ผลของความลาดเอียงของฟันตัดซี่กลางแท้บนและอัตราส่วนโมเมนต์ต่อแรง ต่อการเคลื่อนที่ของฟัน ความเค้นและความเครียดรอบรากฟัน: ระเบียบวิธีไฟไนต์เอลิเมนต์

นางสาว อธิชาต์ กาญจนอุทัย

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต

สาขาวิชาทันตกรรมจัดฟัน ภาควิชาทันตกรรมจัดฟัน

คณะทันตแพทยศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

ปีการศึกษา 2552

THE EFFECT OF INCLINATION OF THE MAXILLARY CENTRAL INCISOR AND THE M/F RATIO ON THE TOOTH MOVEMENT, PERIODONTAL STRESS AND STRAIN: FINITE ELEMENT METHOD

Miss Athicha Kanjanaouthai

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Science Program in Orthodontics
Department of Orthodontics
Faculty of Dentistry
Chulalongkorn University
Academic Year 2009

Thesis Title	THE EFFECT OF INCLINATION OF THE MAXILLARY CENTRAL INCISOR AND THE M/F RATIO ON THE TOOTH MOVEMENT, PERIODONTAL STRESS AND STRAIN: FINITE ELEMENT METHOD.
By	Miss Athicha Kanjanaouthai
Field of Study	Orthodontics
Thesis Advisor	Assistant Professor Paiboon Techalertpaisarn, Ph.D.
Thesis Co-Advisor	Assistant Professor Antheunis Versluis, Ph.D.

Accepted by the Faculty of Dentistry, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

……………………………………………. Dean of the Faculty of Dentistry

(Associate Professor Wacharaporn Tasachan)

THESIS COMMITTEE

…………………………………………….. Chairman

(Associate Professor Vachara Phetcharakupt)

…………………………………………….. Thesis Advisor

(Assistant Professor Paiboon Techalertpaisarn, Ph.D.)

…………………………………………….. Thesis Co-Advisor

(Assistant Professor Antheunis Versluis, Ph.D.)

…………………………………………….. External Examiner

(Nattawoot Depaiwa, Ph.D.)

อธิชาต์ กาญจนอุทัย : ผลของความลาดเอียงของฟันตัดซี่กลางแท้บนและอัตราส่วนโมเมนต์ต่อแรง ต่อการเคลื่อนที่ของฟัน ความเค้นและความเครียดรอบรากฟัน: ระเบียบวิธีไฟไนต์เอลิเมนต์. (THE EFFECT OF INCLINATION OF THE MAXILLARY CENTRAL INCISOR AND THE M/F RATIO ON THE TOOTH MOVEMENT, PERIODONTAL STRESS AND STRAIN: FINITE ELEMENT METHOD) อ.ที่ปรึกษาวิทยานิพนธ์หลัก : ผศ.ทพ.ดร. ไพบูลย์ เตชะเลิศไพศาล, อ.ที่ปรึกษาวิทยานิพนธ์ร่วม : ASSISTANT PROFESSOR ANTHEUNIS VERSLUIS, Ph.D., 88 หน้า.

วัตถุประสงค์ของการศึกษานี้เพื่อศึกษาผลของความลาดเอียงของฟันตัดซี่กลางแท้บน และอัตราส่วนโมเมนต์ต่อแรง ต่อการเคลื่อนที่ในแนวหน้าหลังและแนวดิ่ง ความเค้นและความเครียดรอบรากฟัน โดยสร้างแบบจำลองไฟไนต์เอลิเมนต์ของฟันตัดซี่กลางแท้บนขวาจากค่าเฉลี่ยของขนาดทางกายวิภาค จำนวน 5 แบบจำลอง ที่มีความลาดเอียง 0 10 20 30 และ 40 องศา ในแต่ละแบบจำลองจะได้รับแรงไปทางด้านลิ้น 1 นิวตันที่จุดต่ำกว่าปลายฟันตัด 4.5 มม.และโมเมนต์ซึ่งเปลี่ยนแปลงจาก 8 9 10 11 ถึง 12 นิวตันมิลลิเมตร จากนั้น วัดการเคลื่อนที่ในแนวหน้าหลังของปลายฟันตัดและปลายรากฟัน การเคลื่อนที่ในแนวดิ่งของปลายฟันตัด ความเค้นรอบรากฟันจะถูกแสดงในรูปของตำแหน่งและขนาดของค่าที่สูงที่สุดของความเค้นหลักค่ามากสุดและค่าที่ต่ำที่สุดของความเค้นหลักค่าน้อยสุด ส่วนความเครียดรอบรากฟันถูกนำเสนอในรูปของค่าที่สูงที่สุดของความเครียดหลักมากสุดและค่าที่ต่ำที่สุดของความเครียดหลักน้อยสุด ผลการศึกษาพบว่า เมื่อความลาดเอียงของฟันและอัตราส่วนโมเมนต์ต่อแรงเพิ่มมากขึ้น ปลายฟันตัดมีแนวโน้มเคลื่อนที่ไปทางด้านริมฝีปากและปลายรากฟันมากขึ้น ปลายรากฟันมีแนวโน้มเคลื่อนที่ไปทางด้านลิ้นมากขึ้น และเมื่อความลาดเอียงของฟันเพิ่มขึ้น อัตราส่วนโมเมนต์ต่อแรงที่ทำให้เกิดการเคลื่อนที่แบบฟันเคลื่อนทั้งซี่มีค่าลดลง แต่ตำแหน่งจุดศูนย์กลางความต้านทานของฟันตัดซี่กลางบนในรูปของอัตราส่วนของระยะในแนวดิ่งจากปลายรากฟันต่อความยาวของรากฟันจะค่อนข้างคงที่ เท่ากับ 0.67 ในกรณีของการเคลื่อนที่แบบฟันเคลื่อนทั้งซี่ ตำแหน่งที่เกิดความเค้นแรงอัด และความเครียดแรงอัดที่สูงที่สุด เปลี่ยนแปลงจากบริเวณกลางรากเมื่อมีความลาดเอียงของฟัน 0 องศา เป็นบริเวณปลายรากเมื่อมีความลาดเอียง 40 องศา ในขณะที่ตำแหน่งที่เกิดความเค้นแรงดึงที่สูงที่สุดเปลี่ยนจากบริเวณกลางรากเป็นบริเวณคอฟัน แต่ตำแหน่งที่เกิดความเครียดแรงดึงที่สูงที่สุดยังคงอยู่บริเวณกลางรากฟัน นอกจากนี้ เมื่อมีความลาดเอียงของฟันเพิ่มขึ้น ขนาดของความเค้นแรงอัด ความเครียดแรงอัดและความเครียดแรงดึงที่สูงที่สุดมีค่าเพิ่มขึ้น แต่ขนาดของความเค้นแรงดึงที่สูงที่สุดมีค่าลดลง

ภาควิชา ทันตกรรมจัดฟัน ลายมือชื่อนิสิต..........

สาขาวิชา ทันตกรรมจัดฟัน ลายมือชื่ออ.ที่ปรึกษาวิทยานิพนธ์หลัก..........

ปีการศึกษา 2552 , ลายมือชื่ออ.ที่ปรึกษาวิทยานิพนธ์ร่วม..........

5176141932 : MAJOR ORTHODONTICS

KEYWORDS : ANTEROPOSTERIOR MOVEMENT / CENTER OF RESISTANCE / FINITE ELEMENT METHOD / INCLINATION / MOMENT TO FORCE RATIO / PERIODONTAL STRAIN / PERIODONTAL STRESS / VERTICAL MOVEMENT

ATHICHA KANJANAOUTHAI : THE EFFECT OF INCLINATION OF THE MAXILLARY CENTRAL INCISOR AND THE M/F RATIO ON THE TOOTH MOVEMENT, PERIODONTAL STRESS AND STRAIN: FINITE ELEMENT METHOD. THESIS ADVISOR : ASSISTANT PROFESSOR PAIBOON TECHALERTPAISARN, Ph.D., THESIS CO-ADVISOR : ASSISTANT PROFESSOR ANTHEUNIS VERSLUIS, Ph.D., 88 pp.

The purpose of this study was to determine the effect of inclination of a maxillary central incisor and the moment to force ratio on anteroposterior and vertical movement and periodontal stress and strain by using the finite element method (FEM). Five 3D models of a right maxillary central incisor were constructed based on average anatomical dimensions with 0, 10, 20, 30, and 40 -degree inclination. A constant lingual force of 1 N at 4.5 mm apical to the incisal edge and the moment varied from 8 to 9, 10, 11, and 12 N-mm were applied to each model. Anteroposterior movement of the incisal edge and apex and vertical movement of incisal edge were measured. Periodontal stress and strain were expressed as the areas and magnitude of the highest maximum principal stress and strain and also the lowest minimum principal stress and strain. The results showed that with increasing inclination and the moment to force ratio, the incisal edge tended to move labioapically and the apex tended to move lingually. Moreover, with increased inclination, the moment to force ratio which produced bodily movement decreased but the location of the center of resistance of a maxillary central incisor was relatively constant in terms of the proportion of vertical distance to the root length from the apex, which was approximately 0.67. In bodily movement, the area of maximum compressive stress and strain changed from mid root area in 0° inclination to apical area in 40° inclination; while the area of maximum tensile stress changed from mid root area to cervical area but the area of maximum tensile strain was still in the mid root area. With increased inclination, magnitude of maximum compressive stress and strain and tensile strain increased but maximum tensile stress decreased.

Department : Orthodontics Student's Signature ....

Field of Study : Orthodontics Advisor's Signature ....

Academic Year : 2009 Co-Advisor's Signature ....

ACKNOWLEDGEMENTS

I owe my deepest gratitude to Assist Prof Korapin Mahatumarat who devoted her attention giving wonderful advice and inspiring guidance for this thesis since start until success. She always supports and encourages me through the thesis work. She is my best teacher. And I would like to express the special thanks for my advisor, Assist Prof Paiboon Techalertpaisarn, for all of valuable comment and excellent suggestions with kindness and helpful attitude.

This thesis would not have been possible without the support and advice from my co-advisor, Assist Prof Antheunis Versluis. He has made available his support in a number of ways. He introduced me to the Finite Element Analysis. He also gave a proficient guidance for the analysis. He gave appreciable suggestions, checking and correcting the fault of this thesis.

I would like to special thank Assoc Prof Vachara Phetcharakupt for being the chairman of the thesis committee. Also, I would like to thank Dr. Nattawoot Depaiwa for devoting his time to be the external examiner.

Gratefully special thanks are extended to all of my teachers in Orthodontic Department, Faculty of Dentistry, Chulalongkorn University. I am also indebted to my friends and colleagues to help and support me.

Finally, my graduation would not be achieved without best wish from my parents, Mr. Thongchai and Mrs. Valai Kanjanaouthai, who help me for everything and always gives me the greatest love. I also special thank Dr. Chavit Tunvirachaisakul for his support and encouragement.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Background and Rationale

Orthodontic therapy depends on the reaction of periodontal ligament around teeth to light but continuous force. The two “treatments” used in orthodontic therapy are forces and moments. Prescribing the correct amount of each one can produce the desired type of tooth movement.*(1)* Burstone*(2)* stated that types of tooth movement were determined by the moment to force (M/F) ratio at the bracket.

Finite element method (FEM) is a powerful computer-simulation tool for solving stress – strain problems in the mechanics of solids and structures in engineering.*(3)* It was also widely used for solving numerous engineering problems.

In dentistry, FEM was first introduced in 1973 by Farah JW, et al. in a restorative field.*(4)* Since then, FEM has been increasingly applied as a research tool in dentistry. At present, it can be used in several fields in dentistry by using both two- and three-dimension model.

In the orthodontic field, FEM was first applied two decades ago. FEM was applied to analyze stress and strain in periodontal ligament, bone, and teeth due to the force system. In addition, FEM was used to localize the center of resistance and the center of rotation of a tooth. It was also applied to define tooth movement, in term of distance and direction. As a result, it could define a type of tooth movement by the M/F ratio which was applied to the tooth. Moreover, FEM could determine properties of several kinds of orthodontic appliances, such as transpalatal arch, loops, springs, and miniscrew anchorage.

There are many studies about factors which have an effect on the position of the center of resistance by finite element method. Smith et al*(5)*stated that the position of the center of resistance varied with root length and alveolar bone height. Tanne et al*(6)* also claimed that the position of the center of resistance shifted more cervically to the alveolar crest with a shorter root and lower alveolar bone height. But it was more apical relative to the cervix with reduced alveolar bone height.

Furthermore, Yoshida et al*(7)* determined the initial movement of a tooth by a magnetic sensing system in an in vivo study. They found that the location of the center of resistance depended on the palatal alveolar bone height when anterior teeth were retracted.

However, among all finite element studies which have been mentioned earlier, the long axis of a tooth was perpendicular to the occlusal plane. Labiolingual inclination was not taken into consideration. In reality, an upper central incisor is inclined to the line perpendicular to the occlusal plane approximately 30 degrees*(8-9)*. Besides, in clinical practice, when upper anterior teeth with severe protrusion and proclination were retracted, an increased overbite was usually found.

Research Questions

1. When force and counter-tipping moment to force ratios were kept constant:
    1.1 Does the inclination of an incisor have an effect on tooth movement in anteroposterior and vertical directions?
    1.2 Does the inclination of an incisor have an effect on periodontal stress and strain magnitude and pattern?

2. In each degree of inclination of an incisor and the magnitude of force was kept constant:
    2.1 How the magnitude of the counter-tipping moment to force ratio have an effect on tooth movement in anteroposterior and vertical direction?
    2.2 Does the magnitude of the counter-tipping moment to force ratio have an effect on periodontal stress and strain magnitude and pattern?

Objectives

1. To estimate the effect of the inclination of a central incisor on the movement of an incisor in anteroposterior and vertical directions.
2. To estimate the effect of the inclination of an incisor on periodontal stress and strain magnitude and pattern.
3. To estimate the characteristics of tooth movement when the counter-tipping moment to force ratio was varied in each degree of inclination of an incisor.
4. To estimate the effect of the moment to force ratio on periodontal stress and strain magnitude and pattern in each degree of inclination of an incisor.

Research Hypothesis

1. When force and counter-tipping moment to force ratios were kept constant:
   1.1 The inclination of an incisor has an effect on tooth movement in anteroposterior and vertical directions.
   1.2 The inclination of an incisor has an effect on periodontal stress and strain magnitude and pattern.
2. In each degree of inclination of an incisor and the magnitude of force was kept constant:
   2.1 The magnitude of the counter-tipping moment to force ratio has an effect on tooth movement in anteroposterior and vertical direction.
   2.2 The magnitude of the counter-tipping moment to force ratio has an effect on periodontal stress and strain magnitude and pattern.

Assumption

1. The model was constructed based on average anatomical dimensions of a tooth, periodontal ligament, and bone.*(10-11)*

2. The height of bone which was measured from cervical to the apex was assumed that the heights on both labial and lingual sides in all models were equal in distance.
3. Tooth, periodontal ligament, and bone materials were assumed to be homogeneous, isotropic and linear elastic.

Limitation

Finite element analysis are approximations in material behavior and geometries of the model.*(3)* The results of the analysis are the average among individuals. *(3, 12)* As a result, these results can be used as a guideline to better understand the mechanical response of teeth with different inclinations.

Operational Definitions

1. **Inclination**: Inclination of a tooth is measured by the angle between the long axis of tooth and the line which is perpendicular to the occlusal plane.

2. **Center of resistance**: In a constraining system like a tooth in its alveolus, the center of resistance is defined as that point where pure force will result in translation of the tooth; and there will be no rotational effect.*(13)*

3. **The moment to force ratio (M/F)**: the ratio between the magnitude of couple (M) and the applied force at the bracket (F). The counter-tipping moment to force (Mt/F) ratio needed for translation represents the distance from the bracket to a point from which a single force can produce the same effect. The Mt/F ratio in this study was the same as what is commonly referred to as the M/F ratio in orthodontics.

4. **Anteroposterior movement** is measured the distance that incisal edge and the root apex of an incisor moved in labiolingual axis.

5. **Vertical movement** is measured the distance that incisal edge of an incisor moved in incisoapical axis.

6. **Lingual force** is the force directed to lingual direction and parallel to the occlusal plane.

7. **Counter-tipping moment (Mt)** is the moment against the tooth to tip labiolingual direction.

8. **Counter-rotation moment (Mr)** is the moment against the rotation of a tooth around the long axis.

9. **Finite element method (FEM)** is the tool for this study. FEM is a numerical technique for finding approximate solutions and is used for analyzing physical phenomena in the field of structural, solid and fluid mechanics.*(14)*

Expected Benefit and Application

1. To better understand and explain how inclination affects orthodontic procedure.
2. To assist in assessment of patients, treatment planning, and minimize side effects that would occur during the treatment in patients with anterior maxillary teeth protrusion.

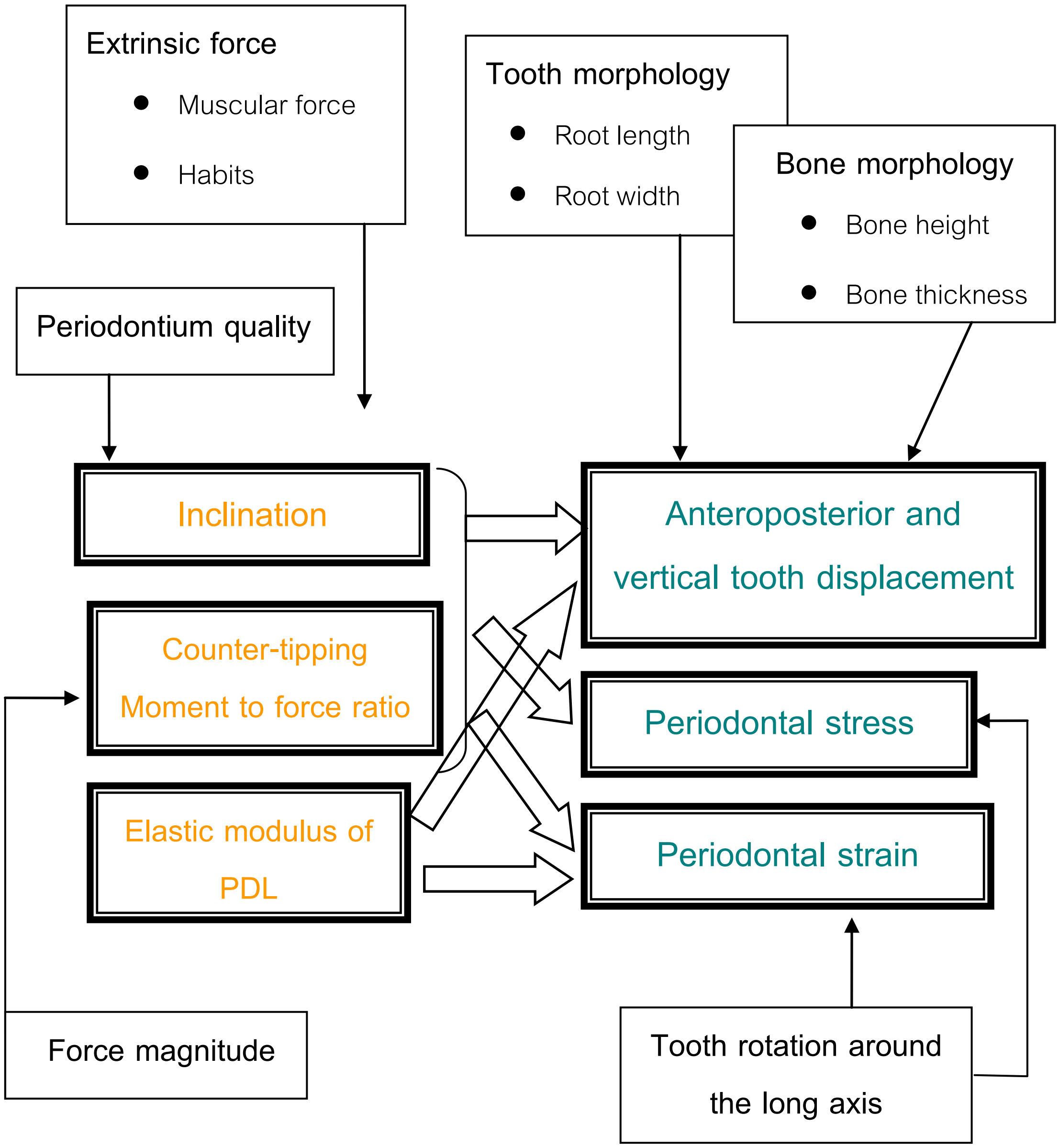
Research Design

This study is a parameter study using numerical analysis.

Administration and Time schedule

1. Preliminary study	
1.1 Review literature	November, 2008 – June, 2009
1.2 Research design	March – July, 2009
1.3 Proposal preparation	June – August, 2009
1.4 Proposal presentation	September, 2009
2 Data manipulation	September – December, 2009
3 Data analysis	December, 2009 – February,2010
4 Report	
4.1 Research report preparation	February – March, 2010

Conceptual Framework



CHAPTER II
LITERATURE REVIEW

Finite Element Method (FEM)

In general, engineering and scientific problems are usually in term of differential equations or integral equations. The solution approaches of these equations consist of 2 ways. Firstly, an analytical method is a mathematical method that finds the exact solution. It is suitable for simple problems. But, in case of complex problems, the approximate method (or numerical method) is the better choice. The finding from this method is approximate solution. There are various ways to solve for approximate method but the most widely used one was Finite Element Method (FEM).*(15)*

The principle of FEM is discretization of the structure of interest into elements. Each element is connected by points at the corners of each element called nodes. These elements and nodes make a grid called a mesh that is programmed to contain the material and structural properties such as Young's modulus and Poisson's ratio. The boundary conditions are defined to simulate constraints and loads. The problem is solved for each element and gathered them together to represent the solution of the entire system. The accuracy of the result from FEM depends, among others, on the number and size of elements..

General procedures in FEM composed of 6 steps: 1) Discretization the structure of problems into a number of elements. 2) Selection of element interpolation functions. 3) Derivation of finite element equation, this step is the most important. 4) Assemblage of all element equation systems of simultaneous equations. 5) Application of boundary conditions into equations. And 6) computation of any other quantity of interest. For example, if we can find movement at any positions of the structure, we can also find stress and strain of this structure.*(16)*

Finite element method was first developed in 1950s by Alexander Hrennikoff and Richard Courant.*(17-18)* It was widely used for solving numerous engineering problems. In early period of FEM, it was limited to expensive industries such as aeronautics, automotive, defenses, and nuclear industries because of expensive mainframe computers. Nowadays, the computer technology is rapidly developed; consequently the power of computers has increased while the price has decreased. As a result, FEM is possible in small industries. Areas of application and potential of this method are also enormous.*(18)*

Application of FEM

FEM has an important role in solving engineering problems. In first to second decades, FEM was mostly used in mechanics of solids and structures, because they were not complicated structures. Since FEM and modern technology have been continually developed, it can be used in more complex structures effectively. Therefore, it is clearly that the use of FEM is possibly applied to any other area besides the engineering field.

FEM in Biomechanics

In medical field, it has been applied to several areas, such as orthopedics, stress analysis of problems of bone or prosthesis, bio-fluid mechanics in cardiovascular system, simulations of the pulsatile blood flow patterns in arterial abnormalities, stress analysis of mechanical properties of the working heart, stress analysis of bioprosthetic heart valves, soft tissue mechanics, deformation of lung, analysis of parenchyma, mechanics of head injury, image reconstruction, electromagnetic field problem, etc.*(14-15)*

In dentistry, FEM was first introduced in 1973 by Farah JW, et al. in a restorative field.*(4)* Since then, FEM has been considerably developed to be a research tool. At present, it can be used in several fields in dentistry by using both two and three dimension model. From the bibliography listed on finite element modeling and simulations in dentistry between 1990 and 2003*(14)*, they involved in dental materials, both the human body own materials and restorative materials; oral and maxillofacial mechanics and surgery; orthodontics: tooth movement, orthodontic appliance; root canals: filling and therapy; dental restorations. The most of listed paper are orthodontic and prosthodontic research.

FEM in orthodontics was first introduced in lately 1980s. Generally, it was mostly devoted in stress and strain analysis in periodontal ligament, bone, and teeth due to tooth movement.*(3, 19-24)* In addition, the direction and characteristics of tooth movement usually depend on center of resistance and center of rotation of a tooth. They also depend on force and moment which were applied to the crown of a tooth, transferred to surrounding structures, and induced biological reactions. Hence, the FEM in early orthodontic study involved the finding of center of resistance and center of rotation of a tooth and movement *(3, 12, 24-25)*, in terms of distance and direction, which was affected by different force and moment. Moreover, the M/F ratio was calculated for each loading regimen to assess type of tooth movement, such as tipping or bodily movement, by determination of stress distribution in periodontal ligament.*(3, 19, 23)* Furthermore, FEM was developed to determine properties of many kinds of appliances. In orthodontic treatment, appliances were developed from many clinicians for different objectives. FEM could also be used to assess the efficacy and results of tooth movement from these appliances. The appliances which were evaluated by FEM are exemplified by transpalatal arch*(26-27)*, many kinds of loops*(28-30)*, molar uprighting spring*(31)*, canine retraction spring*(32)*, rectangular archwire*(33)*, orthopedic appliance*(34)*, bracket designs*(35-36)*, bonding properties*(37)*, etc. Besides, in the temporary anchorage devices (TADs) era, FEM was still used to analyze stability, stress, anchorage effect, and efficacy of various designs of TADs.*(38-40)*

At present, FEM is very popular tool in orthodontic study. It can be used to be a research or teaching tool. The main reason is it possibly simulates the situations that were impossible in the past. For example, it is impossible to set any devices or tools within the periodontal space to evaluate stress because of its too small area.

However, limitations in FEM study are approximations in material behavior and geometries of the model.*(3)* There are numerous anatomic variations in tooth morphology and periodontal space width among individuals that may affect the result of the study.*(3, 12)* In addition, FEM could not represent biological reactions within periodontal ligament. Therefore, the result from FEM study can be used as a guideline and should be applied to an individual orthodontic patient.

Biomechanics in Orthodontics

Orthodontic therapy depends on the reaction of teeth to light but continuous force. The two “drugs” used in orthodontic therapy are forces and moments. Prescribing the correct amount of each one can produce the desired type of tooth movement.*(1)* This branch of knowledge is called “Biomechanics”. Biomechanics in orthodontics is a branch that involves the force systems which produce movement of teeth and dentofacial structures to the desired direction. Consequently, knowledge of the biomechanical principles is necessary for orthodontists to execute an individualized treatment plan.

Force

A force is determined as the action of one body to another. Consequently, that body changes or tends to change the state of rest or the motion of it. For instance, orthodontic force is the action of a wire on the tooth that changes or tends to change the shape or motion of the other tooth. It is either push or pull.*(1)* When the force is divided by size of contact area, there are two types. Firstly, point force or concentrated force is the force that acts on small contact area, for example, the force from elastic that acts on a hook of a bracket. The second one is distributed force. It is the force that acts on large contact area and distributes on that body, for example, the force of tooth acts on periodontal ligaments. In addition, when a body was forced, there are two changes, displacement and deformation. In case of movement happening only, it is called rigid body, such as a tooth. In addition, force is a vector, which means it has direction and magnitude.*(41)*

Moment of force

When a body was exerted by a force not acting through the center of resistance, it tends to rotate around a point or axis. The moment of force about a specified point or line is a measure of the potential of that force to rotate the body about the particular point or line. The magnitude of moment is equal to product of the force times the perpendicular distance from the line of action of force to the point or line about which rotation is being considered.*(41)*

Couple

A couple consists of two force of equal magnitude, with parallel but noncolinear lines of action and opposite directions. These two forces are separated by a perpendicular distance.*(5)* When a couple applies on a rigid body, it will result in pure rotation.

Sign convention

An arbitrary convention is assigned to the force and moment. When all moments tend to produce mesial, labial, or buccal crown movement, they are defined as positive sense. While if they tend to produce distal or lingual crown moment, they are assigned as negative sense. From the occlusal view, moments that tend to rotate teeth so that mesial surfaces will rotate lingually are positive moments, whereas moments that tend to rotate buccally are negative moments.*(1)* In addition, with two dimensional diagrams, clockwise moments will be defined as positive and counterclockwise moments negative.*(5)* With respect to forces, if forces are anterior, lateral, or extrusive, they will be positive. Conversely, forces that are in lingual, mesial, or intrusive direction are in negative.*(1)*

Reference point in an orthodontic movement analysis

Center of crown

The center of crown (Figure 1) is the intersection of three perpendicular axes. The first axis is the long axis of a tooth, the second is directed buccolingually, and the third is directed mesiodistally. This point is usually the proper bracket location.*(41)*

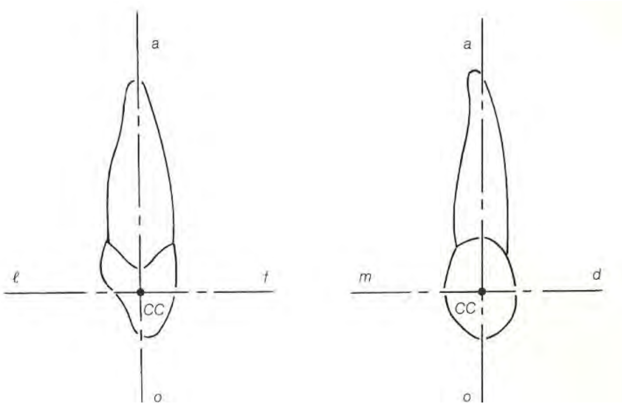


Figure 1 The position of the center of crown*(41)*

Center of resistance*(1, 5)*

Every object or free body has one point on which it can be perfectly balance. If this point is forced, the whole body will move in a parallel and straight line. The body will behave as though its entire mass is concentrated at this single point and the rest of it does not exist. This point is known as the center of gravity or center of mass.

With respect to a constraining system like a tooth in its periodontium, a set of unique constraints, such as periodontal ligaments, blood vessels, connective tissue, and bone, exists that rather alters the position of the center of gravity. This new center is called center of resistance. In other words, the center of resistance is the point on the body (tooth) that a force with a line of action passes through produce translation, i.e., all points on the tooth moving in parallel, straight lines.

The location of the center of resistance is considered as an essential part in the planning of orthodontic tooth movement. If we have the exact knowledge of this center, we can determine the force system applied to the crown of the tooth to achieve the desired tooth movement. Consequently, many authors have devoted their attention to this topic.*(2, 7, 12, 42)*

Burstone and Pryputniewicz*(2)* used laser holography as a tool to determine center of resistance and center of rotation of a maxillary central incisor in three dimensional movement. They found that the center of resistance was at a point one-third of the distance from the alveolar crest to the apex. It is 9.9 millimeters in distance apical to the bracket.

Tanne et al*(12)* used the finite element method to investigate the relationship between M/F ratios and the center of rotation in the three dimensional upper central incisor model. They found that the center of resistance was located at 0.24 times the root length measured apical to the level of alveolar crest. It is 8.39 millimeters in distance apical to bracket.

Geramy*(42)* defined the behavior of initial tooth movement associated with alveolar bone loss situations by carried out the finite element method in three-dimensional models of an upper central incisor. He discovered that the distance between the point of force system application (5.5 mm apical to the incisal edge) and center of resistance was 8.44 millimeters. It could say that the center of resistance was located at 0.42 times the root length measured apical to the alveolar crest.

Yoshida et al*(7)* measured the initial movement of the central incisors with a magnetic sensing system. This study determined the location of the center of resistance and the center of rotation in three human subjects. They found that the location of the center of resistance was at approximately two-thirds of palatal alveolar bone, measured from the root apex.

Furthermore, there are many factors that influence the location of the center of resistance. Several authors described about this topic.*(5-7, 42)*

Smith et al*(5)* stated that there were two important factors that affect the center of resistance. First factor was the position of the center of resistance varied according to root length. The other was its variation according to alveolar bone height.

Tanne et al*(6)* investigated the nature of initial tooth movement associated with varying root lengths and alveolar bone heights by a three-dimensional model in the finite element analysis. He concluded that apicogingival levels of the center of resistance shifted more cervically to the alveolar crest with a shorter root. Its position also shifted toward the alveolar crest with lower alveolar bone height but it was more apical relative to the cervix.

Geramy*(42)* studied the behavior of initial movement associated with alveolar bone loss situations. This study was carried out by finite element method. He found that alveolar bone loss caused center of resistance changed on account of the alterations in bone support. Modifications in the applied force system were needed to produce the same movement as in a tooth with a healthy supporting structure.

Yoshida et al*(7)* investigated the initial movement of central incisors. They concluded that the location of the center of resistance depended on the palatal alveolar bone height when anterior teeth were retracted.

Center of rotation

The center of rotation is the point that a body appear to have rotated around during a non-translational movement. There are several definitions of this point.

Nikolai*(41)* defined that the center of rotation was the intersection of 2 lines coincident with the extensions of the tooth axis before and after movement (Figure 2).

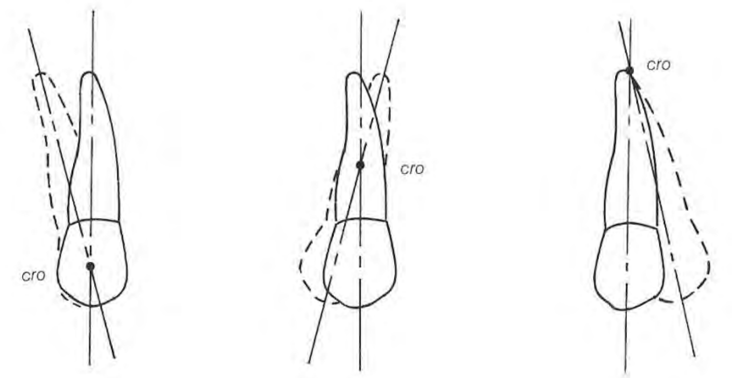


Figure 2 The location of the center of rotation defined by Nikolai*(41)*

Smith et al*(5)* stated that the center of rotation was characterized as a point that a body appears to have rotated, as determined from its initial and final positions. It could be at any points on or off a tooth. A method to define this point was to take two points on the tooth before and after positions, for example, the points at cusp tip and root apex. Then, the points of cusp tip before and after position were connected with a line. The points of root apex before and after position were also connected with a line. The intersection of the perpendicular bisectors of these lines was the center of rotation (Figure 3).

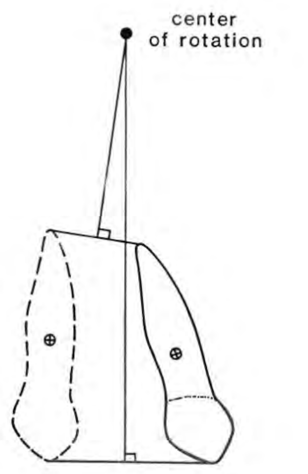


Figure 3 The method to define the center of rotation presented by Smith et al.*(5)*

In addition, Cattaneo et al *(19)* declared that the actual location of center of rotation was determined by the value of M/F ratio and the level of the applied force. Small changes in the M/F ratio would produce large changes in the position of the center of rotation. This finding was in accordance with the study of Burstone et al.*(2)* Another determinant was the magnitude of the applied force. In case of the constant M/F ratio, when the force level was gradually increased, the center of rotation was not a fixed position. But it was displaced after the force level was applied to the tooth.

Type of tooth movement

There are three general ways in tooth movement

1. Translation or bodily movement

Translation is the result of the line of action of a force passing through the center of resistance of a tooth.*(5)* The center of rotation of the tooth movement is located at infinity. All points on the tooth move an equal distance in a parallel, straight line in the same direction of the applied force.*(1)*

However, in reality, it is impossible to apply force at the center of resistance of a tooth. In clinical practice, we have a bracket on the center of crown;

therefore we can apply the force system at this point only. In this case, it can be used the equivalent system that equal to the force system at the center of resistance. This is shown by the following example. When we want to retract anterior teeth in a lingual direction, instead of applying a single force to the center of resistance, we can apply a lingual force and a couple at the center of crown. Since if a point force is applied at the center of crown only, it will produce lingual crown moment and cause a tooth to rotate lingually. Consequently, we need a couple that counter the lingual crown moment that is produced by an applied force which does not pass through the center of resistance. The couple we need is a labial crown couple. The amount of this moment needed for translation is equal to the magnitude of the force multiplied by the perpendicular distance from the line of action of the force to the center of resistance (M = F x d). In addition, an analysis of tooth movement usually determines the ratio between the magnitude of couple (M) and the applied force at the bracket (F). So the M/F ratio needed for translation represents the distance from the bracket to a point from which a single force could produce same effect. This point means the center of resistance. In conclusion, the most useful purpose to determine the M/F ratio which produces translation movement is it can determine the location of the center of resistance (Figure 4).*(2, 5)*

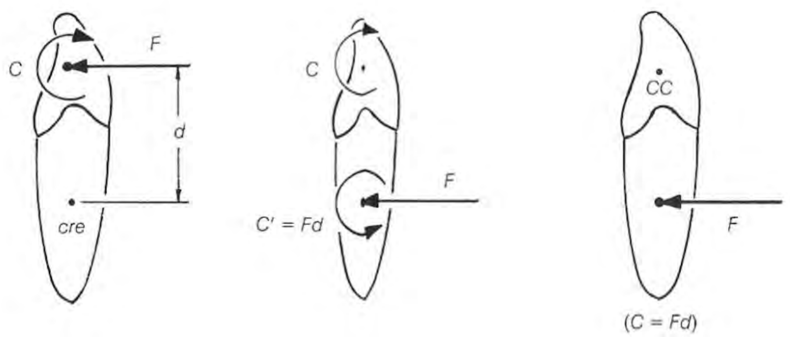


Figure 4 The crown loading in bodily movement. The force system at the bracket (left) is equal to the force system at the center of resistance (right).*(41)*

2. Pure rotation

Pure rotation results from a couple placed on a tooth in any position in the plane of the couple. A single force cannot produce pure rotation. A tooth rotates about its center of resistance so the center of rotation is at the center of resistance. It is illustrated by a movement of points of the tooth along the arc of a circle and the center of resistance is the center of circle. The crown moves one way and the roots moves the opposite way.

3. Generalized rotation*(1, 5, 41)*

This type of movement combines rotation and translation. Any movement is not pure translation or rotation; conversely it is usually described as a combination of these two types of movement. The center of resistance of a tooth will rotate and translate at the same time. Generalized rotation can be divided into 3 characteristics.

3.1 Uncontrolled tipping

Uncontrolled tipping is the result of a single force only which passes through the center of crown and its line of action is perpendicular to the long axis a tooth. The movement of a tooth occurs about a center of rotation which is apical and very close to its center of resistance. The crown moves in the same direction as the force and the root moves in the opposite direction.

3.2 Controlled tipping or crown movement

Controlled tipping occurs when a force and a moment act on the center of crown. A tooth tips about the center of rotation which is at the apex of a tooth. A crown of a tooth moves in the same direction as the force. This type of tooth movement is usually used in severe protrusion of upper anterior teeth. Controlled tipping makes them normal axial inclination. The M/F ratio is less than a distance between the point of force application and the center of resistance of a tooth.

3.3 Root movement or root retraction

This movement is also caused by a force and a moment. A tooth moves about the center of rotation which is at or close to the incisal edge of a tooth. A couple is the main force in this type of movement. A root of a tooth moves in the same direction as the couple. Much bone will be resorbed during this movement. This is the reason that root movement procedures usually require much time. The M/F ratio is more than the distance between the point of application and the center of resistance of a tooth.

CHAPTER III
RESEARCH METHODOLOGY

Variables

Independent variables

- Inclination of a maxillary central incisor
- The counter-tipping moment to force (Mt/F) ratio
- The elastic modulus of periodontal ligament

Dependent variables

- Anteroposterior movement
- Vertical movement
- Periodontal stress
- Periodontal strain

Confounding factors

- Tooth morphology: root length, root width
- Bone morphology: bone height, bone width
- Extrinsic force: muscular force and habits
- Periodontium quality
- Magnitude of force
- Rotation of a tooth around the long axis

Confounding factors were controlled by the following. The magnitude of force in all models was kept constant at 1 Newton. Then, tooth rotation in each model was controlled by counter-rotation moment so that both mesial and distal ends of an incisor moved in the same amount of labiolingual direction. Finally, other confounding factors were controlled because all models in this study were developed from the same model which was rotated in different degrees. Consequently, these factors were excluded from the study.

The Finite Element Model

A three–dimensional finite element model of a right maxillary central incisor was constructed. The model contained a tooth, periodontal ligament (PDL), and alveolar bone. It also consisted of 2,896 nodes and 2,400 eight – node solid elements (Figure 5).

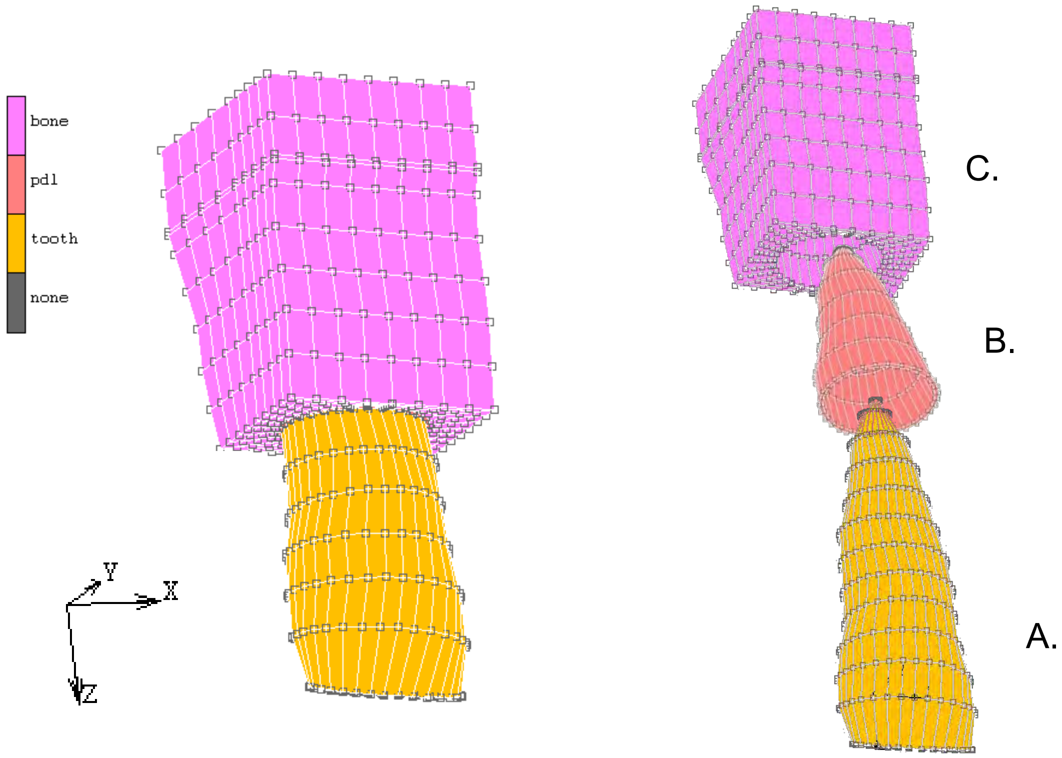
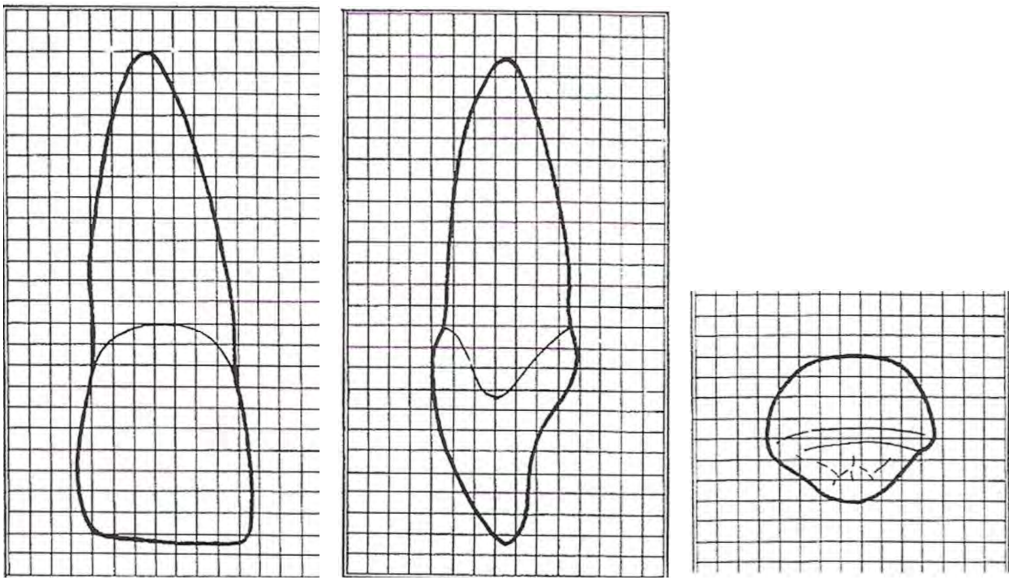


Figure 5 The labial aspect of the three-dimensional finite element model of a right maxillary central incisor and surrounding tissues is shown on the left. The right side shows the components of the model which consist of A) a right maxillary central incisor on the labial aspect, B) periodontal ligament, and C) bone.

The maxillary central incisor was composed of 798 elements. The geometry of the maxillary central incisor was based on average anatomical dimensions from

Wheeler's Dental Anatomy textbook (Figure 6)*(10)*. The length of the tooth which was measured from the incisal edge to the root apex was 23.5 mm. The tooth was divided into the crown and root by cementoenamel junction (CEJ). The crown length was 10.5 mm measured from the lowest point of the incisal edge to the highest point on cementoenamel junction (CEJ) on the labial aspect. The root length was 13 mm measured from the highest point of CEJ to the root apex on the labial aspect. The mesiodistal width of the crown was 8 mm measured at the contact areas. The labiolingual width of the crown was 7 mm measured at the height of contour of labial and lingual sides in the cervical area. These dimensions were modified to get the best possible shape in model construction.



A. B. C.

Figure 6 Graph outlines of a maxillary central incisor. A) The labial aspect. B) The mesial aspect. C) The incisal aspect.*(10)*

The periodontal ligament (PDL) widths at different cervicoapical levels were derived from data of Coolidge (Table 1).*(11)* The PDL covered root surface 11 mm in distance from the apex. In others words, the PDL was 2 mm. below the CEJ. The number of PDL elements was 288 elements.

Table 1 The geometry of the periodontal ligament widths*(11)*

Distance from alveolar crest (mm)	Periodontal ligament widths (mm)			
	Mesial	Distal	Labial	Lingual
11	0.22	0.20	0.25	0.25
10	0.20	0.18	0.22	0.22
8	0.17	0.15	0.20	0.20
6	0.16	0.14	0.18	0.18
4	0.17	0.15	0.20	0.20
2	0.20	0.18	0.22	0.22
0	0.21	0.19	0.24	0.24

The average alveolar bone thickness at the labial and lingual sides was from sampled cephalometric radiographs because there was no data available about the thickness of labial and lingual bone of a maxillary central incisor. Thirty radiographs were sampled for the study. They were from orthodontic patients who had skeletal class I characteristic. Their upper incisors were well aligned and alveolar bones were normal clinically. The patients' age was ranged from 11 to 37 years and the mean age was 24.95 ± 6.82 years. Each radiograph was good quality and was taken with the same x-ray machine (Orthophos3, SIRONA dental systems GmbH. Manufacturer, Bensheim, Germany). The maxillary central incisor root, measured from alveolar crest to the root apex, was divided into 4 equal parts, perpendicular to the long axis of the tooth. Labial and lingual bone thickness were measured in millimeters at five levels: 1) at alveolar crest, 2) midpoint between alveolar crest and mid root, 3) mid root), 4) midpoint between mid root and the apex, and 5) the apex. The mean of anatomical root length was 12.34 mm. At each level, the thickness of alveolar bone was measured from the outer surface of the root to outer surface of bone (Figure 7). The means of alveolar bone thicknesses from these 5 levels were calculated and are shown in table 2. The crest of alveolar bone started at the same level as the height of PDL (2mm below the CEJ). The number of bone elements was 1344. The base of the model was 4 mm thick measure from the apex of the incisor

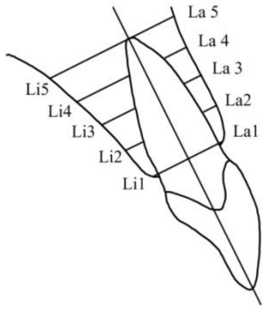


Figure 7 Location of bone thickness measurements

Table 2 Average alveolar bone thickness of 5 levels from figure 7.

Level	Average alveolar bone thickness (mm)	
	Labial	Lingual
At alveolar crest (1)	0.82	0.94
Midpoint between alveolar crest and mid root (2)	1.34	2.32
Mid root (3)	1.55	3.30
Midpoint between mid root and the apex (4)	1.93	4.76
At the apex (5)	4.18	7.63

The long axis of the original model was positioned perpendicular to the occlusal plane. Then, the whole model was rotated in 10, 20, 30, and 40 degrees compared with the original long axis to simulate the inclination of a tooth.

All materials were assumed to be homogeneous, isotropic and linear elastic. The material properties of a tooth, PDL, and alveolar bone, in term of Young's modulus (N/mm^2) and Poisson's ratio, are shown in table 2. These data were gathered from previous studies. *(3, 6, 12, 20-24, 42)*

Table 3 Mechanical properties of the structural elements.*(3, 6, 12, 20-24, 42)*

Structures	Mechanical properties	
	Young's modulus (N/mm^2)	Poisson's ratio
Tooth	20300	0.3
PDL	vary	0.49
Alveolar bone	13700	0.3

The properties of PDL were not well known and many previous studies shown different elastic modulus values.*(21-22, 43)* As a result, in each analysis, the elastic modulus of PDL was varied so that we could explain the direction of the results if the elastic modulus of PDL was changed.

The software used in this study was Marc Mentat 2007 for Windows (MSC.Software Corporation, Santa Ana, CA, USA) on the notebook computer; Intel® Core™ 2 Duo (P7450) 2.13 GHz, 4096 MB RAM, and 298 GB hard disk. The operating system was Microsoft® Windows XP. This program was licensed to Chulalongkorn University.

Three different types of loads were applied at the crown of the upper central incisor on each model (figure 8). These included a lingual force, counter-tipping moment, and counter-rotation moment.

1. **A lingual force** of 1 N, directed to the lingual side, was applied at the node 4.5 mm apical to the incisal edge and midpoint of mesiodistal width. This point corresponded to the location where the center of bracket slot would usually be.*(7)* This magnitude of 1 N was chosen because it corresponded to the force level used in clinical practice.*(44)* The lingual force was parallel to the occlusal plane in every model and kept constant.

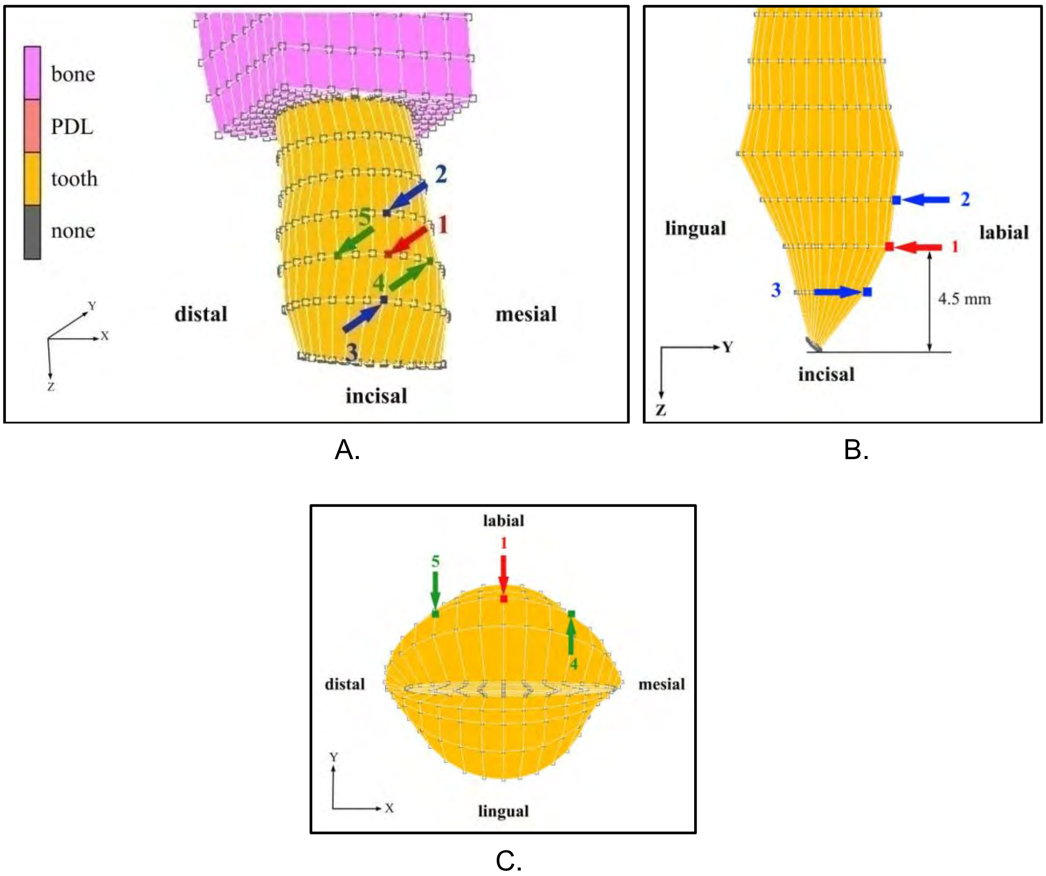


Figure 8 A) The labial aspect of the right maxillary central incisor with location of the applied force and moments. The red arrow (1) is a lingual force of 1 N. The blue arrows (2 and 3) represent the Mt which produces labial crown movement. The green arrows (4 and 5) represent the Mr which produces distolingual rotation. B) The distal aspect of crown, showing the lingual force and Mt. C) The incisal aspect, showing the lingual force and Mr.

2. **Counter-tipping moment** (Mt) comprised two parallel forces of equal magnitude and opposite labiolingual direction. This moment produced labial crown movement. The magnitude of Mt was varied from 8 to 9, 10, 11, and 12 N·mm.

3. **Counter-rotation moment** (Mr) which produced distolingual rotation was applied to counteract the confounding moment. Because the lingual force was applied at the center of mesiodistal width of the crown and the root of the tooth tipped distally, it was mesial to the center of resistance and caused a confounding moment that rotated

the tooth mesiolingually. The Mr was calibrated to make the mesial and distal ends of the incisal edge moved equally in distance and the same direction. The horizontal distance of this couple was 4.87 mm.

The boundary conditions were defined to constrain the model from free body motion. All nodes at the base of the model were fixed in all directions. All nodes on mesial and distal surfaces of bone were fixed in mesiodistal and incisoapical directions , which allowed bending of the bone in labial and lingual directions.*(3)*

Measurement

1. **Anteroposterior movement** of an incisor was measured at 2 nodes which were on the same sagittal plane (figure 9). The first node was at the center of incisal edge, representing the movement of the incisal edge. The second node was at the center of the apex to represent the movement of the apex. Positive and negative values were defined where the node moved to labial and lingual side, respectively. The bodily movement was obtained when these 2 nodes moved in the same distance and direction.
2. **Vertical movement** of an incisor was measured at the center of incisal edge (node No.1 in Figure 9). If this node moved incisally, it would be assigned as positive sense. Conversely, if it moved apically, it would be assigned as negative sense.
3. **Periodontal stress** was measured in terms of the magnitude and areas of the lowest value of minimum principal stress and the highest value of maximum principal stress. The negative value of principal stress was defined as compressive stress whereas the positive value was defined as tensile stress.
4. **Periodontal strain** was measured in terms of the magnitude and areas of the lowest value of minimum principal strain and the highest value of maximum principal strain. The negative value of principal strain was defined as compressive strain whereas the positive value was defined as tensile strain.

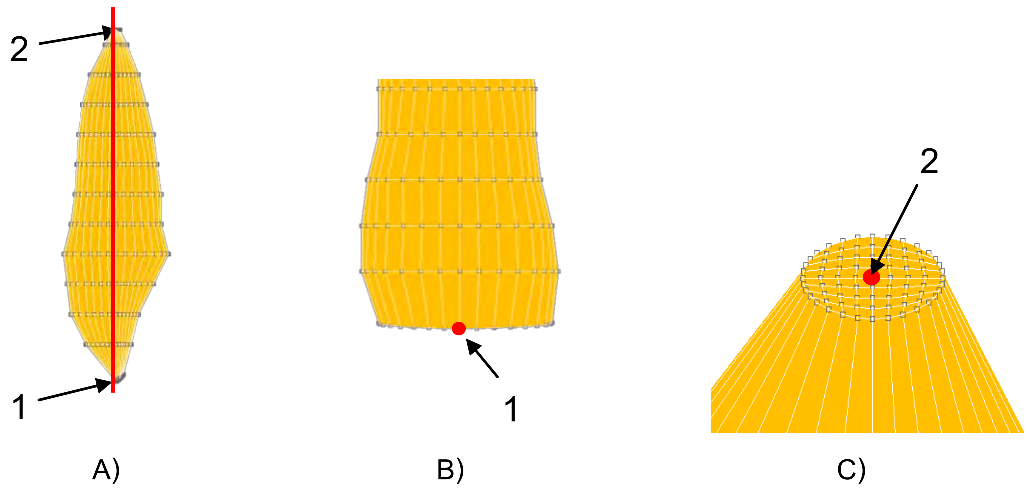


Figure 9 shows the position of 2 nodes. A) In sagittal view, the red line represents mesiodistal plane. Node No.1 is the node at the center of incisal edge. Node No.2 is the node at an apex. B) Labial view of a crown presents the node No.1. C) Oblique view of an apex presents the node No.2.

Data analysis

1. When the Mt/F ratio was kept constant at 8, 9, 10, 11, and 12, and the elastic modulus of PDL was 0.68 N/mm^2 *(3, 6, 12, 20-21, 23-24)*, the relationships between 2 variables as described below were studied.

- Inclination of a tooth and anteroposterior movement of the incisal edge

  Inclination of a tooth and anteroposterior movement of the apex
- Inclination of a tooth and vertical movement
- Inclination of tooth and minimum principal stress in PDL

  Inclination of tooth and maximum principal stress in PDL
- Inclination of tooth and minimum principal strain in PDL

  Inclination of tooth and maximum principal strain in PDL

2. When the inclination of an incisor was kept constant and the elastic modulus of PDL was 0.68 N/mm^2, the relationships between 2 variables as described below were studied.

- Mt/F ratio and anteroposterior movement of the incisal edge
- Mt/F ratio and anteroposterior movement of the apex
- Mt/F ratio and vertical movement
- Mt/F ratio and minimum principal stress in PDL
- Mt/F ratio and maximum principal stress in PDL
- Mt/F ratio and minimum principal strain in PDL
- Mt/F ratio and maximum principal strain in PDL

3. When the inclination of an incisor was 20 degrees and the Mt/F was 10, the relationships between 2 variables as described below were studied.

- The elastic modulus of PDL and anteroposterior movement of the incisal edge
- The elastic modulus of PDL and anteroposterior movement of the apex
- The elastic modulus of PDL and vertical movement
- The elastic modulus of PDL and minimum principal strain in PDL
- The elastic modulus of PDL and maximum principal strain in PDL

CHAPTER IV

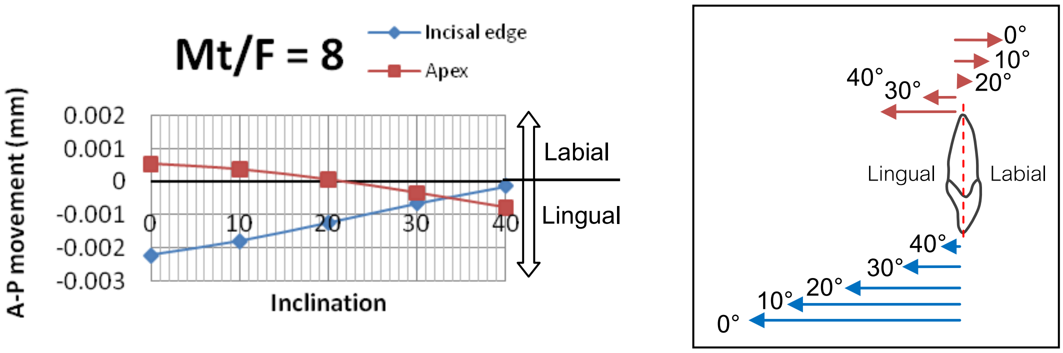
RESULTS

I. The effect of inclination when the Mt/F ratio was kept constrant

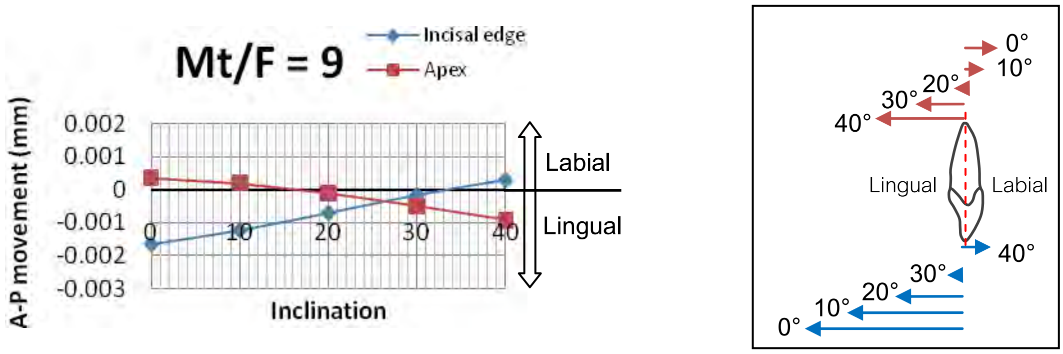
1. Anteroposterior movement of incisal edge and apex (Figure10)

In every Mt/F ratio, anteroposterior movements of the incisal edge and apex were similar in pattern. When the inclination had been increased, slopes of anteroposterior movement of the incisal edge graph increased while those of an apex decreased. In other words, the incisal edge was moved less to the lingual side and then moved more to the labial side. Coversely, an apex was moved less to the labial side and then moved more to the lingual side. However, the points of the intersection between the the incisal edge and the apex graphs were different among all Mt/F ratios. The inclination at the intersection between two graphs represented the inclination that made an incisor move bodily in each Mt/F ratio. These inclinations were about 33, 26.5, 18.5, 9 and lower than 0 degrees when Mt/F ratios were 8, 9, 10, 11, and 12, respectively. As a result, in the inclination which was lower than the inclination at the intersection, a crown movement of an incisor occurred, whereas a root movement occurred in the higher inclination.

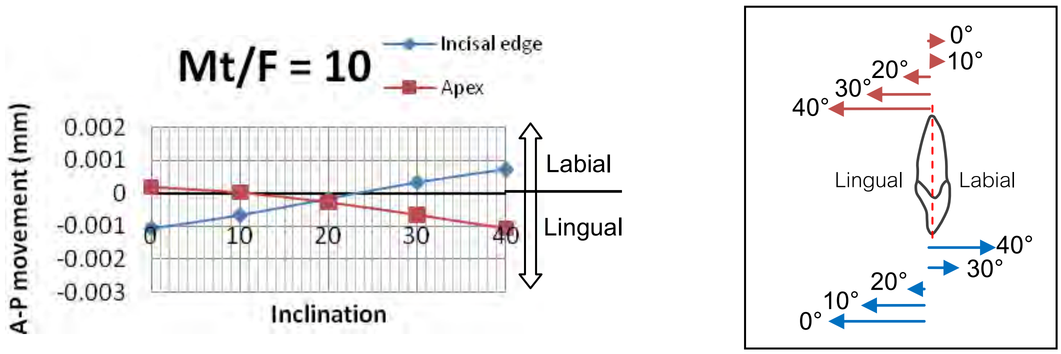
Figure 10, A to E, The relationships between inclination of a tooth and anteroposterior movement of the incisal edge and apex when the Mt/F ratio was kept constant at 8, 9, 10, 11, and 12. Diagrams on the right side show the directions and distance of the incisal edge and apex movement in each inclination.



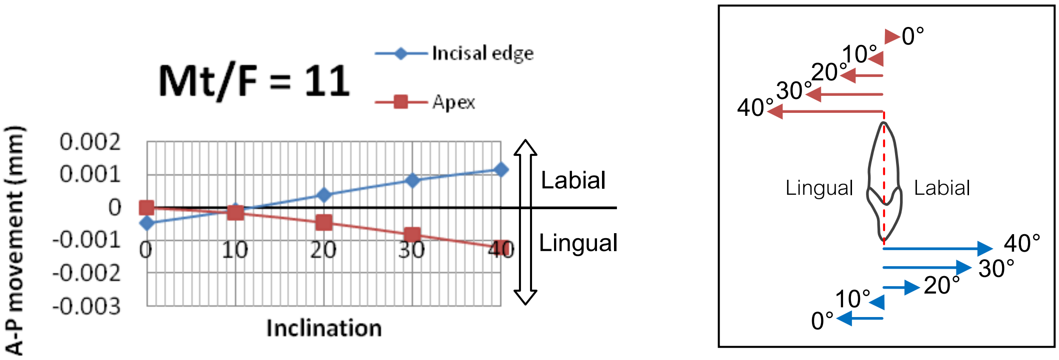
A. Mt/F ratio was 8.



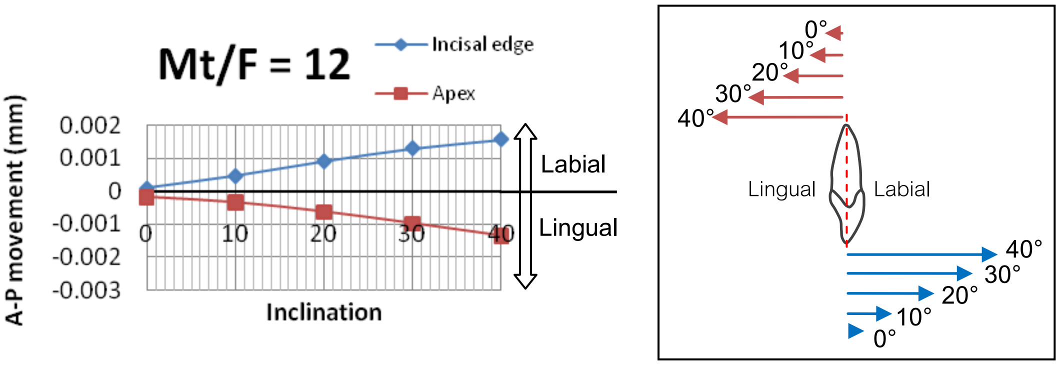
B. Mt/F ratio was 9.



C. Mt/F ratio was 10.



D. Mt/F ratio was 11.



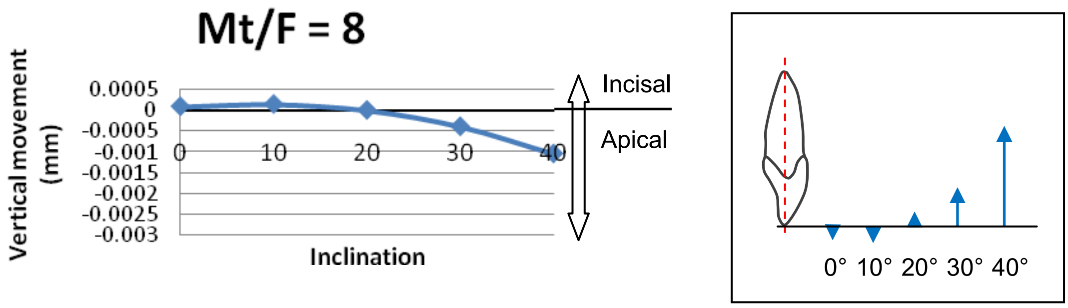
E. Mt/F ratio was 12.

2. Vertical movement of the incisal edge (Figure 11)

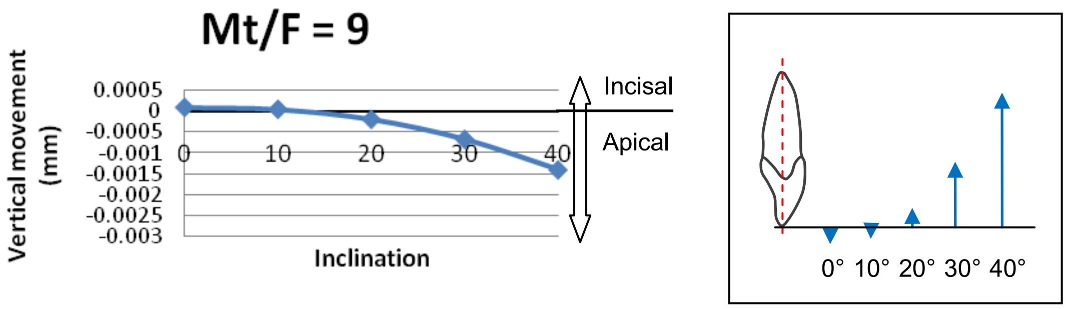
In every Mt/F ratio, when the inclination had been increased, vertical movement of the incisal edge to the apical side tended to gradually increase. It means that the position of incisal edge was changed more apically. The greater inclination associated with the grater rate of vertical movement change. In addition, at Mt/F ratio was 12, the greatest change of vertical movement was observed.

When the movements of the incisal edge in the anteroposterior and vertical direction were considered, it was found that the incisal edge moved labioapically with increased inclination.

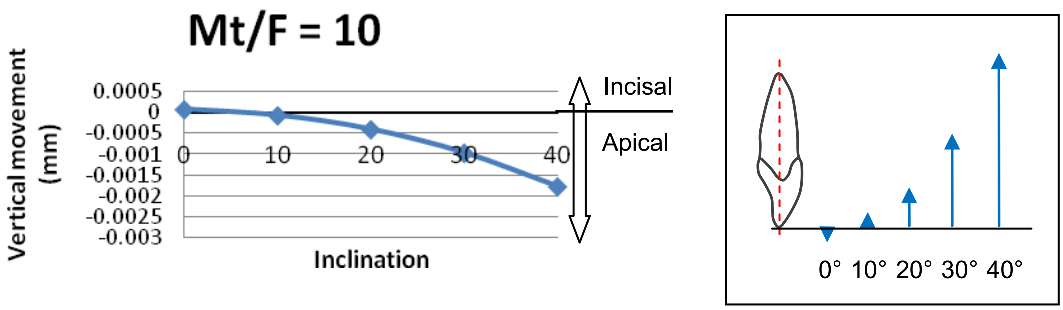
Figure 11, A to E, The relationships between inclination of a tooth and vertical movement of the incisal edge when the Mt/F ratio was kept constant at 8, 9, 10, 11, and 12. Diagrams on the right side show the directions and distance of vertical movement of the incisal edge in each inclination.



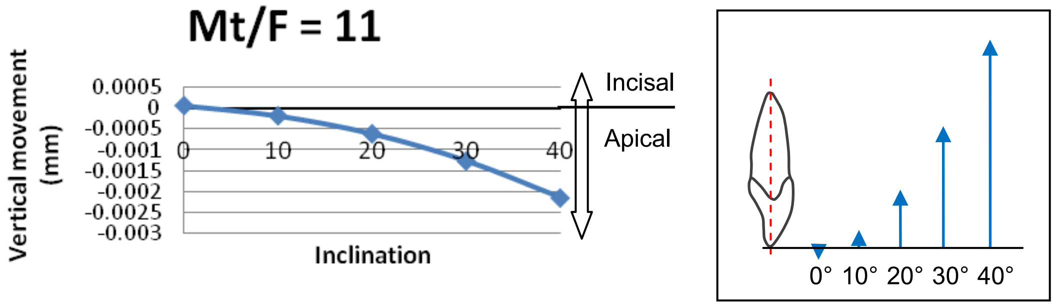
A. Mt/F ratio was 8.



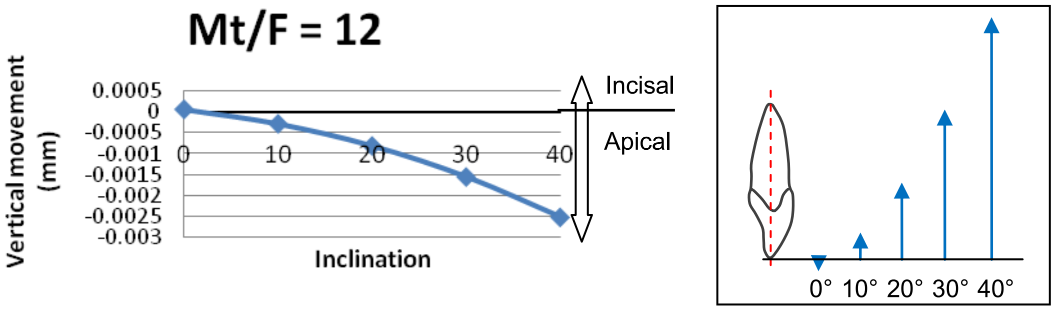
B. Mt/F ratio was 9.



C. Mt/F raio was 10.



D. Mt/F ratio was 11.



E. Mt/F ratio was 12.

3. **Periodontal stress**

In all of Mt/F ratios and inclinations, all values of the lowest minimum principal stress were negative while all values of the highest maximum principal stress were positive. (Table 8 and 11) Therefore, the absolute value of the lowest minimum principal stress was **maximum compressive stress** while that of the highest maximum principal stress was **maximum tensile stress**.

In each Mt/F ratio, magnitude and areas of maximum compressive and tensile stress differed from each other when the inclination was incresed, as described below. (Figure 12 and Table 8)

<u>At Mt/F ratio was 8</u>

The lowest magnitude of maximum compressive (0.03166 N/mm^2) and tensile (0.00517 N/mm^2) stress occurred at the inclination was 20 and 40 degrees, respectively. In contrast, the highest magnitude of maximum compressive (0.06064 N/mm^2) and tensile (0.03587 N/mm^2) stress happened at the inclination was 40 and 0 degrees, respectively. The positions of maximum compressive stress at 0 and 10-degree inclination were in linguocervical area and at 20, 30, and 40 degrees were in distolabial, distal, and distolingual area of an apex, respectively. On the other hand, the positions of maximum tensile stress at the inclination from 0 to 30 degrees were in labiocervical area and at 40 degrees was at 7 mm from an apex on the labial side.

<u>At Mt/F ratio was 9</u>

The lowest magnitude of maximum compressive (0.02619 N/mm^2) and tensile (0.005706 N/mm^2) stress arised at 10 and 40-degree inclination, respectively; whereas the highest magnitude of maximum compressive (0.06565 N/mm^2) and tensile (0.02959 N/mm^2) stress arised at 40 and 0 degrees, respectively. The positions of maximum compressive stress at 0 and 10-degree inclination were in linguocervical area, at 20 degrees was in distal area of an apex, and at 30 and 40 degrees were in distolingual area of an apex. Conversely, the positions of maximum tensile stress at the inclination from 0 to 20 degrees were in labiocervical area and at 30 and 40 degrees were at 7 and 5 mm from an apex on labial side, respectively.

At Mt/F ratio was 10

The lowest magnitude of maximum compressive (0.01955 N/mm^2) and tensile (0.007416 N/mm^2) stress occurred at 10 and 30-degree inclination, respectively; while the highest magnitude of maximum compressive (0.07069 N/mm^2) and tensile (0.02336 N/mm^2) stress took place at 40 and 0 degrees, respectively. The positions of maximum compressive stress at 0 and 10-degree inclination were in linguocervical area and at the inclination from 20 to 40 degrees were in distolingual area of an apex. However, the positions of maximum tensile stress at the inclination from 0 to 20 degrees were in labiocervical area and at 30 and 40 degrees were at 5 mm from an apex on labial side.

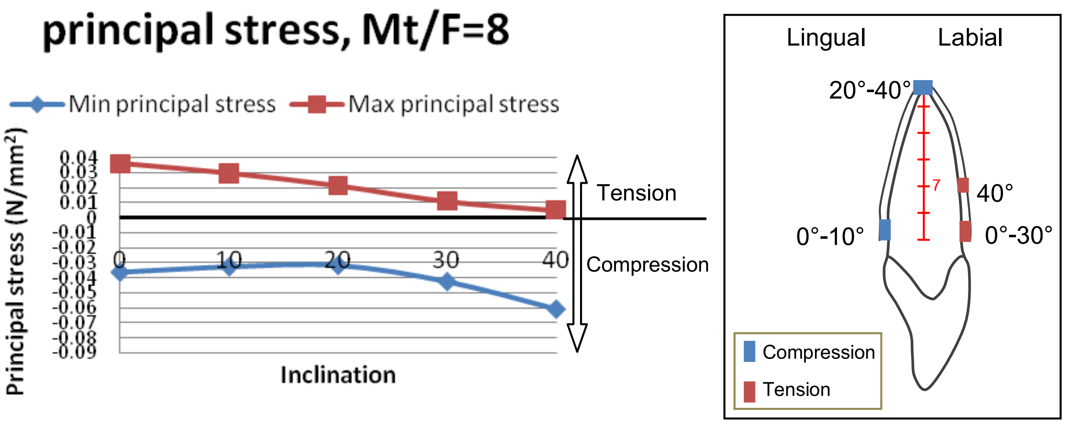
At Mt/F ratio was 11

The lowest magnitude of maximum compressive (0.01642 N/mm^2) and tensile (0.006749 N/mm^2) stress was found at 10 and 20-degree inclination, respectively. But the highest magnitude of maximum compressive (0.07577 N/mm^2) and tensile (0.01704 N/mm^2) stress was found at 40 and 0 degrees, respectively. The position of maximum compressive stress at 0 degree inclination was in linguocervical area. And those at the inclination from 10 to 40 degrees were in disotlingual area of an apex. In contrast, the position of maximum tensile stress at 0-degree inclination was in labiocervical area. Morover, the positions of maximum tensile stress at 10, 20, 30, and 40 degrees were at 7, 5, 5, and 1 mm from an apex on the labial side, respectively.

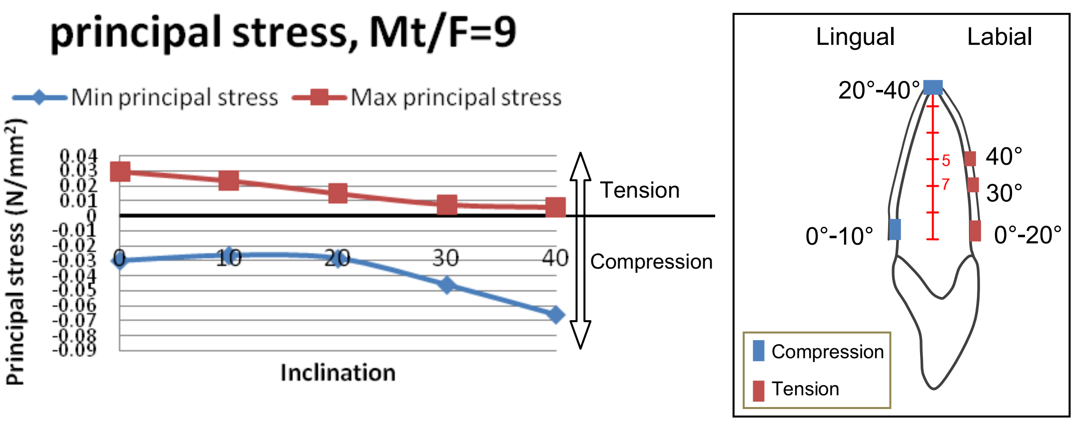
At Mt/F ratio was 12

The lowest magnitude of maximum compressive (0.01353 N/mm^2) and tensile (0.01241 N/mm^2) stress occurred at 0 and 20-degres inclination, respectively. Conversely, the highest of both (0.08104 and 0.02278 N/mm^2 for maximum compressive and tensile stress) occurred at 40-degree inclination. The positions of maximum compressive stress at 0 and 10-degree inclination were at 5 and 1 mm from an apex on the lingual side, respectively. However, the positions of maximum tensile stress at the inclination from 0 to 20 degrees were at 5 mm from an apex on the labial side and at 30 and 40 degrees were at 1 mm from an apex on the labial side.

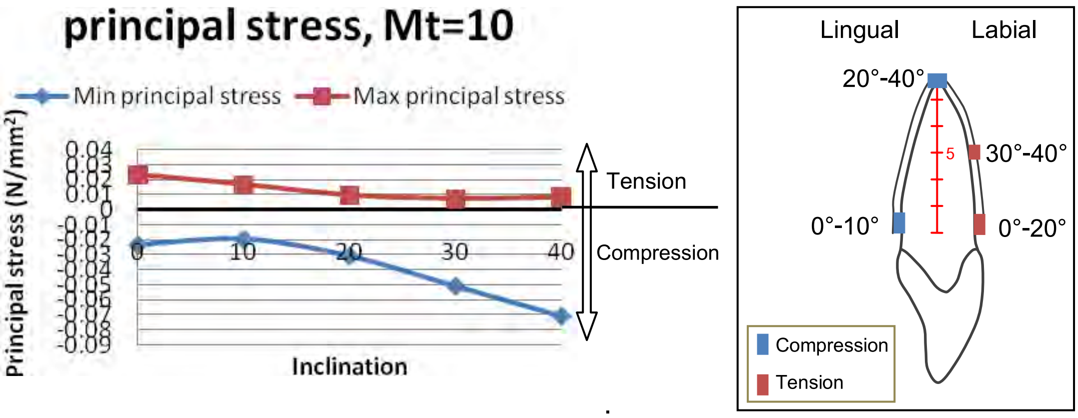
Figure 12, A to E, The relationships between inclination of a tooth and periodontal stress magnitude when the Mt/F ratio was kept constant at 8, 9, 10, 11, and 12. Diagrams on the right side show the positions of maximum compressive and tensile stress in each inclination.



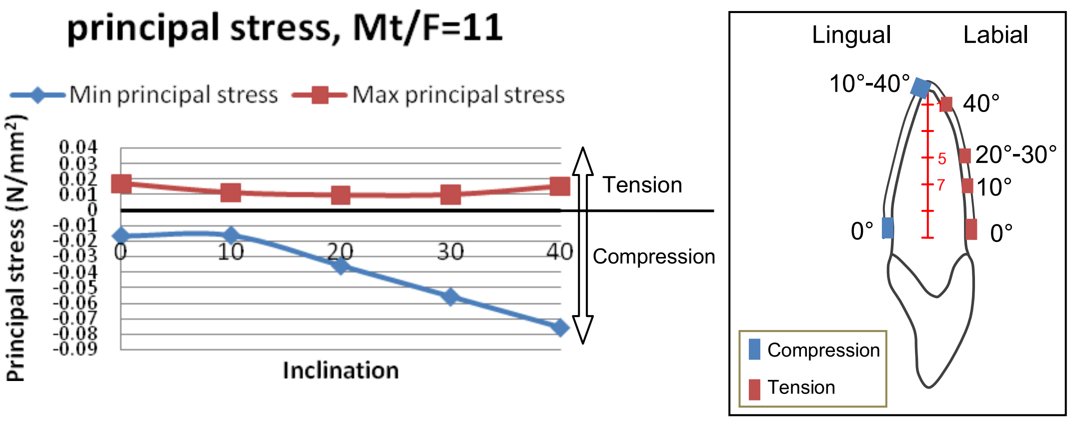
A. Mt/F was 8.



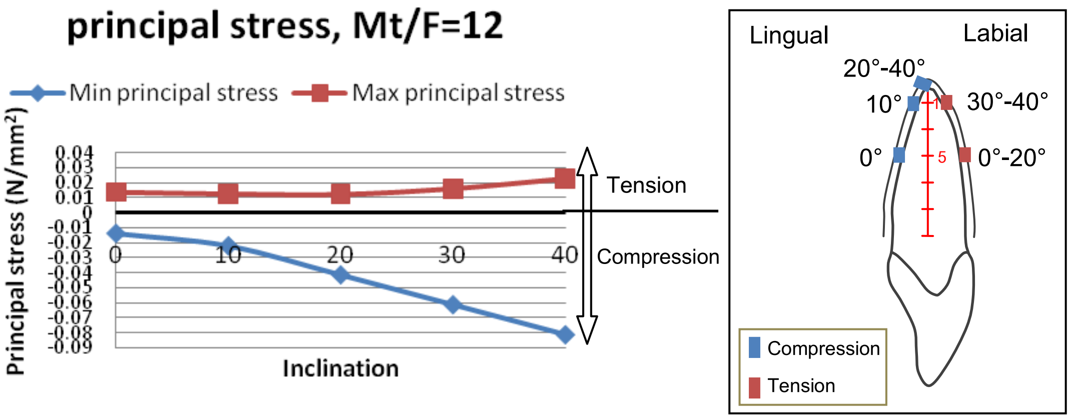
B. Mt/F ratio was 9.



C. Mt/F ratio was 10.



D. Mt/F ratio was 11.



E. Mt/F ratio was 12.

4. **Periodontal strain**

In all of Mt/F ratios and inclinations, all values of the lowest minimum principal strain were negative while all values of the highest maximum principal strain were positive. (Table 9 and 12) Therefore, the absolute value of the lowest minimum principal strain was **maximum compressive strain** while that of the highest maximum principal strain was **maximum tensile strain**.

With incresed inclination, characteristics of changes of maximum compressive and tensile strain in each Mt/F ratio differed from each orther. (Figure 13 and Table 9)

<u>At Mt/F ratio was 8</u>

The lowest magnitude of maximum compressive (0.002872) and tensile (0.002102) strain occurred at 20-degree inclination; while the highest magnitude of maximum compresive (0.005549) and tensile (0.003299) strain arised at 40 and 0-degree inclination, respectively. The positions of maximum compressive strain at 0 and 10-degree inclination were in linguocervical area and at the inclination from 20 to 40 degrees were at distal area of an apex. On the contrary, the position of maximum tensile strain at the inclination from 0 to 20 degrees were in labiocervical area and at 30 and 40 degrees were at 5 mm from an apex on the labial side.

<u>At Mt/F ratio was 9</u>

The lowest magnitude of maximum compressive (0.00248) and tensile (0.00173) strain was presented at 10 and 20 degree of inclination, respectively. Conversely, the highest magnitude of both maximum compressive (0.006001) and tensile (0.003255) strain happened at 40-degree inclination. The positions of maximum compressive strain at 0 and 10-degree inclination were in linguocervical area and at the inclination from 20 to 40 degrees were in distal and distolingual area of an apex. However, the positions of maximum tensile strain of the inclination from 0 to 20 degrees were in labiocervical area and at 30 and 40 degrees were in the labial side of an apex.

<u>At Mt/F ratio was 10</u>

The lowest magnitude of both maximum compressive (0.001852) and tensile (0.001563) strain took place at 10-degree inclination; whereas the highest magnitude of both maximum compressive (0.006529) and tensile (0.003563) strain were found at 40 degrees. The positions of maximum compressive strain at 0 and 10-degree inclination were in linguocervical area and at the inclination from 20 to 40 degrees were in distal and distolingual area of an apex. On the other hand, the positions of maximum tensile strain at 0 and 10-degree inclination were in labiocervical area and at the inclination from 20 to 40 degrees were at 5 mm from an apex on the labial side.

At Mt/F ratio was 11

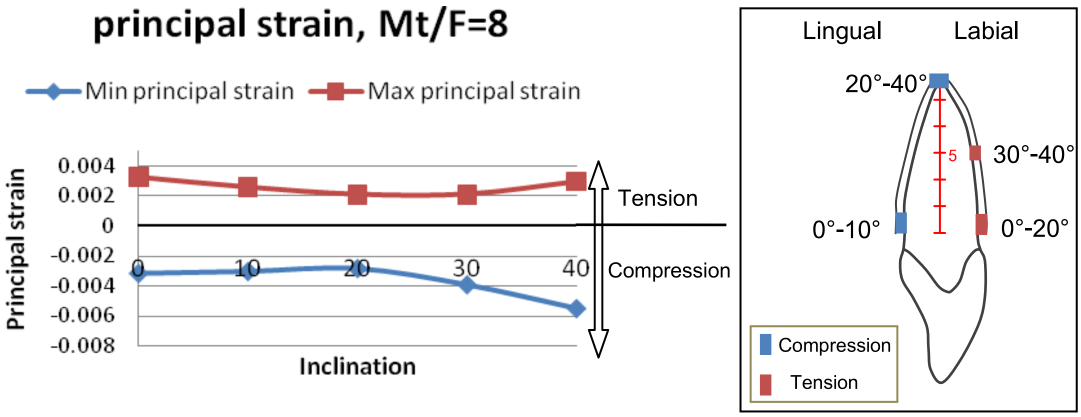
The lowest magnitude of maximum compressive (0.001468) and tensile (0.001187) strain occurred at 0 and 10-degree inclination, respectively. But the highest magnitude of both maximum compressive (0.00712) and tensile (0.003887) strain were shown at 40 degrees. The positions of maximum compressive strain at 0 degree of inclination was in linguocervical area, at 10 degrees was an area at 5 mm from an apex on the lingual side, and at the inclination from 20 to 40 degrees were in distolingual area of an apex. Conversely, the positions of maximum tensile strain at 0 degree of inclination was in labiocervical area, at 10 degrees was an area at 7 mm from an apex on the labial side, and at the inclination from 20 to 40 degrees were an area at 5 mm from an apex on the labial side.

At Mt/F was 12

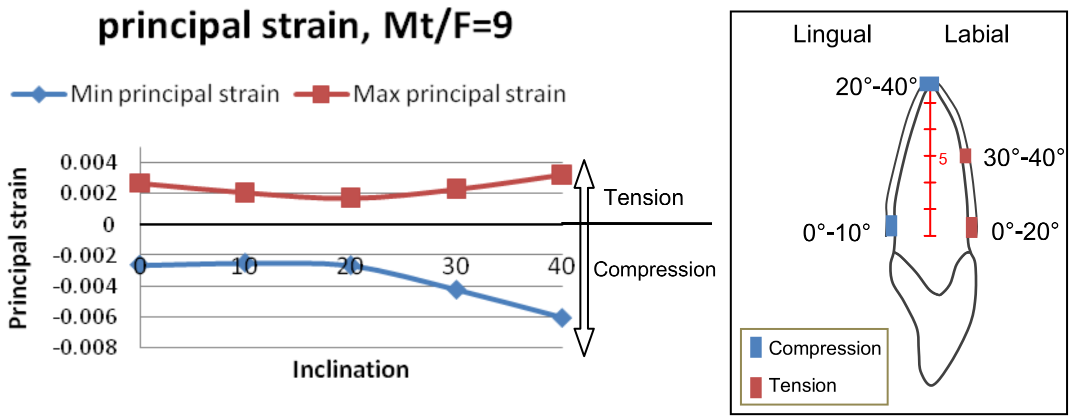
The lowest magnitude of both maximum compressive (0.001193) and tensile (0.001197) strain arised at 0 degree of inclination; whereas the highest magnitude of both maximum compressive (0.007752) and tensile (0.004298) strain were found at 40 degrees. The position of maximum compressive strain at 0 degree of inclination was at 5 mm from an apex on the lingual side. And those at the inclination from 10 to 40 degrees were in distolingual area of an apex. However, the position of maximum tensile strain in every inclination was at 5 mm from an apex on the labial side.

In brief, the inclination which made the lowest magnitude of maximum compressive and tensile strain in each Mt/F ratio was relatively close to the inclination which produce an incisor move bodily. Moreover, in every Mt/F ratio, the greatest magnitude of maximum compressive strain occurred at 40-degree inclination in distolingual area of an apex.

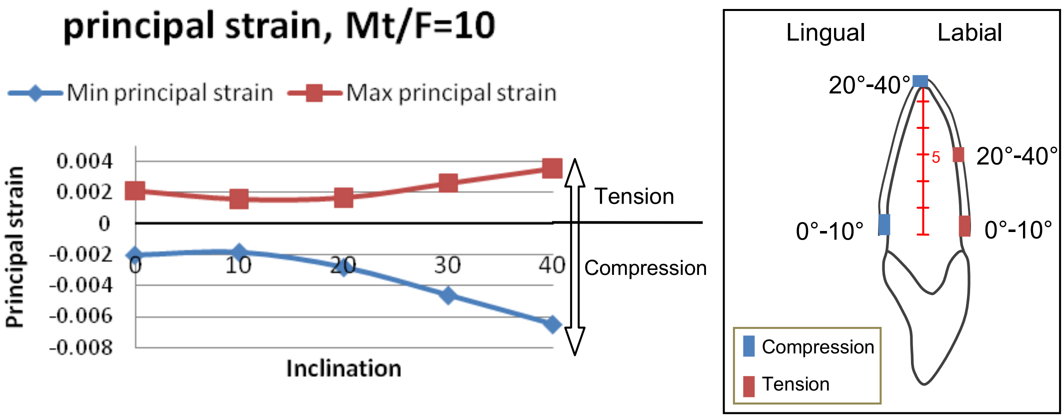
Figure 13, A to E, The relationships between the inclination of a tooth and periodontal strain when the Mt/F ratio was kept constant at 8, 9, 10, 11, and 12. Diagrams on the right side show the positions of maximum compressive and tensile strain in each inclination.



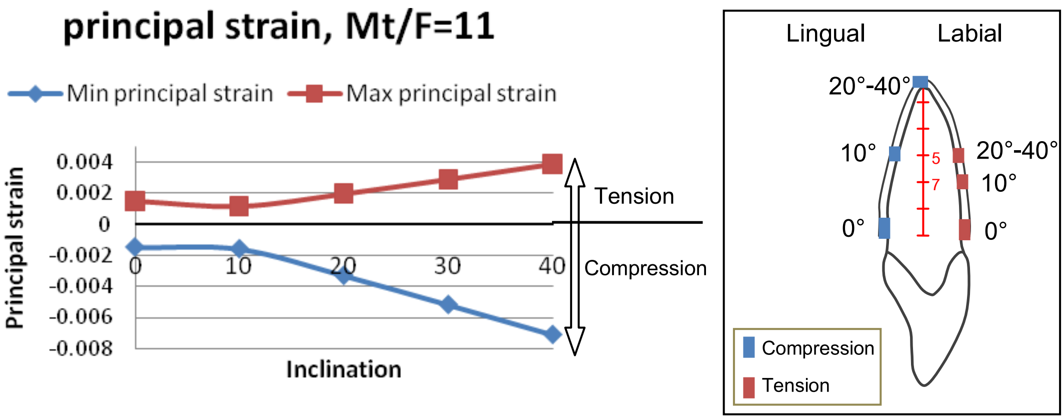
A. Mt/F ratio was 8.



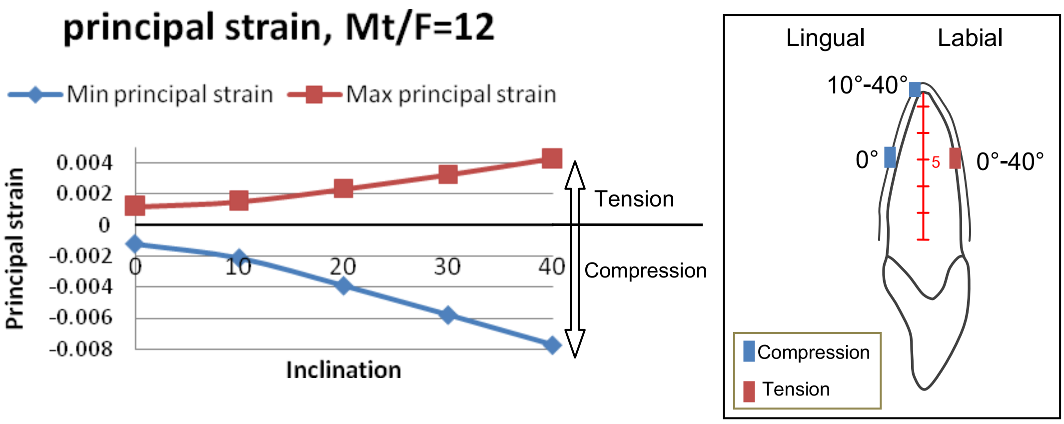
B. Mt/F ratio was 9.



C. Mt/F ratio was 10.



D. Mt/F ratio was 11.



E. Mt/F ratio was 12.

II. The effect of Mt/F ratio when the inclination was kept constant

1. Anteroposterior movement of the incisal edge and apex (Figure 14)

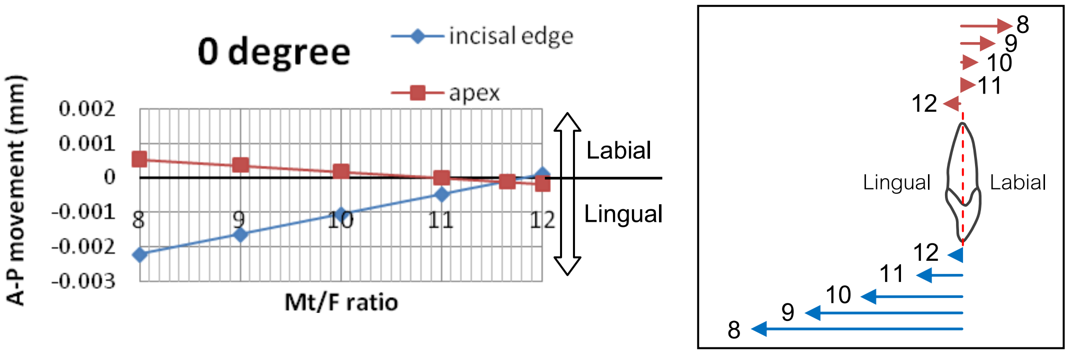
Every inclination had similar tendency of anteroposterior movement of the incisal edge and apex with respect to the pattern of changes when the Mt/F ratio was changed. Both of the anteroposterior movements of the incisal edge and apex had a linear relationship with the Mt/F ratio. When the Mt/F ratio was increased, the incisal edge tended to move less to the lingual side and consequently the position was more to the labial side. In contrast, the apex tended to move less to the labial side and thus the position moved more to the lingual side. Furthermore, in each inclination, the slope of the plotted relationship of incisal edge movement was more than that of an apex movement. In addition, when the inclination increased, the slopes of both incisal edge and apex graphs decreased slightly. (Table 4)

Table 4 The relationships between the inclination of the incisor and magnitude of slopes of graphs plotted between anteroposterior movement and Mt/F ratios of the incisal edge and apex

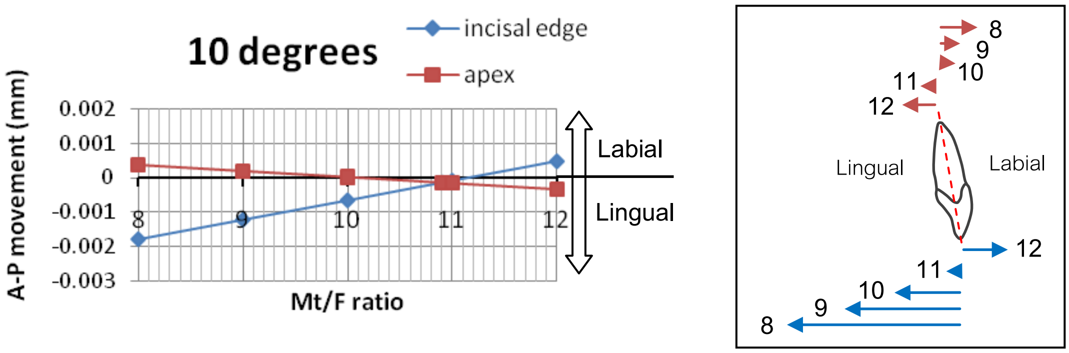
Inclination	Magnitude of slopes of anteroposterior movement graphs	
	Incisal edge	Apex
0	0.000579	0.000178
10	0.000566	0.000177
20	0.000538	0.000171
30	0.000489	0.000159
40	0.000428	0.000142

Nevertheless, the points of the intersection between graphical lines of the incisal edge and apex were different among all inclinations. The intersection between two graphical lines indicated that the incisal edge and apex were moved in the same direction and distance. Therefore, the Mt/F ratio at the intersection represented the Mt/F ratio which produced bodily movement of an incisor. In addition, at 40-degree inclination, the Mt/F ratio at the intersection was lower than 8. To find the exact Mt/F ratio which produced bodily movement, the Mt/F ratio was further reduced to 6. It was found that the Mt/F ratios which created bodily movement were 11.65, 10.91, 9.85, 8.48, and 6.87 when the inclinations were 0, 10, 20, 30, and 40 degrees, respectively. Besides, in each inclination, Mt/F ratios which were lower than these ratios produced crown movement to the lingual side; while the higher ratios created root movement to the lingual side of the incisor.

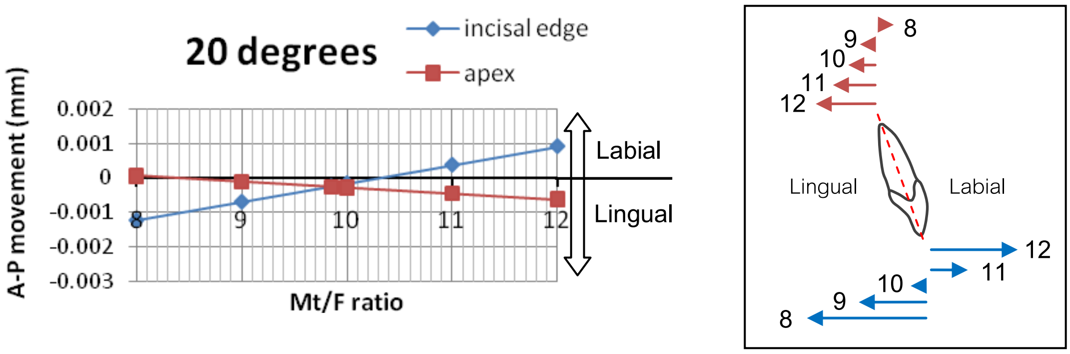
Figure 14, A to E, The relationships between the Mt/F ratio and anteroposterior movements of the incisal edge and apex when the inclination was kept constant at 0, 10, 20, 30, and 40 degrees. Diagrams on the right side show the directions and distances of anteroposterior movement of the incisal edge and apex for each Mt/F ratio.



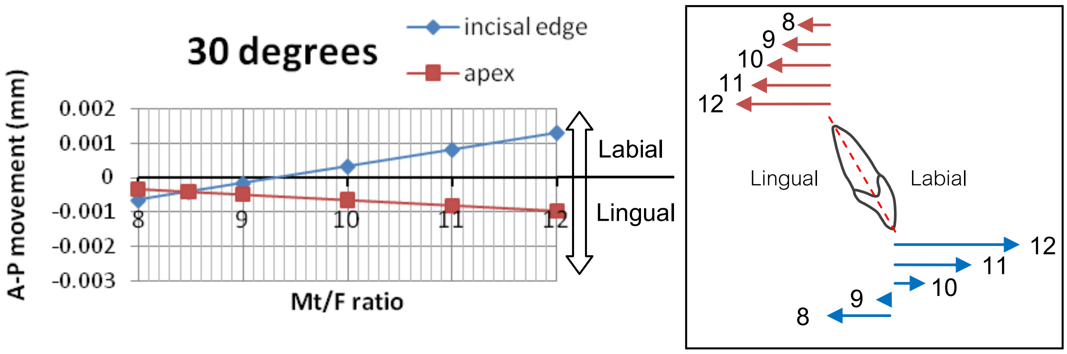
A. The inclination was 0 degree.



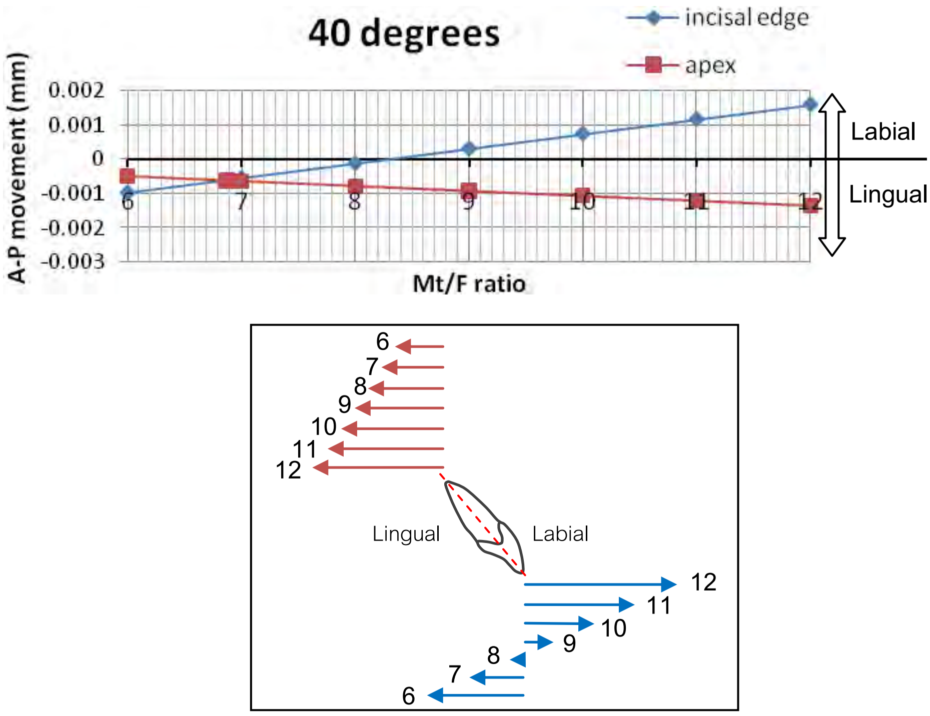
B. The inclination was 10 degrees.



C. The inclination was 20 degrees.



D. The inclination was 30 degrees



E. The inclination was 40 degrees.

As mentioned earlier, the Mt/F ratio which produced bodily movement was equal to the length of the perpendicular projection from the line of action of the force to the center of resistance. In other words, it was the distance in Z-direction in the three-dimensional Cartesian coordinate system (Figure 15). To eliminate the influence of different root length in Z-direction in each inclination, the position of the center of resistance in every model was demonstrated as the proportion of the distance from the center of resistance to the apex (X) to the root length. This root length was an average of 2 lengths in Z axis covered by labial (RLa) and lingual (RLi) alveolar bone. The results showed that when the inclinations of the tooth were 0, 10, 20, 30, and 40 degrees, the proportions (x/root length) were comparable. They were 0.668, 0.671, 0.672, 0.675, and 0.677, respectively. The observed proportions were within a narrow range with a mean of 0.673.

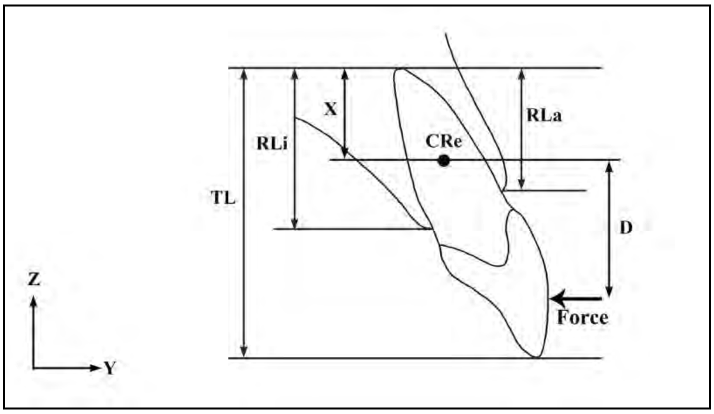


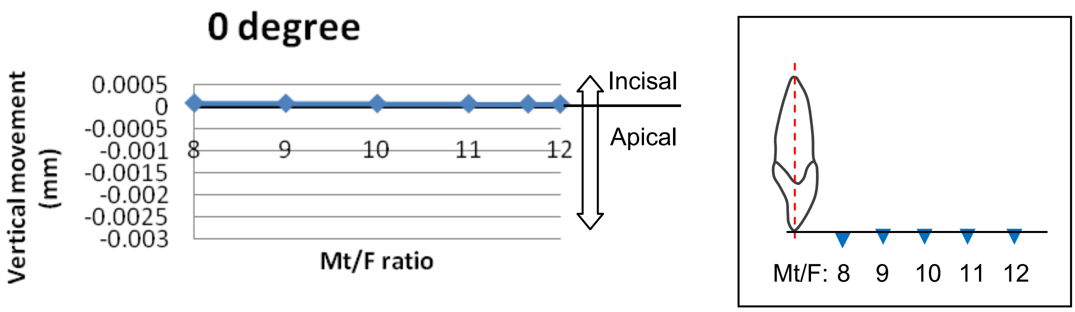
Figure 15 Position of center of resistance with respect to geometries of a central incisor and alveolar bone. CRe = center of resistance of an incisor: TL = tooth length: RLi = root length in Z axis covered by lingual alveolar bone: RLa = root length in Z axis covered by labial alveolar bone: X = distance, perpendicular to the occlusal plane, from the center of resistance to the apex : D = perpendicular distance from the point of force application to the center of resistance; this distace equals the M/F ratio which produced bodily movement.

2. Vertical movement of incisal edge (Figure 16)

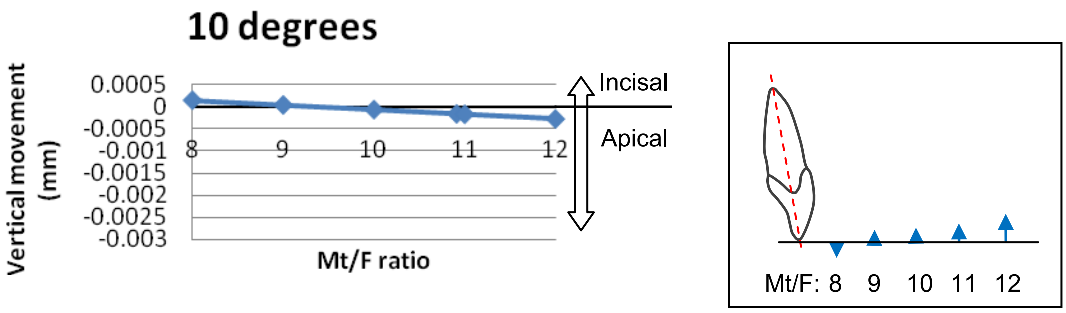
In every inclination, vertical movement of the incisal edge had a linear relationship with the Mt/F ratio. When the Mt/F ratio had been increased, vertical movement of the incisal edge was decreased. In other words, the incisal edge would be more moved apically with the increased Mt/F ratio. Moreover, the slope of vertical movement of the incisal edge was increased when the inclination increased. These slopes were -0.000006, -0.000106, -0.000203, -0.000291, and -0.00037 as the inclinations of the incisor were 0, 10, 20, 30, and 40 degrees, respectively.

When we considered the movement of the incisal edge in the anteroposterior and vertical direction, we found that the incisal edge moved labioapically with increased Mt/F ratio.

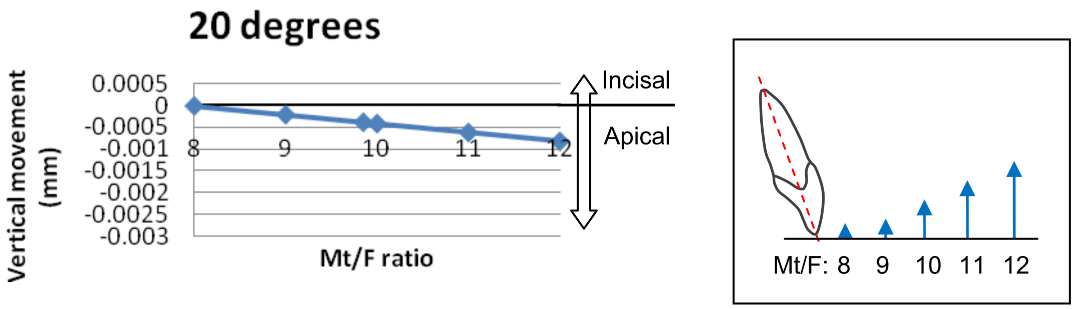
Figure 16, A to E, The relationships between the Mt/F ratio and anteroposterior movement of the incisal edge when the inclination was kept constant at 0, 10, 20, 30, and 40 degrees. Diagrams on the right side show direction and distance of vertical movement of the incisal edge.



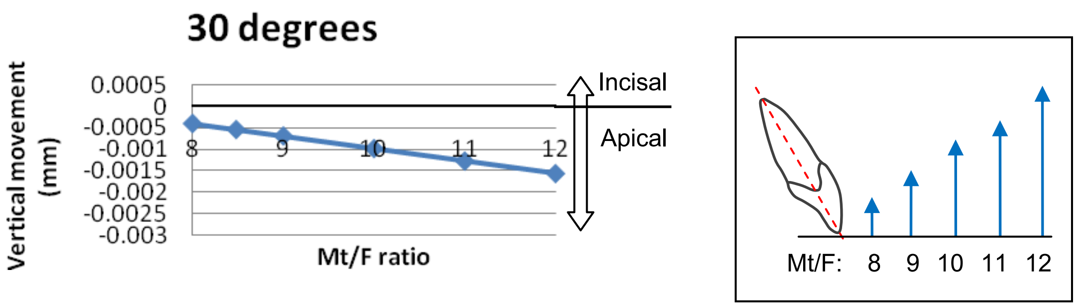
A. The inclination was 0 degree.



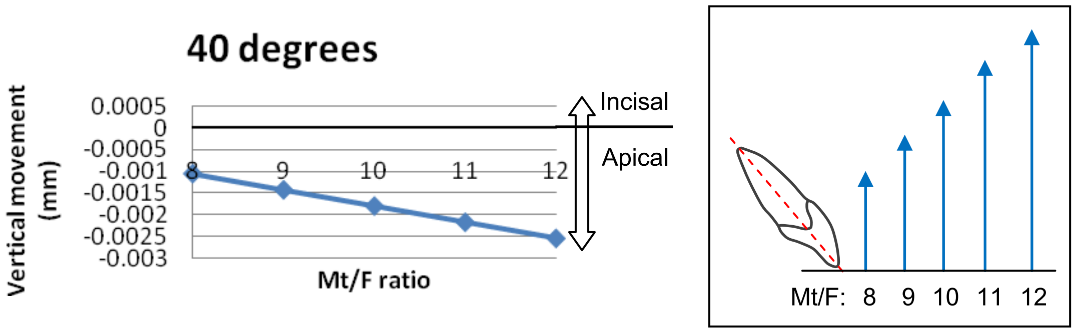
B. The inclination was 10 degrees.



C. The inclination was 20 degrees.



D. The inclination was 30 degrees.



E. The inclination was 40 degrees.

3. Periodontal stress (Figure 17 and Table 11)

<u>At 0-degree inclination</u>

The lowest magnitude of both maximum compressive (0.01297 N/mm^2) and tensile (0.1299 N/mm^2) stress occurred when the Mt/F ratio was 11.65; whereas the highest magnitude of maximum compressive (0.0316 N/mm^2) and tensile (0.03587 N/mm^2) stress was found when the Mt/F ratio was 8. The positions of maximum compressive stress when the Mt/F ratio was from 8 to 11 were in linguocervical area and when the Mt/F ratio was more than 11, they were in the middle of the lingual surface. In contrast, the positions of maximum tensile stress were in labiocervical area when the Mt/F ratio was from 8 to 11 and were in the middle of the labial surface when the Mt/F ratio was more than 11.

At 10-degree inclination

The lowest magnitude of maximum compressive (0.01604 N/mm^2) and tensile (0.01132 N/mm^2) stress happened when the Mt/F ratios were 10.91 and 11, respectively. However, the highest magnitude of both maximum compressive (0.03258 N/mm^2) and tensile (0.02954 N/mm^2) stress happened when the Mt/F ratio was 8. The positions of maximum compressive stress were on the lingual side. They were in cervical, middle, and apical areas when the Mt/F ratios were from 8 to 10, 10.91, and from 11 to 12, respectively. Conversely, the positions of maximum tensile stress were on the labial side. they were in cervical area when the Mt/F ratios were from 8 to 10. And when the Mt/F ratio were 10.91, 11, and 12, they were at 9, 7, and 5 mm from an apex, respectively.

At 20-degree inclination

The lowest magnitude of maximum compressive (0.03005 N/mm^2) and tensile (0.009705 N/mm^2) stress was shown when the Mt/F ratios were 9.85 and 10, respectively. On the contrary, the highest magnitude of maximum compressive (0.04117 N/mm^2) and tensile (0.02125 N/mm^2) stress was found when the Mt/F ratios were 12 and 8, respectively. The positions of maximum compressive stress were at the apex. With the increased Mt/F ratio, these positions were changed from the labial to lingual side. On the other hand, the positions of maximum tensile stress were on the labial side. With the increased Mt/F ratio, these positions were change from cervical to middle areas.

At 30-degree inclination

The lowest magnitude of maximum compressive (0.04242 N/mm^2) and tensile (0.007416 N/mm^2) stress occurred when the Mt/F ratios were 8 and 10, respectively. But the highest magniutude of both maximum compressive (0.06105 N/mm^2) and tensile (0.01618 N/mm^2) stress occurred when the Mt/F ratio was 12. The positions of maximum compressive stress were in distolingual area of an apex; whereas the positions of maximum tensile stress were on the labial side. With the increased Mt/F ratio, these position were changed from cervical to apical areas.

At 40-degree inclination

The lowest magnitude of maximum compressive (0.05519 N/mm^2) and tensile (0.005172 N/mm^2) stress took place when the Mt/F ratios were 6 and 8, respectively. Instead, the highest magnitude of both maximum compressive (0.08104 N/mm^2) and tensile (0.02278 N/mm^2) stress took place when the Mt/F ratio was 12. The position of maximum compressive stress was in distal and distolingual area of an apex. Conversely, the positions of maximum tensile stress were on the labial side and were changed from cervical to apical areas, with the increased Mt/F ratio.

To conclude, in the low degrees of inclination, such as 0 to 20 degrees, the lowest magnitude of maximum compressive and tensile stress occurred when the Mt/F ratios were close to the ratios which produced bodily movement of an incisor. However, in the higher degrees, this relationship was not found. Moreover, in the low degrees of inclination, the areas of maximum compressive and tensile stress were usually found in cervical areas; whereas, in the higher degrees, the areas of maximum compressive stress were found in apical area and those of maximum tensile stess were found along the root surface on the labial side.

In addition, magnitude and areas of minimum and maximum principal stress in each inclination when bodily movement occurred were summarized in table 5

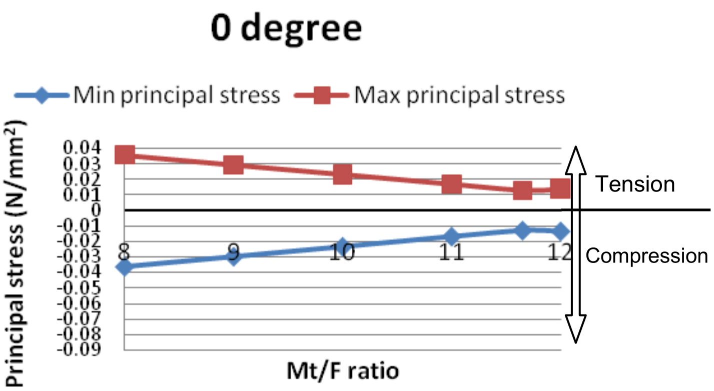
Table 5 Maximum and minimum principal stress (N/mm^2) from bodily movement in each inclination

Inclination	Mt/F	Minimum principal stress		Maximum principal stress	
		magnitude	area	magnitude	area
0	11.65	-0.01297	Li/ 7 mm from apex	0.01299	La/ 5 mm from apex
10	10.91	-0.01604	Li/ 5 mm from apex	0.01151	La/ 9 mm from apex
20	9.85	-0.03005	Li/ apical	0.01019	La/ 9 mm from apex
30	8.48	-0.04319	Li/ apical	0.008597	La/ 9 mm from apex
40	6.87	-0.05572	D/ apical	0.006727	La/ 9 mm from apex

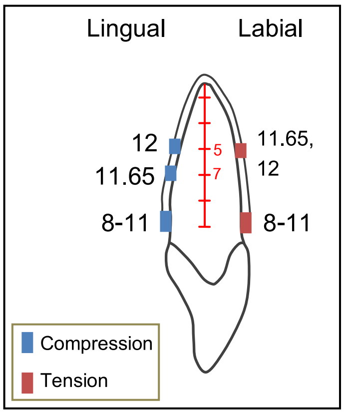
Figure 17, A to E,

1) show the relationships between the Mt/F ratio and principal stress when the inclination of a tooth was kept constant at 0, 10, 20, 30, and 40 degrees.
2) Diagrams on the right side show the positions of maximum compressive and tensile stress.
3) Diagrams show major principal stress distribution when Mt/F ratio was the ratio that produced bodily movement.

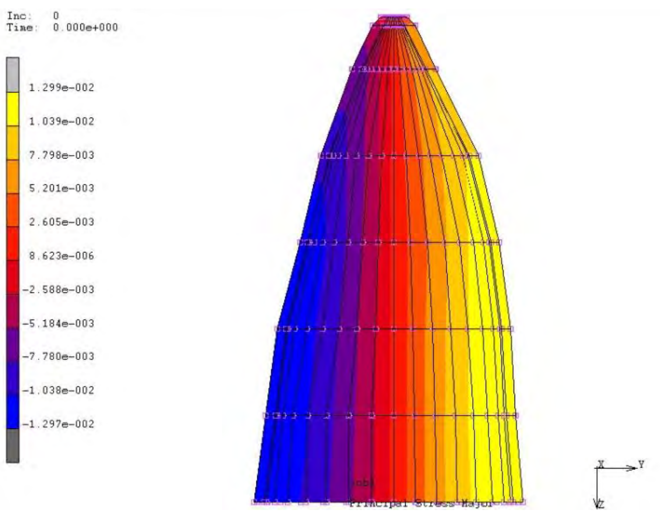
A. The inclination was 0 degree.



1)

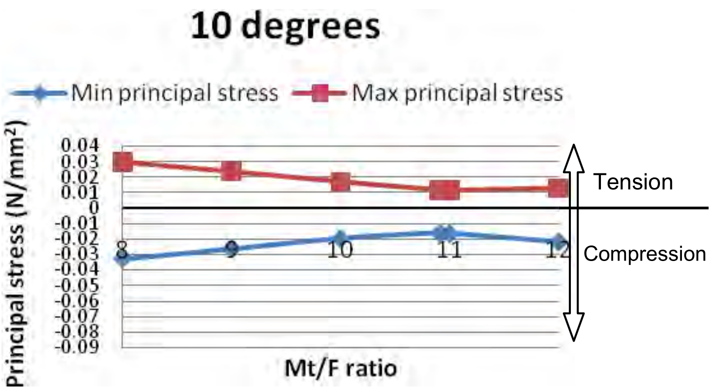


2)

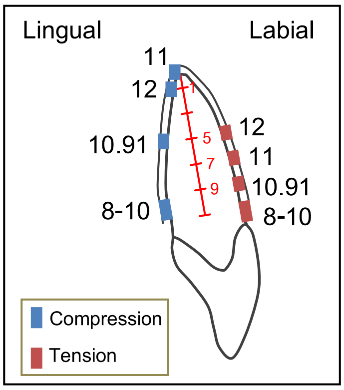


3) Mt/F ratio was 11.65

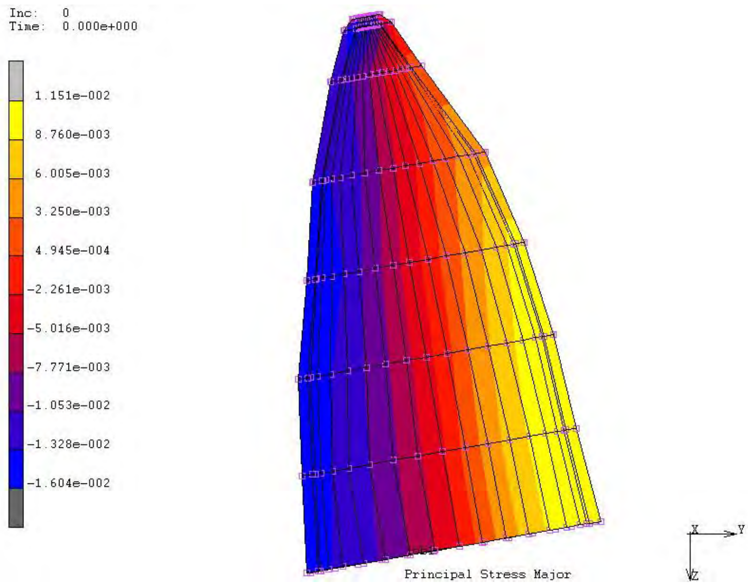
B. The inclination was 10 degrees.



1)

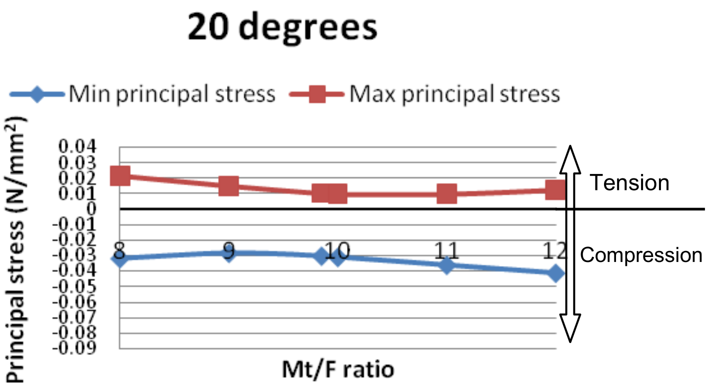


2)

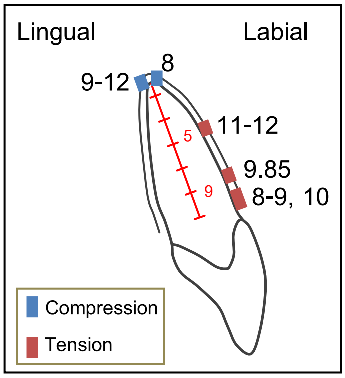


3) Mt/F ratio was 10.91

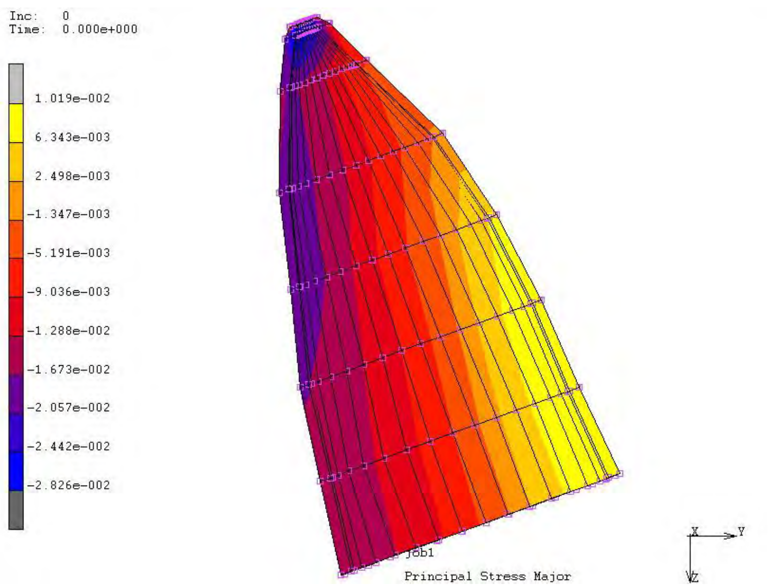
C. The inclination was 20 degrees.



1)

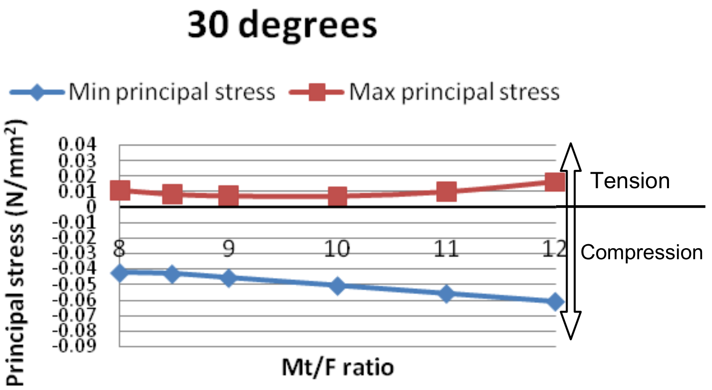


2)

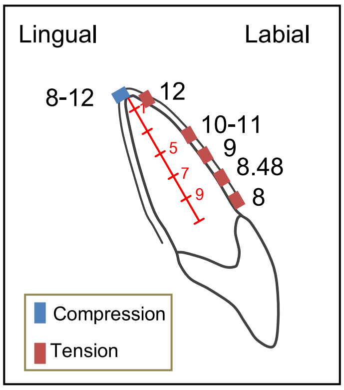


3) Mt/F ratio was 9.85

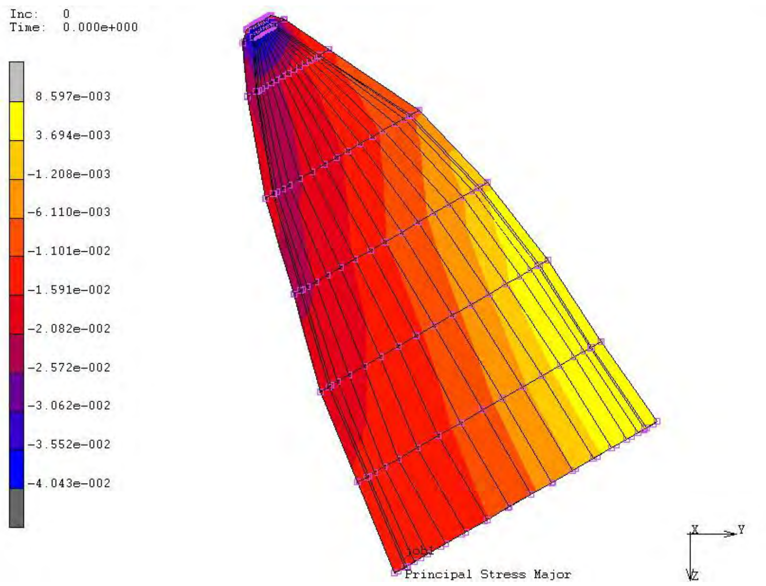
D. The inclination was 30 degrees.



1)

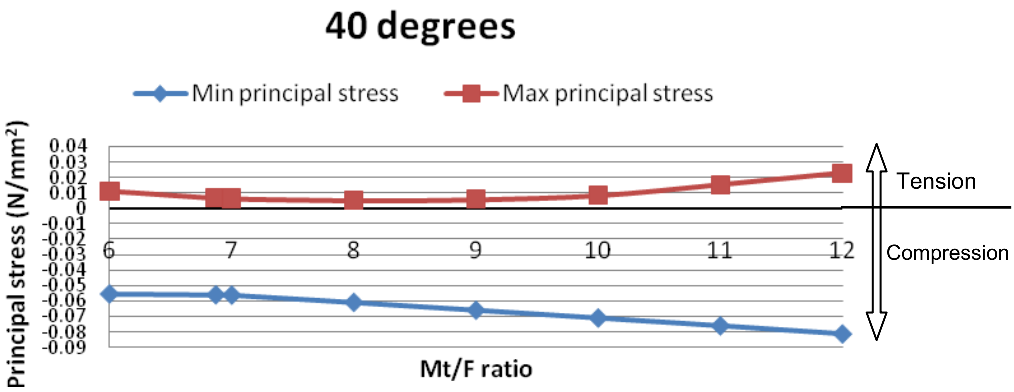


2)

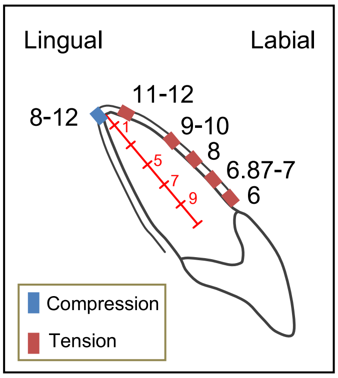


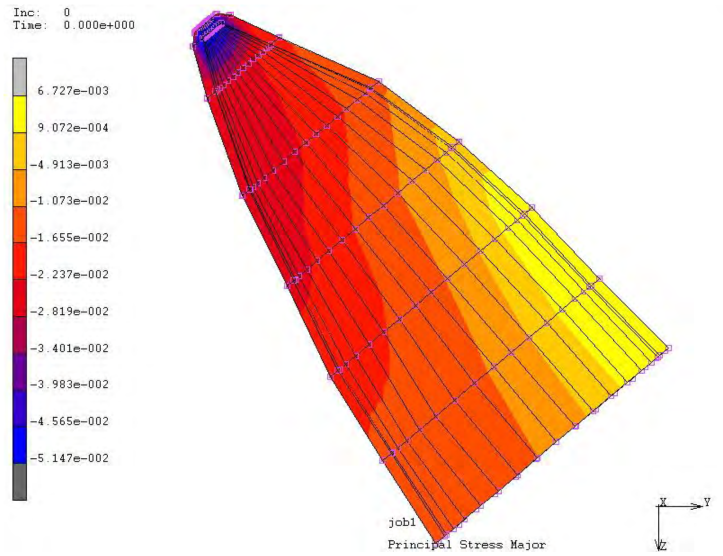
3) Mt/F ratio was 8.48

E. The inclination was 40 degrees.



1)





2)

3) Mt/F ratio was 6.87

4. Periodontal strain (Figure 18 and Table 12)

At 0 degree of inclination

The lowest magnitude of both maximum compressive (0.001124) and tensile (0.001157) strain was presented when the Mt/F ratio was 11.65. The highest magnitude of both (0.003202 and 0.003299 for maximum compressive and tensile strain) was shown when the Mt/F ratio was 8. The positions of maximum compressive strain when the Mt/F ratio was from 8 to 11 were in linguocervical area and when the Mt/F ratio was more than 11, they were in the middle of the lingual surface. In contrast, the positions of maximum tensile strain were in labiocervical area when the Mt/F ratio was from 8 to 11 and were in the middle of the labial surface when the Mt/F ratio was more than 11.

At 10-degree inclination

The lowest magnitude of maximum compressive (0.001574) and tensile (0.001187) strain was found when the Mt/F ratios were 10.91 and 11, respectively. But the highest magnitude of both maximum compressive (0.003068) and tensile (0.002604) strain occurred when the Mt/F ratio was 8. The positions of maximum compressive strain were on the lingual surface. When the Mt/F ratios were from 8 to 10, 10.91 to 11, and 12, the positions were in cervical, middle, and apical areas, respectively. However, the positions of maximum tensile strain were on the labial surface. When the Mt/F ratios were from 8 to 10.91, 11, and 12, these positions were in cervical, 7, and 5 mm from the apex areas, respectively.

At 20-degree inclination

The lowest magnitude of maximum compressive (0.002638) and tensile (0.001622) strain was presented when the Mt/F ratios were 9 and 9.85, respectively. On the other hand, the highest magnitude of both maximum compressive (0.003906) and tensile (0.002333) strain was observed when the Mt/F ratios were 12. The positions of maximum compressive strain were at the apex. With the increased Mt/F ratio, theses positions were change from distolabial to distolingual side of the apex. Instead, the positions of maximum tensile strain were on the labial surface. These positions would be changed from cervical to middle areas of th labial side when the Mt/F ratio increased.

At 30-degree inclination

The lowest magnitude of both maximum compressive (0.003957) and tensile (0.002108) stain happened when the Mt/F ratio was 8. Conversely, the highest magnitude of both (0.005799 and 0.003256 for maximum compressive and tensile strain) was demonstrated when the Mt/F ratio were 12. In all of the inclination, the positions of maximum compressive strain were in distolingual area of the apex; whereas the positions of maximum tensile strain were in 5 mm from the apex areas on the labial side.

At 40-degree inclination

The lowest magnitude of both maximum compressive (0.005143) and tensile (0.002648) strain occurred when the Mt/F ratio was 8. However, the highest magnitude of both (0.007752 and 0.004298 for maximum compressive and tensile strain) were shown when the Mt/F ratio was 12. The positions of maximum compressive and tensile strain in all Mt/F ratio were distolingual area of an apex and 5 mm from the apex on the labial surface, respectively.

On the whole, patterns and characteristics of maximum compressive and tensile strain with the increased Mt/F ratio were similar to those of maximum compressive and tensile stress. In addition, magnitude and areas of minimum and maximum principal strain in each inclination when bodily movement occurred were summarized in table 6

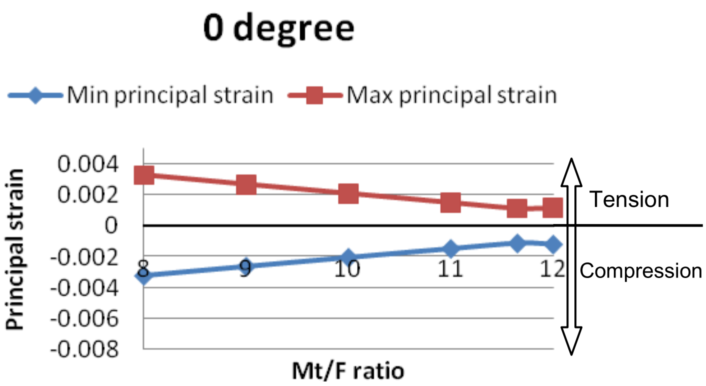
Table 6 Maximum and minimum principal strain from bodily movement in each inclination

Inclination	Mt/F	Minimum principal strain		Maximum principal strain	
		magnitude	area	magnitude	area
0	11.65	-0.001124	Li/ 7 mm from apex	0.001157	La/ 7 mm from apex
10	10.91	-0.001574	Li/ 5 mm from apex	0.00122	La/ cervical
20	9.85	-0.002769	Li/ apical	0.001622	La/ 5 mm from apex
30	8.48	-0.004022	Li/ apical	0.002197	La/ 5 mm from apex
40	6.87	-0.005185	D/ apical	0.002752	La/ 5 mm from apex

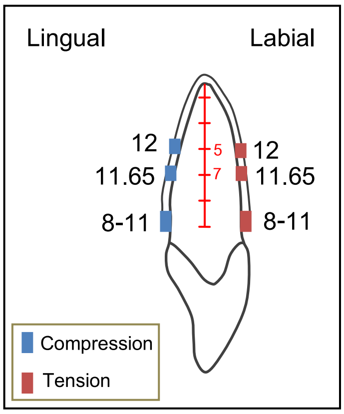
Figure 18, A to E,

1) show the relationships between the Mt/F ratio and principal strain when the inclination of a tooth was kept constant at 0, 10, 20, 30, and 40 degrees.
2) Diagrams on the right side show the positions of maximum compressive and tensile stain.
3) Diagrams show major principal strain distribution when Mt/F ratio was the ratio that produced bodily movement.

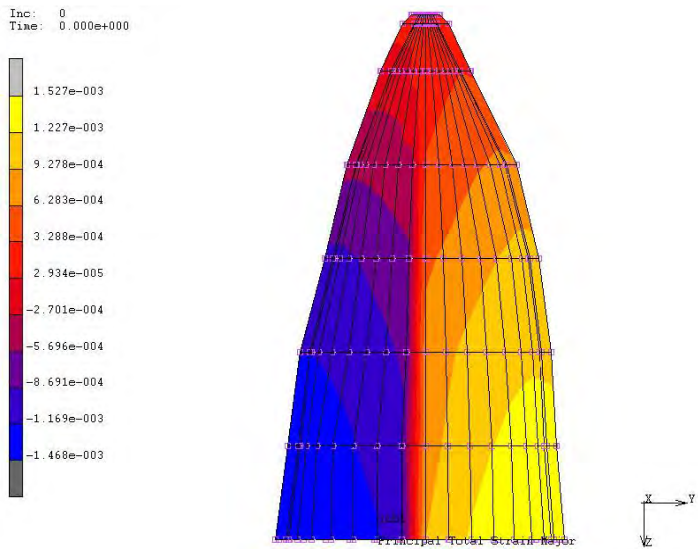
A. The inclination was 0 degree.



1)

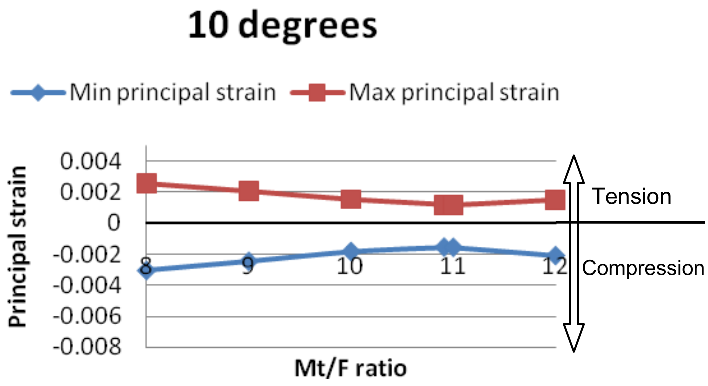


2)

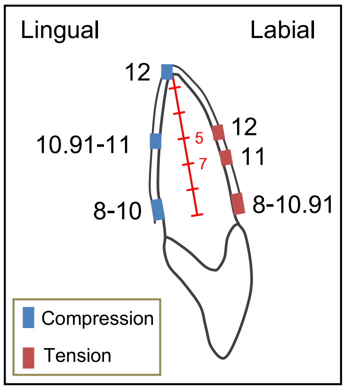


3) Mt/F ratio was 11.65

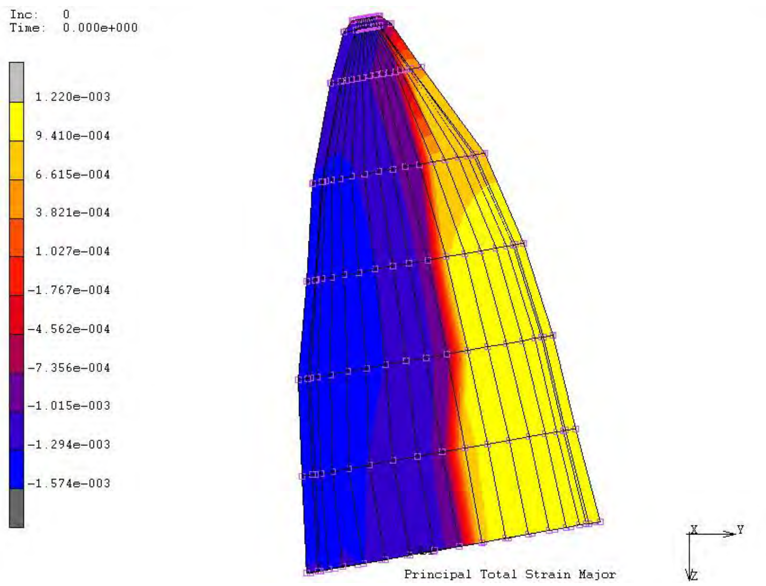
B. The inclination was 10 degrees.



1)

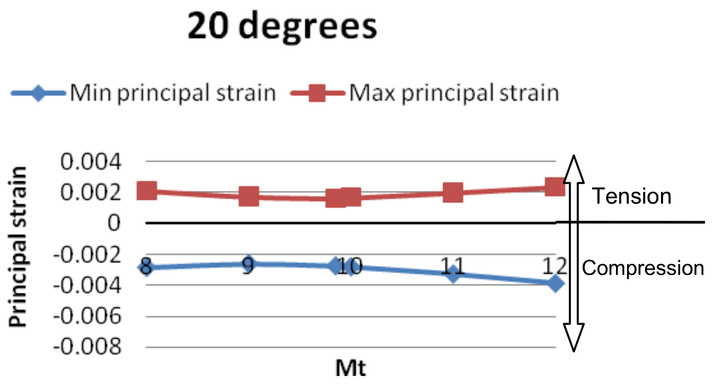


2)

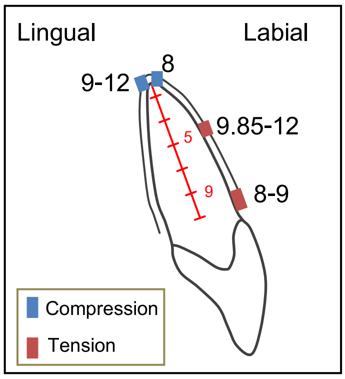


3) Mt/F ratio was 10.91

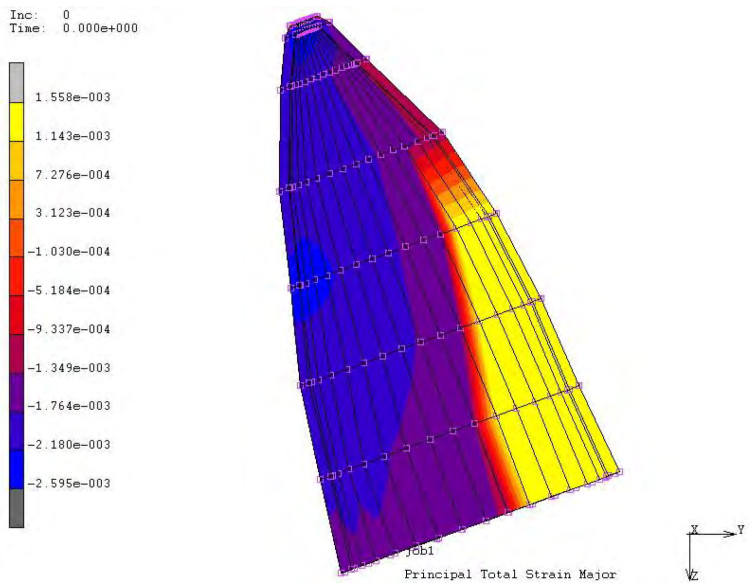
C. The inclination was 20 degrees.



1)

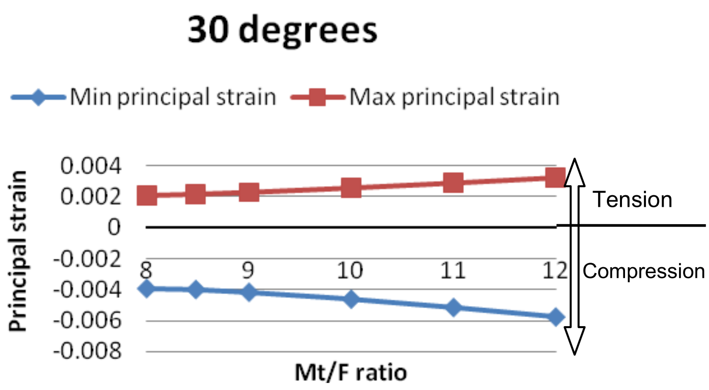


2)

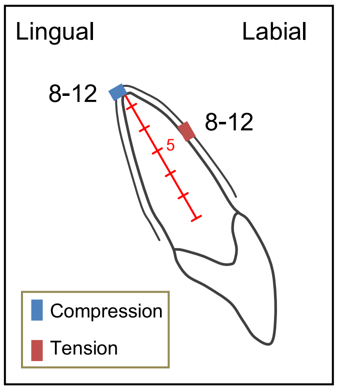


3) Mt/F ratio was 9.85

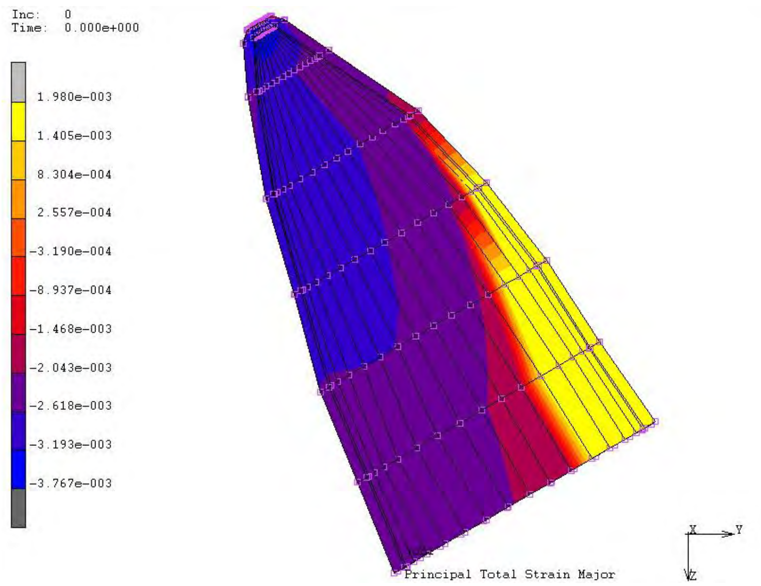
D. The inclination was 30 degrees.



1)

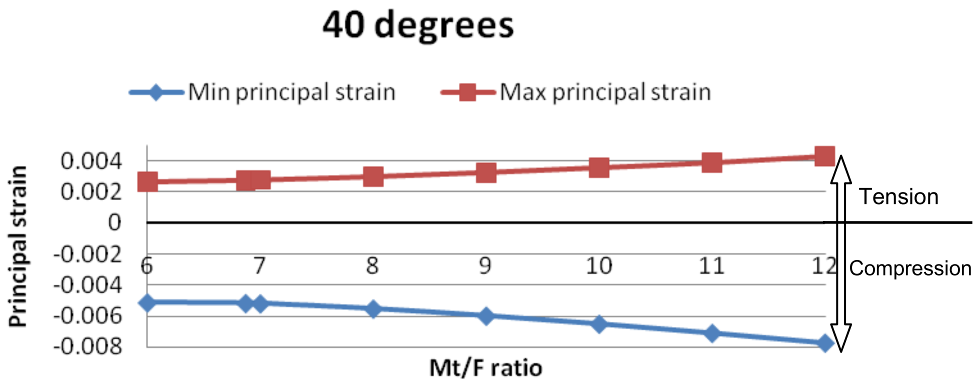


2)

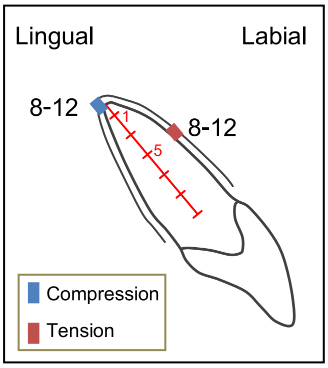


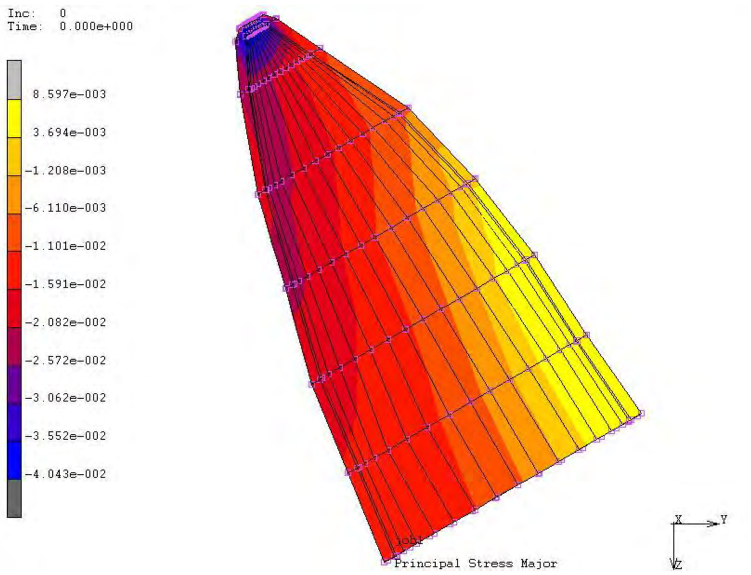
3) Mt/F ratio was 8.48

E. The inclination was 40 degrees.



1)





2)

3) Mt/F ratio was 6.87

III. The effect of the elastic modulus of PDL when the inclination and Mt/F ratio were kept constant

In this part, the inclination of an incisor was fixed at 20 degrees and the Mt/F ratio was fixed at 10. This force system produced root movement. Both of the incisal edge and the apex moved to the lingual side and the apex moved more than the incisal edge.

1. **Anteroposterior movement of the incisal edge and apex (Figure 19)**

When the elastic modulus of PDL had been increased, both of the incisal edge and the apex moved less to the lingual side.

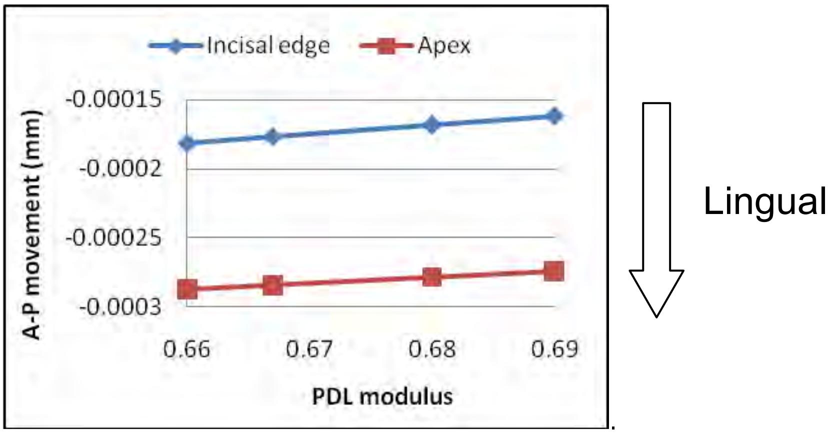


Figure 19 The relationships between anteroposterior movements of the incisal edge and apex and the elastic modulus of PDL.

2. **Vertical movement of the incisal edge**

When the elastic modulus of PDL had been enhanced, the incisal edge moved less to apical side.

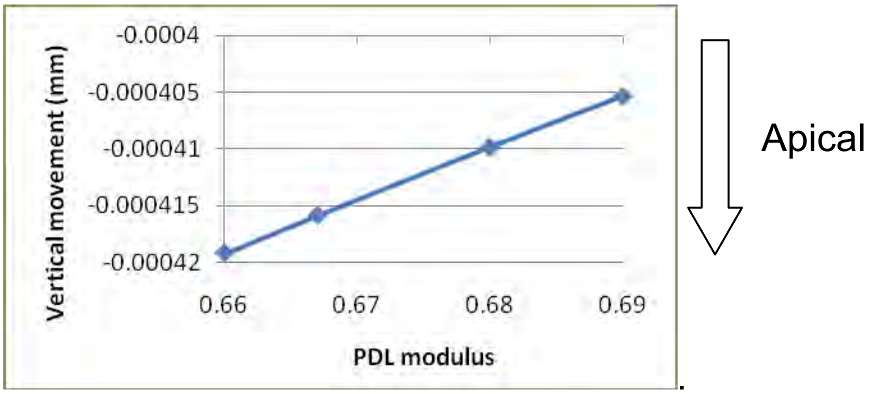


Figure 20 The relationships between vertical movement of the incisal edge and the elastic modulus of PDL.

3. Periodontal strain

When the elastic modulus of PDL had been raised, both of maximum and minimum principal strain magnitude was decreased. But the areas of both are still the same. The position of maximum compressive strain in all of PDL modulus was in distolingual area of an apex while the position of maximum tensile strain in all of PDL modulus was in the area at 5 mm from the apex on the labial side.

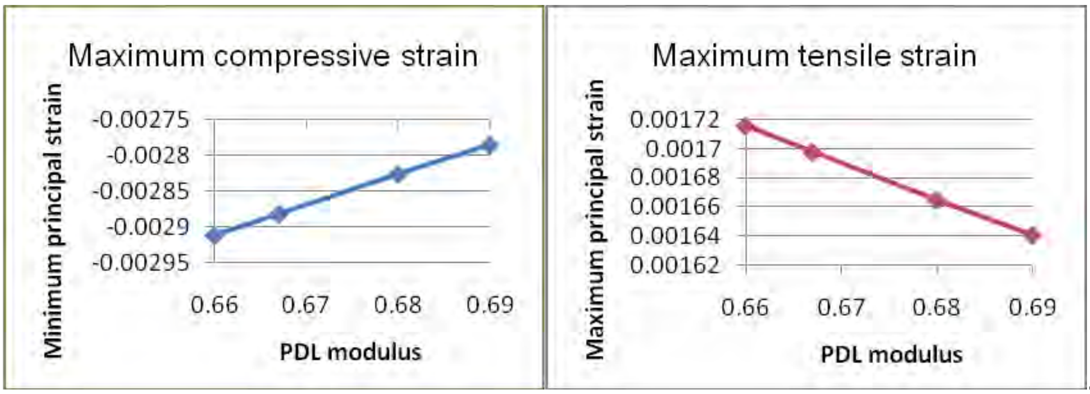


Figure 21 The relationships between periodontal strain and the elastic modulas of PDL

CHAPTER V
DISCUSSION

Anteroposterior movement

The anteroposterior movement graphs of the incisal edge and the apex showed that the slope of the incisal edge was steeper than that of the apex in each inclination with increased Mt/F ratio (Table 4). This indicated that the root apex was more difficult to move than the incisal edge when the force system was changed. Besides, the slope of both graphs slightly decreased with increased inclination. This also suggests that a proclined incisor would respond less to alteration of the force system than a retroclined incisor.

In the present study, the relationship of the position of the center of resistance of a central incisor and its inclination was determined. The position of the center of resistance was located by finding out the Mt/F ratio which produced bodily movement in each inclination. The Mt/F ratio in this study was the same as what is commonly refered to as the M/F ratio in orthodontics. The Mt/F ratio for bodily movement decreased with increased inclination of the incisor. However, when the position of the center of resistance was defined as the proportion to the root length measured from the apex to the alveolar crest, it was shown that these proportions could be approximated for all inclinations. The mean of these values was about 0.67 of the root length. This result is in agreement with previous studies. Burstone and Pryputniewicz*(2)* used laser holography as a tool to determine center of resistance and center of rotation of a maxillary central incisor in three-dimension movement. They showed that the center of resistance was at a point one-third of the distance from the alveolar crest to the apex. In addition, Yoshida et al*(7)* studied the location of the center of resistance in three human subjects using a magnetic sensing system. They found that the location of the center of resistance was at approximately two-thirds of palatal alveolar bone, measured from the root apex.

In contrast, Tanne et al*(12)*, Geramy*(42)*, and Poppe et al*(45)* reported different values. These studies were also performed using a finite element model of a maxillary central incisor. They found the proportions were 0.76, 0.58, and 0.57 of the root length from the apex, respectively. However, unlike the present study, these previous studies did not consider the labiolingual inclination. All of them set the force vector perpendicular to the long axis of the incisor. Moreover, the material properties and the anatomical layout were also different from the current studies. The results of the studies of Geramy and Poppe et al were similar to the results with a 2-dimensional theoretical model based on parabolic root shape by Burstone and Pryputniewicz*(2)*.

The results of the study may have clinical implications. First, in normal inclination, an upper central incisor is inclined to the line perpendicular to the occlusal plane approximately 30 degrees*(8-9)*, so the M/F ratio that should be applied to the incisor should be lower than the theoretical ratio which is approximately 8 to 10*(44)*. Moreover, in clinical practice, when bodily movement of an incisor is required, the appropriate M/F ratio to the inclination of the incisor should be adjusted because the same amount of M/F ratio can produce different effects in different inclinations. From the present study, when the M/F ratio was 10, controlled tipping movement occurred in 10-degree inclination, bodily movement occurred in 20-degree inclination and root movement occurred in 30-degree inclination of the incisor. Finally, in patients with Class II division 1 malocclusion, upper incisors are usually protruded. The desirable movement is controlled tipping to produce normal inclination. As a consequence, the M/F ratio applied at the bracket should be lower than the upright incisor. From the 40-degree inclination model in this study, the M/F should be lower than 6.87. In contrast, in patients with Class II division 2 malocclusion, upper incisors are usually retroclined. Therefore, the root movement is indicated and the M/F ratio should be higher.

Vertical movement

In every inclination, when the Mt/F ratio increased, the incisal edge moved more apically because root movement tended to occur. So, deepbite which usually happens in clinical practice when incisors are retracted results from the insufficient moment for root control.

Moreover, in case of the slope of the linear graph plotted between vertical movement of the incisal edge and the Mt/F ratio, the slope increased with increased inclination. The highest change in vertical position of the incisal edge was found in the 40-degree inclination model, in every Mt/F ratio. The explanation is illustrated by Figure 22. The inclination of an incisor in position A is 20 degrees and in position B is 40 degrees. The illustration shows that when the inclination is changed in the same degree of inclination (from 0 to 20 degrees and from 20 to 40 degrees) and the center of rotation of both are at the apex, the vertical movement of the incisal edge from position O to A (X) is lower than that from A to B (Y) because of the geometry of the circle.

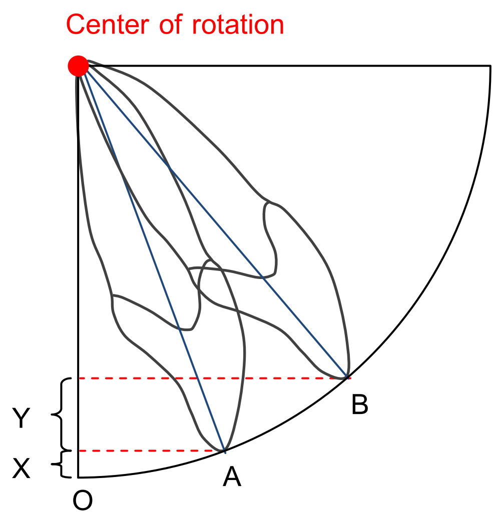


Figure 22 The effect of the inclination of an incisor to the vertical movement of the incisal edge. When the inclination of the incisor is changed in the same amount (O to A and A to B), the vertical movement of the incisal edge is not the same (X is lower than Y).

The result indicates that a proclined incisor would respond more to the change of Mt/F ratio than a retroclined incisor. Consequently, when proclined incisors were retracts with inadequate moment, deepbite will occur more easily than retroclined incisors. Regarding the retroclined incisor, when it is proclined, the vertical position of the incisal edge will not be much affected.

Consideration of anteroposterior and vertical movement simultaneously

The increased Mt/F ratio and inclination of the incisor made the incisor edge move more labioapically. Therefore, in the same force system, a proclined incisor will move more labioapically than a retroclined incisor.

It should be noted that in the 40-degree inclination model, the slope of anteroposterior movement graph was the lowest while the slope of vertical movement graph was the highest among all inclination models. Thus, with regard to retraction of an incisor, the more an incisor is proclined, the more the moment value would be added.

Periodontal stress

From the model of 0-degree inclination, when the controlled tipping movement was performed (Mt/F ratio < 11.65), both maximum compressive and tensile stress occurred at the cervical part of the periodontal ligament. This finding coincided with the studies of Field et al*(46)*, Geramy*(22)*, Zhao et al*(47)*, Shaw et al*(48)*, Rudolph et al*(49)*, Tanne et al*(50)*, Puente et al*(51)*, and McGuinness et al*(52)*. In contrast, during bodily movement (Mt/F ratio = 11.65), stress was almost uniform distribution. Maximum compressive and tensile stress occurred at the mid root areas on the lingual and labial sides, respectively. This finding was in accordance with the relevant studies (Cobo et al*(20)*, Zhao et al*(47)*, and Andersen et al*(53)*). However, it does not agree with the results of Rudolph et al, who found that stress was distributed throughout the PDL and concentrated more at the cervical area. In addition, bodily movement produced the lowest magnitudes of maximum compressive and tensile stress, when compared with controlled tipping and root movement. These magnitudes were 0.01297 and 0.01299 N/mm^2 (129.7 and 129.9 g/cm^2), respectively. Compressive stress in this finding is two times larger than in the study of Cobo et al*(20)* which found that compressive stress from bodily movement of canine distalization ranged between approximately 35 – 60 g/cm^2. Furthermore, the classic concept of the optimal force proposed by Schwarz*(54)* in 1932 stated that optimal force should approximate the capillary vessels' blood pressure which was 20 – 26 g/cm^2. Conversely, bioprogressive therapy by Ricketts*(55)* suggested that the optimal force was 100 g/cm^2 of enface root surface. Lee*(56)* reported an increased stress value of 197 g/cm^2 to be optimal for tooth movement. Because the topic of optimal force is still controversy, our stress magnitude is in the range of the reported value.

In the increased inclination models, controlled tipping movement created maximum compressive stress at the apex and maximum tensile stress in the cervical area. Likewise, in bodily movement, maximum compressive stress also occurred at the apex and maximum tensile stress occurred at 2 mm below the cervical area of the PDL (Table 5). It is clear that compressive stress would occur in the apical area of the PDL when an incisor was inclined to the occlusal plane. It can be explained in terms of force vectors (Figure 23). A force vector at the center of crown and parallel to the occlusal plane angled to the long axis of a tooth. Consequently, this vector is divided into 2 vectors, perpendicular (A) and parallel (B) to the long axis*(5)*. One of these vectors directs to intrude the incisor and create compressive stress at the apex.

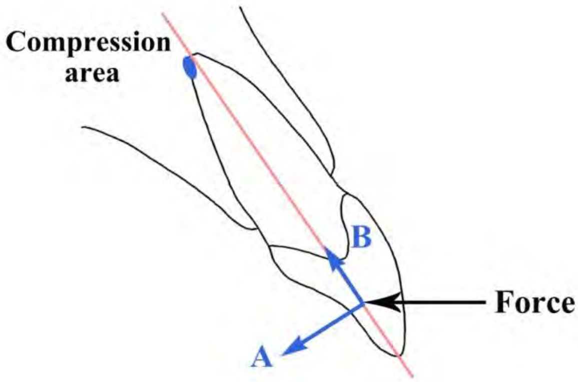


Figure 23 A force vector is divided into 2 vectors, perpendicular (A) and parallel (B) to the long axis. Vector B directs to the apex and causes compressive stress at the apex.

Furthermore, in case of bodily movement, when the inclination increased, the magnitude of maximum compressive stress increased while the magnitude of maximum tensile stress decreased. Especially in the 40-degree inclination which represented incisor protrusion, the highest magnitude of maximum compressive stress occurred in the apical area. The magnitude of maximum compressive stress in 40-degree inclination model in all Mt/F ratios was beyond the range of reported optimal stress as drescribed above. It is noticeable that these findings relate to the reports of root resorption. A maxillary central incisor is usually reported to be the most common of root resorption after orthodontic treatment*(57)*. Freitas et al*(58)* demonstrated that overjet correction and retraction of maxillary central incisor apices correlated significantly with root resoprtion degree. Sameshima GT et al*(59-60)* also reported that the greater the overjet, the greater the root resorption for all maxillary anterior teeth. And horizontal displacement of the incisor apices was also significantly associated with root resorption. Moreover, Parker et al*(61)* investigated the most predictive factors of external apical root resorption. They concluded that apical and incisal vertical movements and increase in incisor proclination were the strong predictors.

Periodontal strain

On the whole, patterns of strain distribution resemble those of stress distribution. In the 0-degree inclination model, controlled tipping movement (Mt/F ratio < 11.65) made maximum compressive and tensile strain occurred at the cervical area at the lingual and labial sides, respectively. Conversely, bodily movement (Mt/F ratio = 11.65) caused uniform strain distribution throughout the PDL. The maximum compressive and tensile strain occurred in the mid root area.

In the increased inclination models, espeacially in 40-degree inclination, all Mt/F ratios produced maximum compressive strain at the apex and maximum tensile strain in the mid root area. This findings give the impression that the area of maximum compressive strain relate to the incidence of root resorption as described above.

The effect of the elastic modulus of the PDL

In previous published studies, the elastic modulus of the PDL was presented in several values. Tanne et al *(6, 12, 24)* introduced the material properties of the PDL as linear elastic which elastic moduli were 0.68 N/mm^2. This value was frequently quoted *(3, 20-21, 23, 47)*. Andersen et al *(53)* determined the elastic stiffness of the PDL by finite element models and strain - gauge technique as research tools. They proposed that the stiffness of the PDL was 0.07 MPa. In contrast, many authors demonstrated the properties of the PDL as nonlinear *(19, 45, 62-65)*. Poppe et al*(45)* suggested to simulate the nonlinear character by using a bilinear parameter set. The mean Young's modulus of the first phase of movement was 0.05 MPa and the second phase was 0.28 MPa.

Due to no data available about the exact value of elastic modulus of the periodontal ligament, the elastic modulus of PDL of 0.68 N/mm^2 was used in this study because this value was used in previous studies which were frequently cited and used in many later studies *(3, 6, 12, 20-21, 23-24)*. Besides, the 20-degree inclination model with the 10-Mt/F ratio was used as the main model in the analysis because they are the middle values of the values of inclinations and the Mt/F ratios. It was found that when the elastic modulus increased, both anteroposterior and vertical movements decreased. It reveals that the incisor will be more difficult to move with the more modulus value of PDL. Furthermore, the more modulus value of PDL produces magnitude of both compressive and tensile strain decreased, while the areas of both are still the same.

In addition, the reason for the high magnitude of compressive stress which was found in the 40-degree inclination model can be the elastic modulus of the PDL used in this study. The value of 0.68 N/mm^2 is relatively high, compare with other studies *(45-46, 48, 53, 66)*. Moreover, Cattaneo et al *(62)* reported the stress level in compressive area in the non-linear PDL model was lower than that in the linear PDL. Thus, the result of stress magnitude from this study would be decreased if the PDL properties were changed. Although the magnitude of stress from the present study was not precise, the trend of changes of compressive and tensile stress would be beneficial.

This study has several limitations. Although the mechanical properties of the PDL have been reported to be nonlinear and anisotropic *(62, 65)*, homogeneous, isotropic and linear elastic properties were assumed in this study. Moreover, the geometry of a maxillary central incisor was based on average anatomical dimensions. The results of this analysis thus apply to an average among individuals *(3, 12)*. As a consequence, our results can be used as a guideline to better understand the mechanical response of teeth with different inclinations.

Further investigation should be performed with more accurate simulation of loading and approximation of material.

Conclusion

The present study investigated the biomechanical aspect of tooth movement and examined the effect of the inclination of the incisor and Mt/F ratio to anteroposterior and vertical movement, periodontal stress and strain. This study used a finite element analysis as a research tool. It was concluded that with increased inclination, -

1. The incisal edge tended to move labioapically.
2. The M/F ratio needed for bodily movement decreased
3. The location of the center of resistance of a maxillary central incisor was approximately constant in terms of the proportion to the root length measured from the apex to the alveolar crest at about 0.67 of the root length.

From bodily movement with increased inclination, we conclude that:-

4. The area of maximum compressive stress and strain changed from mid root area to apical area.
5. The area of maximum tensile stress changed from mid root area to cervical area. But the area of maximum tensile strain was still in the mid root area.
6. Magnitude of maximum compressive stress and strain increased.
7. Magnitude of maximum tensile stress decreased but maximum tensile strain increased.

References

(1) Marcotte, M. R. Biomechanics in orthodontics. Toronto: B.C. Decker, 1990.

(2) Burstone, C. J., and Pryputniewicz, R. J. Holographic determination of centers of rotation produced by orthodontic forces. Am J Orthod 77(4) (Apr 1980): 396-409.

(3) Jeon, P. D., Turley, P. K., Moon, H. B., and Ting, K. Analysis of stress in the periodontium of the maxillary first molar with a three-dimensional finite element model. Am J Orthod Dentofacial Orthop 115(3) (Mar 1999): 267-74.

(4) Farah, J. W., and Craig, R. G. Finite element stress analysis of a restored axisymmetric first molar. J Dent Res 53(4) (Jul-Aug 1974): 859-66.

(5) Smith, R. J., and Burstone, C. J. Mechanics of tooth movement. Am J Orthod 85(4) (Apr 1984): 294-307.

(6) Tanne, K., Nagataki, T., Inoue, Y., Sakuda, M., and Burstone, C. J. Patterns of initial tooth displacements associated with various root lengths and alveolar bone heights. Am J Orthod Dentofacial Orthop 100(1) (Jul 1991): 66-71.

(7) Yoshida, N., Jost-Brinkmann, P. G., Koga, Y., Mimaki, N., and Kobayashi, K. Experimental evaluation of initial tooth displacement, center of resistance, and center of rotation under the influence of an orthodontic force. Am J Orthod Dentofacial Orthop 120(2) (Aug 2001): 190-7.

(8) Jacobson, A., and Caufield, P. W. Introduction to radiographic cephalometry. Jacobson A, editor. Philadelphia: Lea & Febiger, 1985.

(9) Rakosi, T. An atlas and manual of cephalometric radiography. Philadelphia: Lea & Febiger, 1982.

(10) Ash, M. M., and Nelson, S. J. Wheeler's dental anatomy, physiology, and occlusion. St. Louis: Saunders, 2003.

(11) Coolidge, E. D. The thickness of the human periodontal membrane. J Am Dent Assoc 24 (1937): 1960 - 70.

(12) Tanne, K., Koenig, H. A., and Burstone, C. J. Moment to force ratios and the center of rotation. Am J Orthod Dentofacial Orthop 94(5) (Nov 1988): 426-31.

(13) Burstone, C. J. Modern edgewise mechanics and the segmented arch technique. Glendora: Ormco, 1995.

(14) Mackerle, J. Finite element modelling and simulations in dentistry: a bibliography 1990-2003. Comput Methods Biomech Biomed Engin 7(5) (Oct 2004): 277-303.

(15) Gallagher, R. H., Simon, B. R., Johnson, P. C., and Gross, J. F. Finite Elements in Biomechanics. U.S.A.: John Wiley & Sons Ltd., 1982.

(16) Dechaumpai, P. Finite element method in engineering. 2nd ed. Bangkok: Chulalongkorn University Press, 1999.

(17) Widas, P. Introduction to Finite Element Analysis[Online]. 1997. Available from: http://www.sv.vt.edu/classes/MSE2094_NoteBook/97ClassProj/num/widas/history.html [2009, June 2]

(18) Fagan, M. J. Finite element analysis: Theory and practice. Essex: Longman, 1992.

(19) Cattaneo, P. M., Dalstra, M., and Melsen, B. 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) (May 2008): 681-9.

(20) Cobo, J., Arguelles, J., Puente, M., and Vijande, M. Dentoalveolar stress from bodily tooth movement at different levels of bone loss. Am J Orthod Dentofacial Orthop 110(3) (Sep 1996): 256-62.

(21) Cobo, J., Sicilia, A., Arguelles, J., Suarez, D., and Vijande, M. 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) (Nov 1993): 448-54.

(22) Geramy, A. 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) (Feb 2002): 21-33.

(23) Jeon, P. D., Turley, P. K., and Ting, K. Three-dimensional finite element analysis of stress in the periodontal ligament of the maxillary first molar with simulated bone loss. Am J Orthod Dentofacial Orthop 119(5) (May 2001): 498-504.

(24) Tanne, K., Sakuda, M., and Burstone, C. J. Three-dimensional finite element analysis for stress in the periodontal tissue by orthodontic forces. Am J Orthod Dentofacial Orthop 92(6) (Dec 1987): 499-505.

(25) Reimann, S., Keilig, L., Jager, A., and Bourauel, C. Biomechanical finite-element investigation of the position of the centre of resistance of the upper incisors. Eur J Orthod 29(3) (Jun 2007): 219-24.

(26) Kojima, Y., and Fukui, H. Effects of transpalatal arch on molar movement produced by mesial force: a finite element simulation. Am J Orthod Dentofacial Orthop 134(3) (Sep 2008): 335 e1-7; discussion -6.

(27) Bobak, V., Christiansen, R. L., Hollister, S. J., and Kohn, D. H. Stress-related molar responses to the transpalatal arch: a finite element analysis. Am J Orthod Dentofacial Orthop 112(5) (Nov 1997): 512-8.

(28) Coimbra, M. E., Penedo, N. D., de Gouvea, J. P., Elias, C. N., de Souza Araujo, M. T., and Coelho, P. G. Mechanical testing and finite element analysis of orthodontic teardrop loop. Am J Orthod Dentofacial Orthop 133(2) (Feb 2008): 188 e9-13.

(29) Baek, S. H., Shin, S. J., Ahn, S. J., and Chang, Y. I. Initial effect of multiloop edgewise archwire on the mandibular dentition in Class III malocclusion subjects. A three-dimensional finite element study. Eur J Orthod 30(1) (Feb 2008): 10-5.

(30) Chang, Y. I., Shin, S. J., and Baek, S. H. Three-dimensional finite element analysis in distal en masse movement of the maxillary dentition with the multiloop edgewise archwire. Eur J Orthod 26(3) (Jun 2004): 339-45.

(31) Kojima, Y., Mizuno, T., and Fukui, H. A numerical simulation of tooth movement produced by molar uprighting spring. Am J Orthod Dentofacial Orthop 132(5) (Nov 2007): 630-8.

(32) Kojima, Y., Mizuno, T., Umemura, S., and Fukui, H. A numerical simulation of orthodontic tooth movement produced by a canine retraction spring. Dent Mater J 26(4) (Jul 2007): 561-7.

(33) Jayade, V., Annigeri, S., Jayade, C., and Thawani, P. Biomechanics of torque from twisted rectangular archwires. A finite element investigation. Angle Orthod 77(2) (Mar 2007): 214-20.

(34) Tanne, K., Hiraga, J., Kakiuchi, K., Yamagata, Y., and Sakuda, M. Biomechanical effect of anteriorly directed extraoral forces on the craniofacial complex: a study using the finite element method. Am J Orthod Dentofacial Orthop 95(3) (Mar 1989): 200-7.

(35) Knox, J., Kralj, B., Hubsch, P., Middleton, J., and Jones, M. L. An evaluation of the quality of orthodontic attachment offered by single- and double-mesh bracket bases using the finite element method of stress analysis. Angle Orthod 71(2) (Apr 2001): 149-55.

(36) Ghosh, J., Nanda, R. S., Duncanson, M. G., Jr., and Currier, G. F. Ceramic bracket design: an analysis using the finite element method. Am J Orthod Dentofacial Orthop 108(6) (Dec 1995): 575-82.

(37) Knox, J., Kralj, B., Hubsch, P. F., Middleton, J., and Jones, M. L. An evaluation of the influence of orthodontic adhesive on the stresses generated in a bonded bracket finite element model. Am J Orthod Dentofacial Orthop 119(1) (Jan 2001): 43-53.

(38) Chen, F., Terada, K., and Handa, K. Anchorage effect of various shape palatal osseointegrated implants: a finite element study. Angle Orthod 75(3) (May 2005): 378-85.

(39) Chen, F., Terada, K., Hanada, K., and Saito, I. Anchorage effects of a palatal osseointegrated implant with different fixation: a finite element study. Angle Orthod 75(4) (Jul 2005): 593-601.

(40) Veziroglu, F., Uckan, S., Ozden, U. A., and Arman, A. Stability of zygomatic plate-screw orthodontic anchorage system: a finite element analysis. Angle Orthod 78(5) (Sep 2008): 902-7.

(41) Nikolai, R. J. Bioengineering analysis of orthodontic mechanics. Philadelphia: Lea & Febiger, 1985.

(42) Geramy, A. 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) (Apr 2000): 399-405.

(43) Tanne, K., Yoshida, S., Kawata, T., Sasaki, A., Knox, J., and Jones, M. L. An evaluation of the biomechanical response of the tooth and periodontium to orthodontic forces in adolescent and adult subjects. Br J Orthod 25(2) (May 1998): 109-15.

(44) Proffit, W. R., and Fields, H. W. Contemporary Orthodontics. 3rd ed. St. Louis: Mosby, 2000.

(45) Poppe, M., Bourauel, C., and Jager, A. Determination of the elasticity parameters of the human periodontal ligament and the location of the center of resistance of single-rooted teeth a study of autopsy specimens and their conversion into finite element models. J Orofac Orthop 63(5) (Sep 2002): 358-70.

(46) Field, C., Ichim, I., Swain, M. V., Chan, E., Darendeliler, M. A., Li, W., et al. Mechanical responses to orthodontic loading: a 3-dimensional finite element multi-tooth model. Am J Orthod Dentofacial Orthop 135(2) (Feb 2009): 174-81.

(47) Zhao, Z., Fan, Y., Bai, D., Wang, J., and Li, Y. The adaptive response of periodontal ligament to orthodontic force loading - a combined biomechanical and biological study. Clin Biomech (Bristol, Avon) 23 Suppl 1 (2008): S59-66.

(48) Shaw, A. M., Sameshima, G. T., and Vu, H. V. Mechanical stress generated by orthodontic forces on apical root cementum: a finite element model. Orthod Craniofac Res 7(2) (May 2004): 98-107.

(49) Rudolph, D. J., Willes, P. M. G., and Sameshima, G. T. A finite element model of apical force distribution from orthodontic tooth movement. Angle Orthod 71(2) (Apr 2001): 127-31.

(50) Tanne, K. Stress distributions in the periodontal membrane associated with various moment to force ratios in orthodontic force systems. J Osaka Univ Dent Sch 27 (Dec 1987): 1-9.

(51) Puente, M. I., Galban, L., and Cobo, J. M. Initial stress differences between tipping and torque movements. A three-dimensional finite element analysis. Eur J Orthod 18(4) (Aug 1996): 329-39.

(52) McGuinness, N. J., Wilson, A. N., Jones, M. L., and Middleton, J. A stress analysis of the periodontal ligament under various orthodontic loadings. Eur J Orthod 13(3) (Jun 1991): 231-42.

(53) Andersen, K. L., Pedersen, E. H., and Melsen, B. Material parameters and stress profiles within the periodontal ligament. Am J Orthod Dentofacial Orthop 99(5) (May 1991): 427-40.

(54) Schwarz, A. M. Tissue changes incident to orthodontic tooth movement. Int J Orthod 18 (1932): 331-2.

(55) Ricketts, R. M., Bench, R. W., Gugino, C. F., Hilgers, J. J., and Schulhof, R. J. Bioprogressive Therapy: Book1. United States of America: Rocky Mountain/Orthodontics, 1980.

(56) Lee, B. W. The force requirements for tooth movement. Part III: The pressure hypothesis tested. Aust Orthod J 14(2) (Mar 1996): 93-7.

(57) Harris, E. F. Root resorption during orthodontic therapy. Semin Orthod 6 (2000): 183-94.

(58) de Freitas, M. R., Beltrao, R. T., Janson, G., Henriques, J. F., and Chiqueto, K. Evaluation of root resorption after open bite treatment with and without extractions. Am J Orthod Dentofacial Orthop 132(2) (Aug 2007): 143 e15-22.

(59) Sameshima, G. T., and Sinclair, P. M. Predicting and preventing root resorption: Part II. Treatment factors. Am J Orthod Dentofacial Orthop 119(5) (May 2001): 511-5.

(60) Sameshima, G. T., and Sinclair, P. M. Predicting and preventing root resorption: Part I. Diagnostic factors. Am J Orthod Dentofacial Orthop 119(5) (May 2001): 505-10.

(61) Parker, R. J., and Harris, E. F. Directions of orthodontic tooth movements associated with external apical root resorption of the maxillary central incisor. Am J Orthod Dentofacial Orthop 114(6) (Dec 1998): 677-83.

(62) Cattaneo, P. M., Dalstra, M., and Melsen, B. The finite element method: a tool to study orthodontic tooth movement. J Dent Res 84(5) (May 2005): 428-33.

(63) Cattaneo, P. M., Dalstra, M., and Melsen, B. Strains in periodontal ligament and alveolar bone associated with orthodontic tooth movement analyzed by finite element. Orthod Craniofac Res 12(2) (May 2009): 120-8.

(64) Ona, M., and Wakabayashi, N. Influence of alveolar support on stress in periodontal structures. J Dent Res 85(12) (Dec 2006): 1087-91.

(65) Toms, S. R., and Eberhardt, A. W. A nonlinear finite element analysis of the periodontal ligament under orthodontic tooth loading. Am J Orthod Dentofacial Orthop 123(6) (Jun 2003): 657-65.

(66) Viecilli, R. F., Katona, T. R., Chen, J., Hartsfield, J. K., Jr., and Roberts, W. E. Three-dimensional mechanical environment of orthodontic tooth movement and root resorption. Am J Orthod Dentofacial Orthop 133(6) (Jun 2008): 791 e11-26.

APPENDIX

Table 7 The relationships between the inclination of an incisor and anteroposterior and vertical movement of the incisor in each Mt/F ratio.

Mt/F ratio	Inclination	Anteroposterior movement		Vertical movement
		incisal edge	apex	
8	0	-0.002224	0.000537	0.000084
8	10	-0.001797	0.000369	0.000139
8	20	-0.001242	0.000063	-0.000004
8	30	-0.000655	-0.000340	-0.000395
8	40	-0.000137	-0.000784	-0.001047
9	0	-0.001646	0.000358	0.000078
9	10	-0.001230	0.000192	0.000032
9	20	-0.000706	-0.000107	-0.000207
9	30	-0.000165	-0.000499	-0.000686
9	40	0.000291	-0.000927	-0.001418
10	0	-0.001066	0.000180	0.000072
10	10	-0.000668	0.000017	-0.000073
10	20	-0.000168	-0.000279	-0.000410
10	30	0.000325	-0.000658	-0.000978
10	40	0.000719	-0.001069	-0.001787
11	0	-0.000488	0.000002	0.000066
11	10	-0.000098	-0.000162	-0.000180
11	20	0.000370	-0.000450	-0.000613
11	30	0.000813	-0.000817	-0.001268
11	40	0.001148	-0.001212	-0.002158
12	0	0.000091	-0.000176	0.000060
12	10	0.000466	-0.000338	-0.000286
12	20	0.000908	-0.000621	-0.000816
12	30	0.001303	-0.000976	-0.001560
12	40	0.001575	-0.001354	-0.002527

Table 8 The relationships between the inclination of an incisor and the magnitude and areas of maximum and minimum principal stress in each Mt/F ratio.

Mt/F ratio	Inclination	Minimum principal stress		Maximum principal stress	
		Magnitude	area	Magnitude	area
8	0	-0.03616	Li/ cervical	0.03587	La/ cervical
8	10	-0.03258	Li/ cervical	0.02954	La/ cervical
8	20	-0.03166	La/ apical	0.02125	La/ cervical
8	30	-0.04242	D/ apical	0.01095	La/ cervical
8	40	-0.06064	Li/ apical	0.00517	La/ 7 mm from apex
9	0	-0.02971	Li/ cervical	0.02959	La/ cervical
9	10	-0.02619	Li/ cervical	0.02348	La/ cervical
9	20	-0.02825	D/ apical	0.01489	La/ cervical
9	30	-0.04577	Li/ apical	0.00755	La/ 7 mm from apex
9	40	-0.06565	Li/ apical	0.00571	La/ 5 mm from apex
10	0	-0.02328	Li/ cervical	0.02336	La/ cervical
10	10	-0.01955	Li/ cervical	0.01685	La/ cervical
10	20	-0.03084	Li/ apical	0.00971	La/ cervical
10	30	-0.05082	Li/ apical	0.00742	La/ 5 mm from apex
10	40	-0.07069	Li/ apical	0.00836	La/ 5 mm from apex
11	0	-0.01682	Li/ cervical	0.01704	La/ cervical
11	10	-0.01642	Li/ apical	0.01132	La/ 7 mm from apex
11	20	-0.03598	Li/ apical	0.00975	La/ 5 mm from apex
11	30	-0.05591	Li/ apical	0.01006	La/ 5 mm from apex
11	40	-0.07577	Li/ apical	0.01534	La/ 1 mm from apex
12	0	-0.01353	Li/ 5 mm from apex	0.01387	La/ 5 mm from apex
12	10	-0.02181	Li/ 1 mm from apex	0.01272	La/ 5 mm from apex
12	20	-0.04117	Li/ apical	0.01241	La/ 5 mm from apex
12	30	-0.06105	Li/ apical	0.01618	La/ 1 mm from apex
12	40	-0.08104	Li/ apical	0.02278	La/ apical

Table 9 The relationships between the inclination of an incisor and the magnitude and areas of maximum and minimum principal strain in each Mt/F ratio.

Mt/F ratio	Inclination	Minimum principal strain		Maximum principal strain	
		Magnitude	area	Magnitude	area
8	0	-0.003202	Li/ cervical	0.003299	La/ cervical
8	10	-0.003068	Li/ cervical	0.002604	La/ cervical
8	20	-0.002872	La/ apical	0.002102	La/ cervical
8	30	-0.003957	D/ apical	0.002108	La/ 5 mm from apex
8	40	-0.005549	Li/ apical	0.002986	La/ 5 mm from apex
9	0	-0.002612	Li/ cervical	0.002702	La/ cervical
9	10	-0.002480	Li/ cervical	0.002095	La/ cervical
9	20	-0.002638	D/ apical	0.001730	La/ cervical
9	30	-0.004199	Li/ apical	0.002315	La/ 5 mm from apex
9	40	-0.006001	Li/ apical	0.003255	La/ 5 mm from apex
10	0	-0.002034	Li/ cervical	0.002117	La/ cervical
10	10	-0.001852	Li/ cervical	0.001563	La/ cervical
10	20	-0.002826	Li/ apical	0.001665	La/ 5 mm from apex
10	30	-0.004642	Li/ apical	0.002599	La/ 5 mm from apex
10	40	-0.006529	Li/ apical	0.003563	La/ 5 mm from apex
11	0	-0.001468	Li/ cervical	0.001527	La/ cervical
11	10	-0.001581	Li/ 5 mm from apex	0.001187	La/ 7 mm from apex
11	20	-0.003302	Li/ apical	0.001983	La/ 5 mm from apex
11	30	-0.005184	Li/ apical	0.002914	La/ 5 mm from apex
11	40	-0.007120	Li/ apical	0.003887	La/ 5 mm from apex
12	0	-0.001193	Li/ 5 mm from apex	0.001197	La/ 5 mm from apex
12	10	-0.002111	Li/ apical	0.001528	La/ 5 mm from apex
12	20	-0.003906	Li/ apical	0.002333	La/ 5 mm from apex
12	30	-0.005799	Li/ apical	0.003256	La/ 5 mm from apex
12	40	-0.007752	Li/ apical	0.004298	La/ 5 mm from apex

Table 10 The relationships between the Mt/F ratios and anteroposterior and vertical movement of the incisor in each inclination.

Inclination	Mt/F ratio	Mr	Anteroposterior movement		Vertical movement
			incisal edge	apex	
0	8	0.338	-0.002224	0.000537	0.000084
0	9	0.390	-0.001646	0.000358	0.000078
0	10	0.438	-0.001066	0.000180	0.000072
0	11	0.492	-0.000488	0.000002	0.000066
0	**11.7**	**0.526**	**-0.000112**	**-0.000114**	**0.000062**
0	12	0.542	0.000091	-0.000176	0.000060
10	8	0.370	-0.001797	0.000369	0.000139
10	9	0.414	-0.001230	0.000192	0.000032
10	10	0.487	-0.000668	0.000017	-0.000073
10	**10.9**	**0.521**	**-0.000150**	**-0.000146**	**-0.000171**
10	11	0.527	-0.000098	-0.000162	-0.000180
10	12	0.580	0.000466	-0.000338	-0.000286
20	8	0.404	-0.001242	0.000063	-0.000004
20	9	0.470	-0.000706	-0.000107	-0.000207
20	**9.85**	**0.517**	**-0.000251**	**-0.000252**	**-0.000379**
20	10	0.526	-0.000168	-0.000279	-0.000410
20	11	0.580	0.000370	-0.000450	-0.000613
20	12	0.633	0.000908	-0.000621	-0.000816
30	8	0.483	-0.000655	-0.000340	-0.000395
30	**8.48**	**0.510**	**-0.000417**	**-0.000417**	**-0.000536**
30	9	0.541	-0.000165	-0.000499	-0.000686
30	10	0.599	0.000325	-0.000658	-0.000978
30	11	0.656	0.000813	-0.000817	-0.001268
30	12	0.713	0.001303	-0.000976	-0.001560
40	6	0.446	-0.000993	-0.000500	0.000307
40	**6.87**	**0.502**	**-0.000621**	**-0.000623**	**0.000629**
40	7	0.509	-0.000565	-0.000642	-0.000677
40	8	0.574	-0.000137	-0.000784	-0.001047
40	9	0.638	0.000291	-0.000927	-0.001418
40	10	0.701	0.000719	-0.001069	-0.001787
40	11	0.765	0.001148	-0.001212	-0.002158
40	12	0.828	0.001575	-0.001354	-0.002527

Table 11 The relationships between the Mt/F ratios and the magnitude and areas of maximum and minimum principal stress in each inclination.

Inclination	Mt/F ratio	Minimum principal stress		Maximum principal stress	
		Magnitude	area	Magnitude	area
0	8	-0.03616	Li/ cervical	0.03587	La/ cervical
0	9	-0.02971	Li/ cervical	0.02959	La/ cervical
0	10	-0.02328	Li/ cervical	0.02336	La/ cervical
0	11	-0.01682	Li/ cervical	0.01704	La/ cervical
0	**11.7**	**-0.01297**	**Li/ 7 mm from apex**	**0.01299**	**La/ 5 mm from apex**
0	12	-0.01353	Li/ 5 mm from apex	0.01387	La/ 5 mm from apex
10	8	-0.03258	Li/ cervical	0.02954	La/ cervical
10	9	-0.02619	Li/ cervical	0.02348	La/ cervical
10	10	-0.01955	Li/ cervical	0.01685	La/ cervical
10	**10.9**	**-0.01604**	**Li/ 5 mm from apex**	**0.01151**	**La/ 9 mm from apex**
10	11	-0.01642	Li/ apical	0.01132	La/ 7 mm from apex
10	12	-0.02181	Li/ apical	0.01272	La/ 5 mm from apex
20	8	-0.03166	La/ apical	0.02125	La/ cervical
20	9	-0.02825	D/ apical	0.01489	La/ cervical
20	**9.85**	**-0.03005**	**Li/ apical**	**0.01019**	**La/ 9 mm from apex**
20	10	-0.03084	Li/ apical	0.00971	La/ cervical
20	11	-0.03598	Li/ apical	0.00975	La/ 5 mm from apex
20	12	-0.04117	Li/ apical	0.01241	La/ 5 mm from apex
30	8	-0.04242	D/ apical	0.01095	La/ cervical
30	**8.48**	**-0.04319**	**Li/ apical**	**0.00860**	**La/ 9 mm from apex**
30	9	-0.04577	Li/ apical	0.00755	La/ 7 mm from apex
30	10	-0.05082	Li/ apical	0.00742	La/ 5 mm from apex
30	11	-0.05591	Li/ apical	0.01006	La/ 5 mm from apex
30	12	-0.06105	Li/ apical	0.01618	La/ 1 mm from apex
40	6	-0.05519	D/ apical	0.01123	La/ cervical
40	**6.87**	**-0.05572**	**D/ apical**	**0.00673**	**La/ 9 mm from apex**
40	7	-0.05592	D/ apical	0.00632	La/ 9 mm from apex
40	8	-0.06064	Li/ apical	0.00517	La/ 7 mm from apex
40	9	-0.06565	Li/ apical	0.00571	La/ 5 mm from apex
40	10	-0.07069	Li/ apical	0.00836	La/ 5 mm from apex
40	11	-0.07577	Li/ apical	0.01534	La/ 1 mm from apex
40	12	-0.08104	Li/ apical	0.02278	La/ 1 mm from apex

Table 12 The relationships between the Mt/F ratios and the magnitude and areas of maximum and minimum principal strain in each inclination.

Inclination	Mt/F ratio	Minimum principal strain		Maximum principal strain	
		Magnitude	area	Magnitude	area
0	8	-0.003202	Li/ cervical	0.003299	La/ cervical
0	9	-0.002612	Li/ cervical	0.002702	La/ cervical
0	10	-0.002034	Li/ cervical	0.002117	La/ cervical
0	11	-0.001468	Li/ cervical	0.001527	La/ cervical
0	**11.7**	**-0.001124**	**Li/ 7 mm from apex**	**0.001157**	**La/ 7 mm from apex**
0	12	-0.001193	Li/ 5 mm from apex	0.001197	La/ 5 mm from apex
10	8	-0.003068	Li/ cervical	0.002604	La/ cervical
10	9	-0.002480	Li/ cervical	0.002095	La/ cervical
10	10	-0.001852	Li/ cervical	0.001563	La/ cervical
10	**10.9**	**-0.001574**	**Li/ 5 mm from apex**	**0.001220**	**La/ cervical**
10	11	-0.001581	Li/ 5 mm from apex	0.001187	La/ 7 mm from apex
10	12	-0.002111	Li/ apical	0.001528	La/ 5 mm from apex
20	8	-0.002872	La/ apical	0.002102	La/ cervical
20	9	-0.002638	D/ apical	0.001730	La/ cervical
20	**9.85**	**-0.002769**	**Li/ apical**	**0.001622**	**La/ 5 mm from apex**
20	10	-0.002826	Li/ apical	0.001665	La/ 5 mm from apex
20	11	-0.003302	Li/ apical	0.001983	La/ 5 mm from apex
20	12	-0.003906	Li/ apical	0.002333	La/ 5 mm from apex
30	8	-0.003957	D/ apical	0.002108	La/ 5 mm from apex
30	**8.48**	**-0.004022**	**Li/ apical**	**0.002197**	**La/** 5 mm from apex
30	9	-0.004199	Li/ apical	0.002315	La/ 5 mm from apex
30	10	-0.004642	Li/ apical	0.002599	La/ 5 mm from apex
30	11	-0.005184	Li/ apical	0.002914	La/ 5 mm from apex
30	12	-0.005799	Li/ apical	0.003256	La/ 5 mm from apex
40	6	-0.005143	D/ apical	0.002648	La/ 5 mm from apex
40	**6.87**	**-0.005185**	**D/ apical**	**0.002752**	**La/ 5 mm from apex**
40	7	-0.005205	D/ apical	0.002772	La/ 5 mm from apex
40	8	-0.005549	Li/ apical	0.002986	La/ 5 mm from apex
40	9	-0.006001	Li/ apical	0.003255	La/ 5 mm from apex
40	10	-0.006529	Li/ apical	0.003563	La/ 5 mm from apex
40	11	-0.007120	Li/ apical	0.003887	La/ 5 mm from apex
40	12	-0.007752	Li/ apical	0.004298	La/ 5 mm from apex

Table 13 The effect of the elastic modulus of PDL when the inclination and Mt/F ratio were kept constant at 20-degree inclination and 10-Mt/F ratio

Elastic modulus of PDL	Anteroposterior movement		Vertical movement	Principal strain	
	Incisal edge	Apex		Minimum	Maximum
0.66	-0.000182	-0.000287	-0.000419	-0.002912	0.001716
0.667	-0.000177	-0.000284	-0.000416	-0.002882	0.001698
0.68	-0.000168	-0.000279	-0.000410	-0.002826	0.001665
0.69	-0.000162	-0.000274	-0.000405	-0.002785	0.001641

BIOGRAPHY

Miss Athicha Kanjanaouthai was born in Bangkok on April 2^{nd}, 1982. She graduated in Doctor of Dental Surgery Degree from Faculty of Dentistry, Chulalongkorn University in 2006 with second class honor. Then, she had worked as a dentist at Phrajomklao Hospital in Petchburi province for 2 years. Since 2008, she has studied in Master of Science Program in Orthodontics at Faculty of Dentistry, Chulalongkorn University.