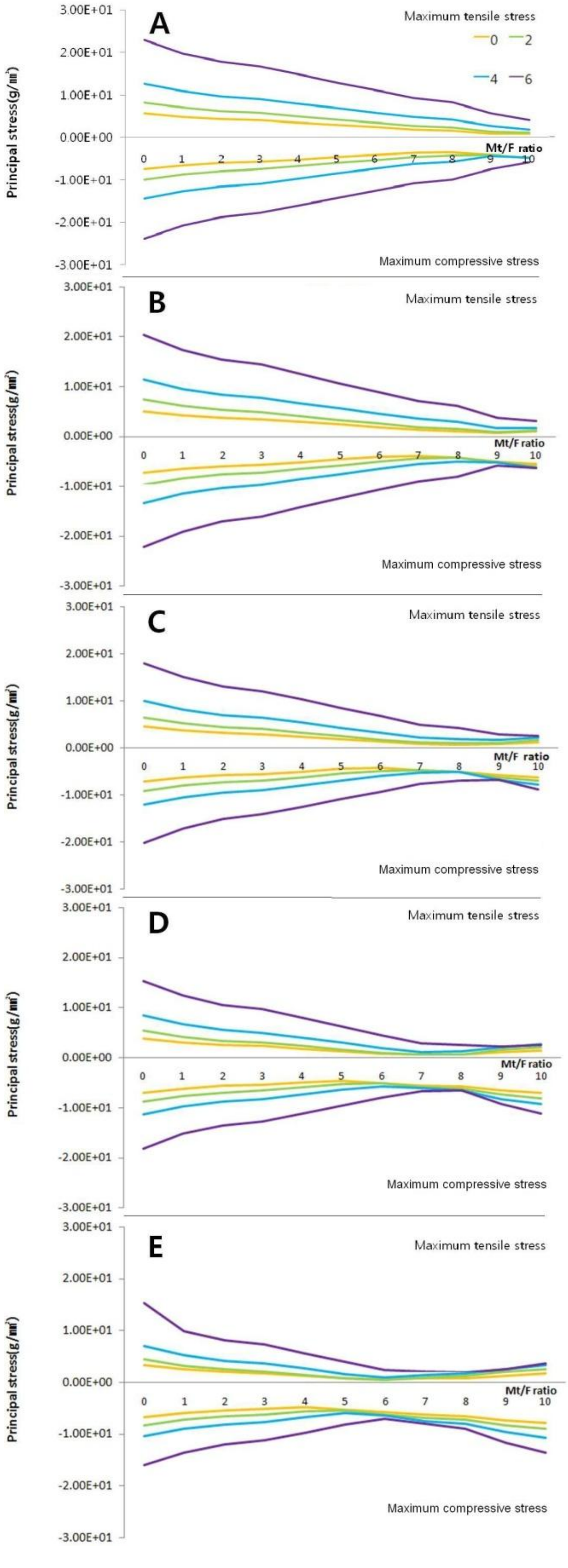

A
B
C
D
E
Principal stress(g/㎟)
3.00E+01
2.00E+01
1.00E+01
0.00E+00
-1.00E+01
-2.00E+01
-3.00E+01
Maximum tensile stress
Maximum compressive stress
Mt/F ratio
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6

Fig. 9. Relationship between the M_t/F ratio and the principal stress with alveolar bone loss level 0,2,4,6 mm.

With more alveolar bone loss, the stress changes more sharply. As the incisor inclines more facially at the same alveolar bone loss, M_t/F ratio for lowest stress becomes smaller. A : facial inclination 0 ° ; B : facial inclination 5 ° ; C : facial inclination 10 ° ; D : facial inclination 15 ° ; E : facial inclination 20 °

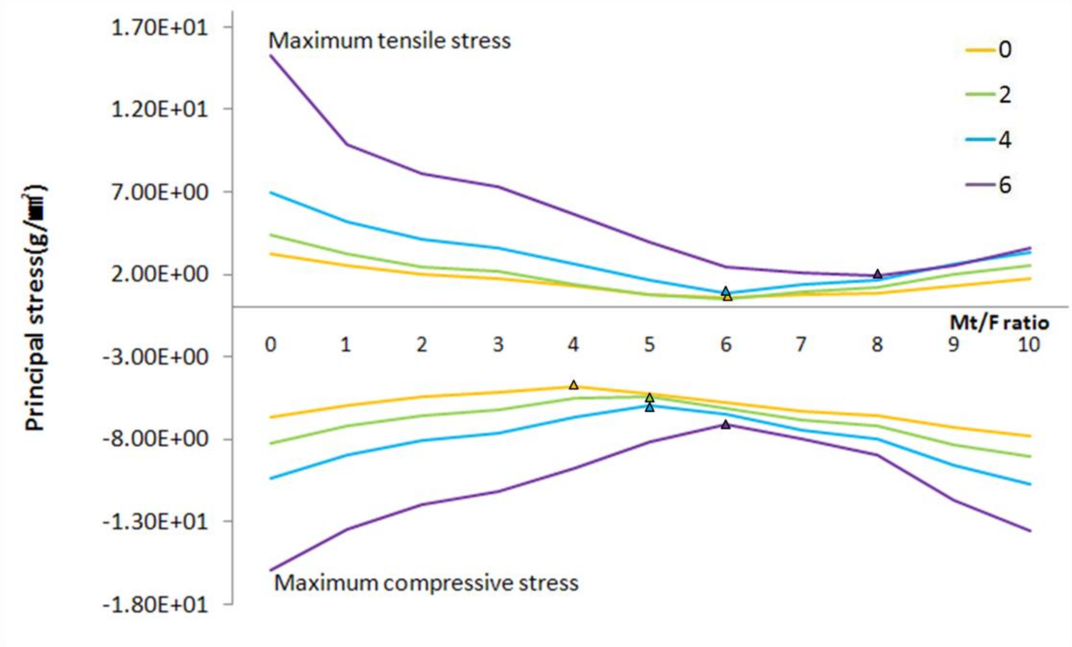


Fig. 10. Relationship between the M_t/F ratio and the principal stress with 20 ° inclination. The lowest stress was presented with triangular point on the graph. With more alveolar bone loss, the stress changes more sharply when M_t/F ratio varies. Also the variation of the stress value between various bone levels becomes larger when M_t/F gets closer to 0 or 10 .

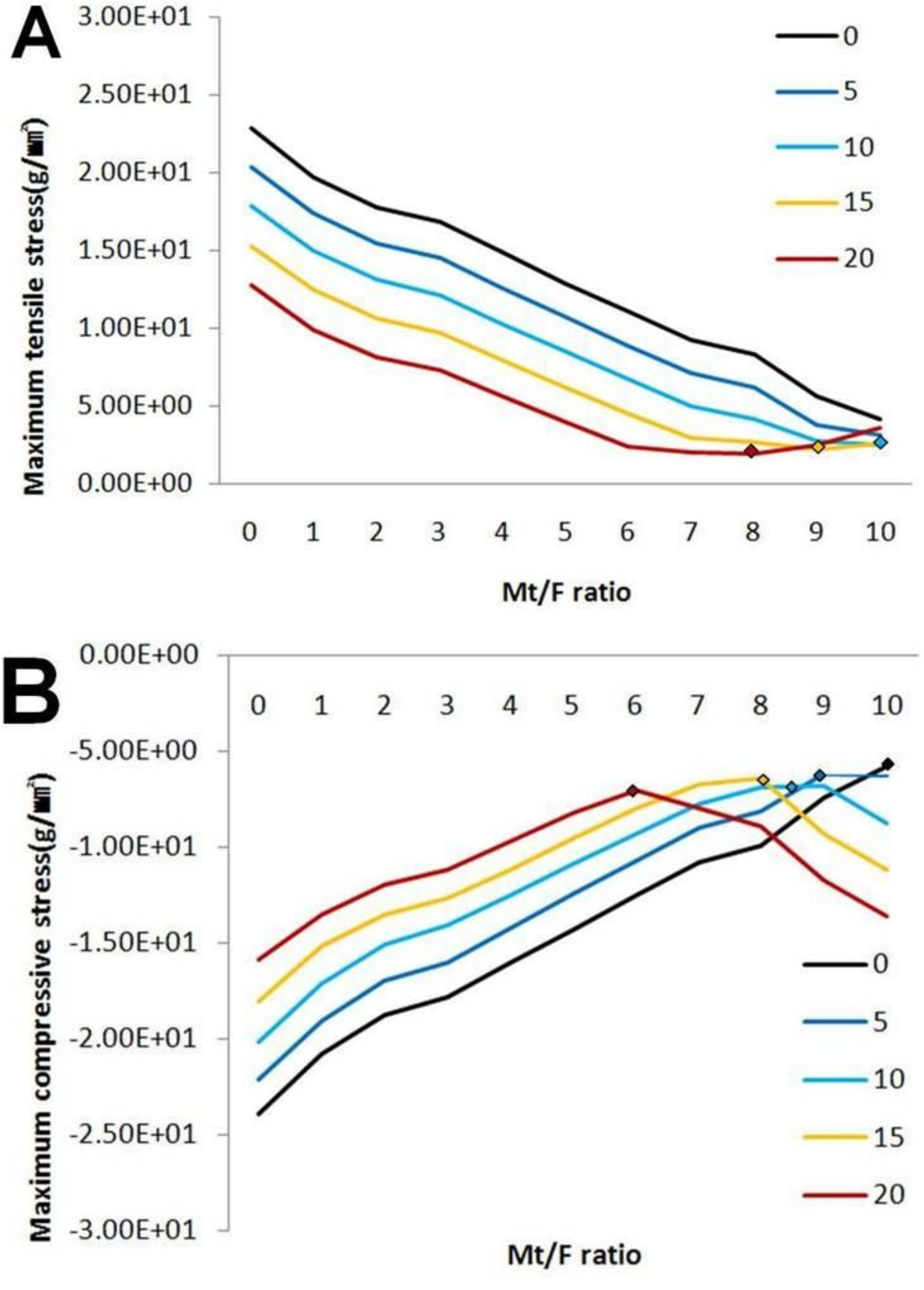

A
Maximum tensile stress(g/㎟)
3.00E+01
2.50E+01
2.00E+01
1.50E+01
1.00E+01
5.00E+00
0.00E+00
0
1
2
3
4
5
6
7
8
9
10
Mt/F ratio
0
5
10
15
20
B
Maximum compressive stress(g/㎟)
0.00E+00
-5.00E+00
-1.00E+01
-1.50E+01
-2.00E+01
-2.50E+01
-3.00E+01
0
1
2
3
4
5
6
7
8
9
10
Mt/F ratio
0
5
10
15
20

Fig. 11. Relationship between the M_t/F ratio and the principal stress under the same alveolar bone loss(6mm) with various inclination of the incisor(0,5,10,15,20°) The smallest stresses were represented with the rhombic point on the graph. As the incisor inclines more facially at the same alveolar bone loss level, M_t/F ratio for lowest principal stress gets smaller.

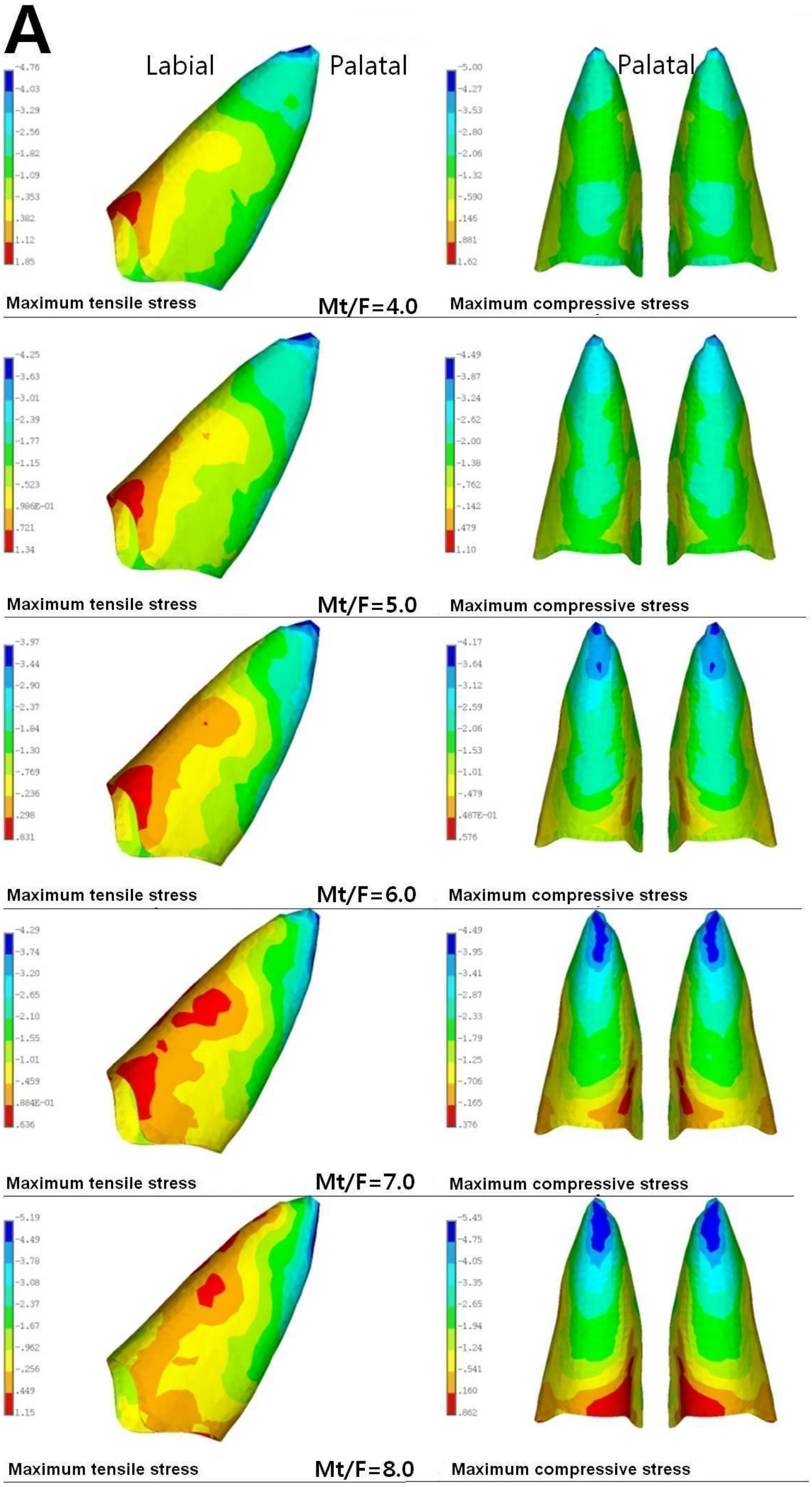
A : Maximum tensile stress

B : Maximum compressive stress.

Note that the smallest stress for 0 and 5° were not represented on the graph because they occur at M_t/F ratio larger than 10.

D. Stress distribution patterns with M_t/F

Fig. 12 shows stress distribution patterns with M_t/F near the M_t/F_{cont} according to a linear color scale(positive is tensile, negative is compressive). With increasing M_t/F ratio around the M_t/F_{cont}, compressive stresses that dominate in the labial apical region(M/F below the M/F_{cont}) move to palatal apical area(M/F over the M/F_{cont}). Meanwhile, tensile stresses dominate in the labial area(M/F below the M/F_{cont}) move from the cervical to midroot(M/F over the M/F_{cont}). These patterns were similar for all the experimental conditions.


A
Labial
Palatal
Palatal
-4.76
-4.03
-3.29
-2.56
-1.82
-1.09
-.353
.382
1.12
1.85
-5.00
-4.27
-3.53
-2.80
-2.06
-1.32
-.590
.146
.881
1.62
Maximum tensile stress
Mt/F=4.0
Maximum compressive stress
-4.25
-3.63
-3.01
-2.39
-1.77
-1.15
-.523
.986E-01
.721
1.34
-4.49
-3.87
-3.24
-2.62
-2.00
-1.38
-.762
-.142
.479
1.10
Maximum tensile stress
Mt/F=5.0
Maximum compressive stress
-3.97
-3.44
-2.90
-2.37
-1.84
-1.30
-.769
-.236
.298
.831
-4.17
-3.64
-3.12
-2.59
-2.06
-1.53
-1.01
-.479
.487E-01
.576
Maximum tensile stress
Mt/F=6.0
Maximum compressive stress
-4.29
-3.74
-3.20
-2.65
-2.10
-1.55
-1.01
-.459
.884E-01
.636
-4.49
-3.95
-3.41
-2.87
-2.33
-1.79
-1.25
-.706
-.165
.376
Maximum tensile stress
Mt/F=7.0
Maximum compressive stress
-5.19
-4.49
-3.78
-3.08
-2.37
-1.67
-.962
-.256
.449
1.15
-5.45
-4.75
-4.05
-3.35
-2.65
-1.94
-1.24
-.541
.160
.862
Maximum tensile stress
Mt/F=8.0
Maximum compressive stress

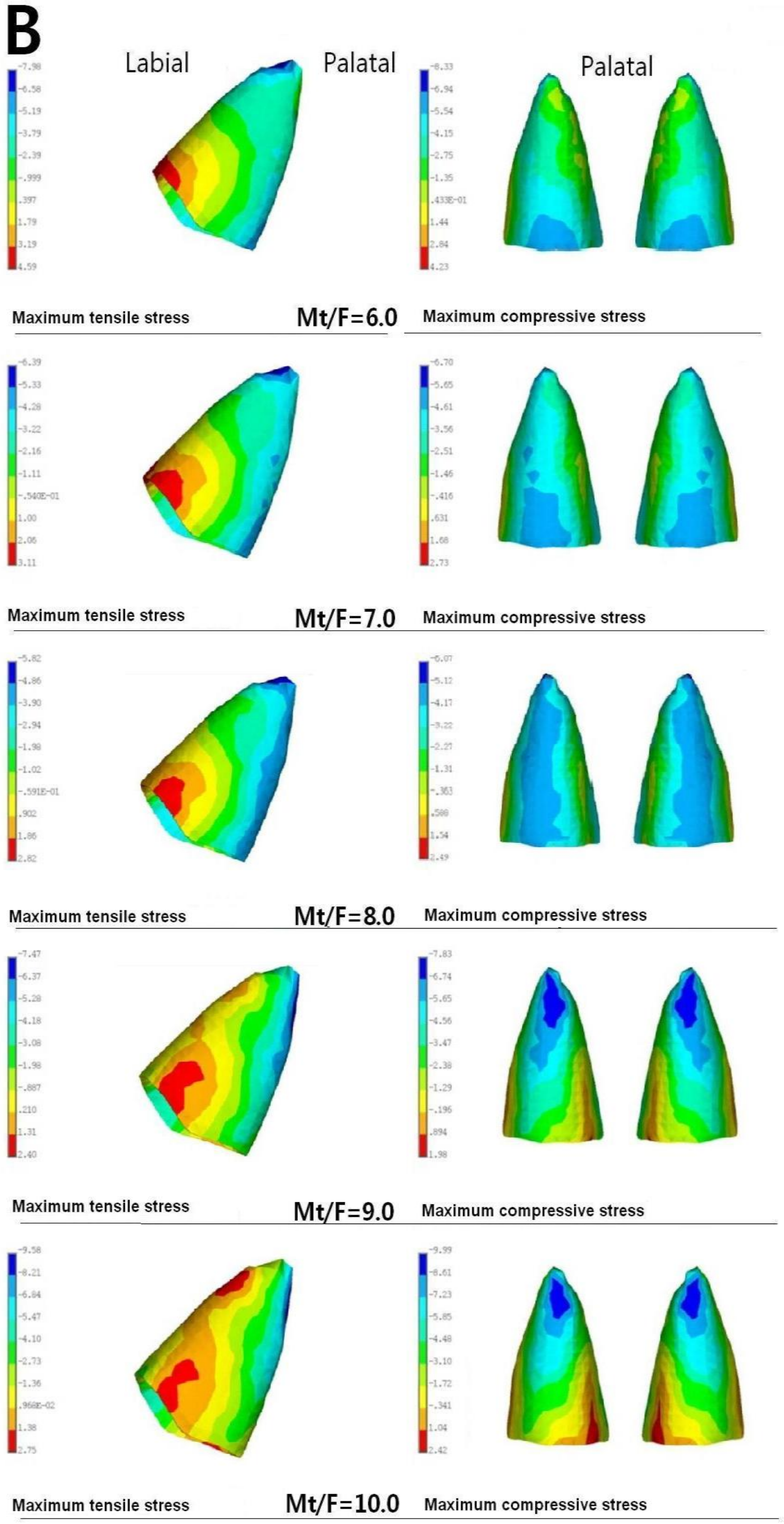
B
Labial
Palatal
Palatal
-7.98
-6.58
-5.19
-3.79
-2.39
-.999
.397
1.79
3.19
4.59
-8.33
-6.94
-5.54
-4.15
-2.75
-1.35
.433E-01
1.44
2.84
4.23
Maximum tensile stress
Mt/F=6.0
Maximum compressive stress
-6.39
-5.33
-4.28
-3.22
-2.16
-1.11
-.540E-01
1.00
2.06
3.11
-6.70
-5.65
-4.61
-3.56
-2.51
-1.46
-.416
.631
1.68
2.73
Maximum tensile stress
Mt/F=7.0
Maximum compressive stress
-5.82
-4.86
-3.90
-2.94
-1.98
-1.02
-.591E-01
.902
1.86
2.82
-6.07
-5.12
-4.17
-3.22
-2.27
-1.31
-.363
.588
1.54
2.49
Maximum tensile stress
Mt/F=8.0
Maximum compressive stress
-7.47
-6.37
-5.28
-4.18
-3.08
-1.98
-.887
.210
1.31
2.40
-7.83
-6.74
-5.65
-4.56
-3.47
-2.38
-1.29
-.196
.894
1.98
Maximum tensile stress
Mt/F=9.0
Maximum compressive stress
-9.58
-8.21
-6.84
-5.47
-4.10
-2.73
-1.36
.968E-02
1.38
2.75
-9.99
-8.61
-7.23
-5.85
-4.48
-3.10
-1.72
-.341
1.04
2.42
Maximum tensile stress
Mt/F=10.0
Maximum compressive stress

Fig. 12. Stress distribution patterns with M_t/F near the M_t/F_{cont} according to a linear color scale(positive is tensile, negative is compressive). Maximum tensile stress and Maximum compressive stress were plotted with M_t/F.

Note that compressive stress is distributed in apical area while tensile stress in cervical or mid root area.

A: alveolar bone loss 0mm, incisor inclination 15°, Controlled tipping occurs when $M_t/F = 6$.

B : alveolar bone loss 6mm, incisor inclination 15°, Controlled tipping occurs when $M_t/F = 8$.

IV. Discussion

The maxillary central incisor was chosen because it undergoes the most detailed tooth movement and is at higher risk for root resorption than all other teeth except the maxillary lateral incisor(Sameshima and Sinclair, 2001).

There are many studies investigated stress distribution according to orthodontic loading, but they dealt with upright incisor and force perpendicular to occlusal plane(Cobo et al., 1996; Cobo et al., 1993; Shaw et al., 2004; Tanne et al., 1987). Moreover, studies investigated alveolar bone loss and stress distribution did not assume facial inclination of teeth, which is far from clinical situation(Brunsvold, 2005; Cobo et al., 1996; Cobo et al., 1993; Geramy, 2000). Since central incisors with alveolar bone loss usually have more facial inclination due to pathologic migration, treatment objective should be controlled tipping, rather than bodily movement. Also for these tooth, orthodontic forces are usually not perpendicular to the occlusal plane. So this study evaluated how inclination and bone loss affects the M/F ratio for controlled tipping and stresses.

As these teeth are proclined than normal inclination, they should be retracted. In terms of stress distribution, the lowest level of stress on the apical area occurs with controlled tipping(Burstone, 1966). So the type of movement with these teeth should be controlled tipping with or without intrusion according to the vertical position of the incisor to prevent EARR.

Often correction of flared incisor with horizontal bone loss involves a combination of retraction and intrusion. And mere retraction of the flared teeth would lead to a deepening of the bite(Melsen, 2012). In this study, force was applied parallel to the occlusal plane without intrusive vector. Adding intrusive force results in inclination of the direction of net force, which is similar condition to the greater inclination of the tooth with horizontal force only. So in this study, intrusive force was not applied.

First, the current results for an average incisor were compared with previous study dealt with proclined teeth to validate the analysis(Kanjanaouthai et al., 2012). For the incisor which has average inclination(60 degree to the occlusal plane) with no alveolar bone loss, controlled tipping movement was simulated when M_t/F ratio was smaller than 8.5. And this study found that under this condition, maximum compressive stress occurred at the apex region and maximum tensile stress at labial cervical area which is corresponds with previous study(Kanjanaouthai et al., 2012).

To evaluate movement of the incisor, 3-dimensional displacement of apex ⊿($\sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}$) was used. By definition of Burstone(Tanne et al., 1987), center of rotation should be at the apex when controlled tipping is simulated. A simple 2 dimensional idea suggests that ⊿y(anterior-posterior displacement) of the apex would be 0 if controlled tipping occurs. But in this study even though rotation was controlled by counter rotational moment(M_r), direction of the force provided intrusion effect on the teeth due to the inclination. As a result, the apex did move not only in 2 dimensional anterior posterior direction, but also in 3 dimensional way. So in this study, controlled tipping was assumed to be simulated when ⊿($\sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}$) was smallest in given bone level and inclination. Due to the intrusive movement of the apex, smallest value of ⊿ did not become 0.

In this study, the incisor was modeled at inclination over the average(0˚, 5˚, 10˚, 15˚, 20˚) with alveolar bone loss (0mm, 2mm, 4mm, 6mm). In controlled tipping movement of the incisor, the maximum compressive stress migrated to the apex, while the maximum tensile stress migrated from cervical area to the middle of the root. This finding about distribution of stress corresponds with the study of Kanjanaouthai et al(Kanjanaouthai et al., 2012). There were more compressive stresses concentrated at the apex of incisors with a high degree of inclination than in incisors that are more upright(Kanjanaouthai et al., 2012). For the upright incisors without inclination, when bodily movement was simulated maximum compressive and tensile stress occurred at midroot areas(Cobo et al., 1996). Some studies also showed that most of the force from tipping was concentrated at the crest of the alveolar bone and not at the apex in upright incisor(Rudolph et al., 2001). In this study, labial inclination results in an increased intrusive force component parallel to the long axis that thus creates increased compressive stress conditions at the apex and also tension in the PDL in the longitudinal direction. As a result, maximum compressive stress was distributed at the apex area even though controlled tipping was simulated.

Recent study showed that apical root resorption is related with higher forces or high PDL stress(Cheng et al., 2009) and analysis of recent data has related EARR to maximum absolute compressive stress in the PDL(Viecilli et al., 2009). As facial inclination of incisor cause concentration of compressive stress on the apex, this can lead to more root resorption, which is common clinical situation(Sameshima and Sinclair, 2001). This finding corresponds with literatures suggest that increasing the angle between the central incisor and the palatal plane was strongly correlated with increasing EARR (Parker and Harris, 1998) and movement of teeth with mature roots, extensive root movement, and intrusive mechanics enhance the risk of EARR(Dermaut and De Munck, 1986).

Previous studies showed that alveolar bone resorption caused an increase in the maximum tensile stress and maximum compressive stress, relative to that found with a normal bone height(Geramy, 2002). In this study, when bone loss increases under the same incisor inclination the displacement of the apex and maximum compressive and tensile stresses also increased. The variation of ⊿ and stresses at each level of alveolar bone loss was smaller during controlled tipping than uncontrolled tipping or root movement. As more bone loss was simulated, ⊿ and stresses changed more sharply when Mt/F varies. Which means in patients with alveolar bone loss, inadequate force system causes radical change in displacement of apex and stress at the apical area. As EARR occurs during treatment when forces at the apex exceed the resistance and reparative ability of the periapical tissues, (Parker and Harris, 1998) applied force and moment magnitudes must be reduced in proportion in order to maintain physiologically tolerable movements without further damage to these supporting structures(Geramy, 2000).

Some studies showed that the moment/force ratio (at the bracket level) required to produce bodily movement increases in association with alveolar bone loss(Cobo et al., 1996; Cobo et al., 1993). In this study, M_t/F ratio required to produce controlled tipping movement increased in association with alveolar bone loss. In contrast to the effect of bone loss, inclination of incisor resulted in decreasing of M_t/F ratio for controlled tipping. By summing up the effect of bone loss and inclination, this study showed that M/F ratio for controlled tipping can be determined in treating labial PTM of the incisor.

The load-transfer mechanism from the tooth through the PDL to the alveolar bone depends on the physical properties and the morphology of the periodontium(Bourauel et al., 1999; Cobo et al., 1993; Middleton et al., 1996). The limitation of this study is the approximation of the material behavior and geometries of the tooth model. Recent studies used micro CT to make 3-D tooth and alveolar bone structure(Cattaneo et al., 2005), but the three-dimensional model created in this experiment is an average model of the maxillary central incisor. Some authors suggest that thickness of the PDL is not constant (Richardson, 1967), has an approximate width of 0.25 mm _+ 50%, with an hourglass shape, narrowest at the midroot level(Cobo et al., 1996). Different thickness of PDL can affect the distribution of stress in the PDL and the movement pattern of the tooth.

In this study, the PDL was modeled as a relatively simple linearly elastic isotropic material. But, some studies showed that the PDL being a nonlinear, multi-phasic, and visco-elastic material (Wills et al., 1976) (Toms et al., 2002). According to recent studies PDL has a nonlinear stress-strain relationship which has basic shape with a low-stiffness toe region and a high-stiffness slope(Toms et al., 2002).

A fine tuning of the FE-models and of the material properties of the various tissues is necessary in order to better determine the stress distributions within the whole periodontium and the movement patterns of the tooth under orthodontic loading.

Conclusion

The purpose of this study was the to determine the effect of alveolar bone loss together with inclination of the tooth on the magnitude and distribution of stresses within the PDL for a maxillary central incisor when controlled tipping was simulated with FEA. The results of the present study are as follows.

1. As more bone loss occurs the displacement of the apex(Δ) becomes larger under the same inclination of the incisor and M/F ratio. The variation of Δ between each level of bone loss becomes smaller as M/F ratio get closer to the M/F_{cont} under the same inclination.
2. As incisor is more inclinced, M/F_{cont} becomes smaller, while alveolar bone loss resulted in increased M/F_{cont} .
3. M/F ratio for uncontrolled tipping or root movement caused larger principal stress than M/F_{cont}. With more alveolar bone loss, the stress changes more sharply as M/F ratio varies under the same inclination.
4. When M/F ratio varies near the M/F_{cont}, compressive stresses dominate in the labial apical region(M/F below M/F_{cont})move to palatal apical area(M/F over the M/F_{cont}). Meanwhile, tensile stresses dominate in the labial area(M/F below M/F_{cont}) move from the cervical to midroot(M/F over the M/F_{cont}).

The results of this study will be the basis of further research examining the stress distribution process of PDL after orthodontic loading. When bone loss increases the displacement of the apex and maximum compressive and tensile stresses also increased. Also Δ and stresses changed more sharply when M/F ratio varies. Which means inadequate force system causes larger displacement of the apex and higher stress at the apical area in patients with alveolar bone loss and facial inclination of the incisor.

References

Atmaram GH, Mohammed H. 1981. "Estimation of physiologic stresses with a natural tooth considering fibrous PDL structure." *J Dent Res*. 60(5):873-877.

Bennett J MR, Trevisi H. 2001. systemized orthodontic treatment mechanics. Mosby.

Bourauel C, Freudenreich D, Vollmer D, Kobe D, Drescher D, Jager A. 1999. "Simulation of orthodontic tooth movements. A comparison of numerical models." *J Orofac Orthop*. 60(2):136-151.

Boyd RL, Leggott PJ, Quinn RS, Eakle WS, Chambers D. 1989. "Periodontal implications of orthodontic treatment in adults with reduced or normal periodontal tissues versus those of adolescents." *Am J Orthod Dentofacial Orthop*. 96(3):191-198.

Brezniak N, Wasserstein A. 2002a. "Orthodontically induced inflammatory root resorption. Part I: The basic science aspects." *Angle Orthod*. 72(2):175-179.

Brezniak N, Wasserstein A. 2002b. "Orthodontically induced inflammatory root resorption. Part II: The clinical aspects." *Angle Orthod*. 72(2):180-184.

Brunsvold MA. 2005. "Pathologic tooth migration." *J Periodontol*. 76(6):859-866.

Burstone CJ. 1966. "The mechanics of the segmented arch techniques." *Angle Orthod*. 36(2):99–120.

Cattaneo PM, Dalstra M, Melsen B. 2005. "The finite element method: a tool to study orthodontic tooth movement." *J Dent Res*. 84(5):428–433.

Cattaneo PM, Dalstra M, Melsen B. 2008. "Moment–to–force ratio, center of rotation, and force level: a finite element study predicting their interdependency for simulated orthodontic loading regimens." *Am J Orthod Dentofacial Orthop*. 133(5):681–689.

Cheng LL, Turk T, Elekdag–Turk S, Jones AS, Petocz P, Darendeliler MA. 2009. "Physical properties of root cementum: Part 13. Repair of root resorption 4 and 8 weeks after the application of continuous light and heavy forces for 4 weeks: a microcomputed–tomography study." *Am J Orthod Dentofacial Orthop*. 136(3):320 e321–310; discussion 320–321.

Cobo J, Arguelles J, Puente M, Vijande M. 1996. "Dentoalveolar stress from bodily tooth movement at different levels of bone loss." *Am J Orthod Dentofacial Orthop*. 110(3):256–262.

Cobo J, Sicilia A, Arguelles J, Suarez D, Vijande M. 1993. "Initial stress induced in periodontal tissue with diverse degrees of bone loss by an orthodontic force: tridimensional analysis by means of the finite element method." *Am J Orthod Dentofacial Orthop*. 104(5):448–454.

Coolidge ED. 1937. "The thickness of human periodontal membrane." *J Am Dent Assoc*. 24:1260–1270.

Dermaut LR, De Munck A. 1986. "Apical root resorption of upper incisors caused by intrusive tooth movement: a radiographic study." *Am J Orthod Dentofacial Orthop*. 90(4):321–326.

Geramy A. 2000. "Alveolar bone resorption and the center of resistance modification (3–D analysis by means of the finite element method)." *Am J Orthod Dentofacial Orthop*. 117(4):399–405.

Geramy A. 2002. "Initial stress produced in the periodontal membrane by orthodontic loads in the presence of varying loss of alveolar bone: a three–dimensional finite element analysis." *Eur J Orthod*. 24(1):21–33.

Kanjanaouthai A, Mahatumarat K, Techalertpaisarn P, Versluis A. 2012. "Effect of the inclination of a maxillary central incisor on periodontal stress: finite element analysis." *Angle Orthod*. 82(5):812–819.

Lindskog–Stokland B, Wennstrom JL, Nyman S, Thilander B. 1993. "Orthodontic tooth movement into edentulous areas with reduced bone height. An experimental study in the dog." *Eur J Orthod*. 15(2):89–96.

Melsen B. 2001. "Tissue reaction to orthodontic tooth movement––a new paradigm." *Eur J Orthod*. 23(6):671–681.

Melsen B. 2012. Adult orthodontics. Blackwell Publishing, p. 212.

Middleton J, Jones M, Wilson A. 1996. "The role of the periodontal ligament in bone modeling: the initial development of a time–dependent finite element model." *Am J Orthod Dentofacial Orthop*. 109(2):155–162.

Min Y−G. 1998. A study about the change of the centers of resistance according to the difference of alveolar bone heights and root lenghts during anterior teeth retraction using the laser reflection technique. Yonsei University, Seoul,Korea, p. 5.

Parker RJ, Harris EF. 1998. "Directions of orthodontic tooth movements associated with external apical root resorption of the maxillary central incisor." *Am J Orthod Dentofacial Orthop*. 114(6):677−683.

Re S, Corrente G, Abundo R, Cardaropoli D. 2000. "Orthodontic treatment in periodontally compromised patients: 12−year report." *Int J Periodontics Restorative Dent*. 20(1):31−39.

Richardson ER. 1967. "Comparative thickness of the human periodontal membrane of functioning versus non−functioning teeth." *J Oral Med*. 22(4):120−126.

Rudolph DJ, Willes PMG, Sameshima GT. 2001. "A finite element model of apical force distribution from orthodontic tooth movement." *Angle Orthod*. 71(2):127−131.

Sameshima GT, Sinclair PM. 2001. "Predicting and preventing root resorption: Part I. Diagnostic factors." *Am J Orthod Dentofacial Orthop*. 119(5):505−510.

Shaw AM, Sameshima GT, Vu HV. 2004. "Mechanical stress generated by orthodontic forces on apical root cementum: a finite element model." *Orthod Craniofac Res*. 7(2):98−107.

Tanne K, Sakuda M, Burstone CJ. 1987. "Three−dimensional finite element analysis for stress in the periodontal tissue by orthodontic forces." *Am J Orthod Dentofacial Orthop.* 92(6):499−505.

Thilander B. 1996. "Infrabony pockets and reduced alveolar bone height in relation to orthodontic therapy." *Semin Orthod.* 2(1):55−61.

Toms SR, Lemons JE, Bartolucci AA, Eberhardt AW. 2002. "Nonlinear stress−strain behavior of periodontal ligament under orthodontic loading." *Am J Orthod Dentofacial Orthop.* 122(2):174−179.

Towfighi PP, Brunsvold MA, Storey AT, Arnold RM, Willman DE, McMahan CA. 1997. "Pathologic migration of anterior teeth in patients with moderate to severe periodontitis." *J Periodontol.* 68(10):967−972.

Viecilli R, Katona T, Roberts W. 2007. "Optimization of microCT data processing for modelling of dental structures in orthodontic studies." *Comput Methods Biomech Biomed Engin.* 10(4):257−263.

Viecilli RF, Katona TR, Chen J, Hartsfield JK, Jr., Roberts WE. 2008. "Three−dimensional mechanical environment of orthodontic tooth movement and root resorption." *Am J Orthod Dentofacial Orthop.* 133(6):791 e711−726.

Viecilli RF, Katona TR, Chen J, Hartsfield JK, Jr., Roberts WE. 2009. "Orthodontic mechanotransduction and the role of the P2X7 receptor." *Am J Orthod Dentofacial Orthop.* 135(6):694 e691−616; discussion 694−695.

Wills DJ, Picton DC, Davies WI. 1976. "A study of the fluid systems of the periodontium in macaque monkeys." *Arch Oral Biol*. 21(3):175–185.

국문요약

치조골 높이와 치축 전방 경사가 상악 전치의 치근막 응력 분포에 미치는 영향

: 유한 요소 분석

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최근 성인 교정 환자의 증가와 함께 치조골 소실이 일어난 치아의 이동에 대한 이해의 필요성이 대두되었다. 심한 치조골 소실이 일어난 경우 병적 치아 이동으로 인해 전치의 순측 경사가 발생하는데, 치조골 소실과 전방 경사가 동반된 치아의 이동에 대한 유한 요소 연구는 부족한 편이다. 이 연구의 목적은 유한 요소 분석법을 이용하여 조절성 경사 이동 시 치조골 소실과 치축 전방 경사가 상악 전치의 치근막 응력 크기 및 분포에 미치는 영향을 조사하는데 있다. 연구 결과는 다음과 같다.

1. 동일한 치축 경사에서 치조골 소실이 일어날수록 치근단의 변위량이 컸으며 이는 비조절성 경사 이동과 치근 이동 시 더욱 크게 나타났다. 각 치조골 소실 조건간의 치근단 변위량 차이는 Mt/F ratio가 M/F_{cont}에 가까워 질수록 감소하였다.
2. 전치가 전방 경사될 수록, M/F_{cont}는 감소하였으나 치조골 소실은 M/F_{cont}를 증가시켰다.
3. 치조골 소실이 증가 할수록 치근막 응력 값은 Mt/F ratio의 변화에 의해 더 급격한 변화를 보였다. 최대 인장, 압축 응력 값은 비조절성 경사 이동이나 치근 이동 시에 조절성 경사 이동보다 더 크게 나타났다.

4. M/F_{cont} 값 주변에서 Mt/F ratio를 변화시켰을 때, 최대 압축 응력은 주로 순측 치근단 부위에서 구개측 치근단 부위에 분포하였다. 대조적으로 최대 인장 응력은 순측 치경부에서 치근 중앙 부위에 분포하였다.

본 결과는 교정력을 가한 후 치근막에 나타나는 응력 분포를 이해하는 추가적인 연구의 기초가 될 것이다. 치조골 소실 시 치근단의 변위량과 최대 인장, 압축 응력의 크기가 증가하였으며, Mt/F ratio 의 변화에 의해 변위량과 응력 분포의 급격한 변화를 보였다. 이것은 치조골 소실과 치축 전방 경사를 보이는 환자에서 잘못된 힘체계로 인해 치근단 부위의 변위량 증가와 과도한 응력 분포의 가능성이 높아짐을 시사한다.

핵심되는 말: 유한 요소 분석법, 응력, 치조골 소실, 병적 치아 이동, 상악 전치