T.C.
YEDITEPE UNIVERSITY

INSTITUTE OF HEALTH SCIENCES

DEPARTMENT OF ORTHODONTICS

THE EVALUATION OF THE TORQUE CONTROL PARAMETERS IN UPPER INCISORS WITH FINITE ELEMENT ANALYSIS DURING POSTERIOR EXPANSION IN CLEAR ALIGNER TREATMENTS

DOCTOR OF PHILOSOPHY THESIS

EYLÜL ÖGÜT ÖZUĞUR

ISTANBUL – 2024

T.C.
YEDITEPE UNIVERSITY

INSTITUTE OF HEALTH SCIENCES

DEPARTMENT OF ORTHODONTICS

THE EVALUATION OF THE TORQUE CONTROL PARAMETERS IN UPPER INCISORS WITH FINITE ELEMENT ANALYSIS DURING POSTERIOR EXPANSION IN CLEAR ALIGNER TREATMENTS

DOCTOR OF PHILOSOPHY THESIS

EYLÜL ÖGÜT ÖZUĞUR

SUPERVISOR

Prof. Dr. DERYA GERMEÇ ÇAKAN

ISTANBUL – 2024

THESIS APPROVAL FORM

Institute : Yeditepe University Institute of Health Sciences

Programme : Orthodontics PhD

Title of the Thesis : The Evaluation of the Torque Control Parameters in Upper Incisors with Finite Element Analysis During Posterior Expansion in Clear Aligner Treatments

Owner of the Thesis : Eylül Ögüt Özuğur

Examination Date : 05.07.2024

This study has been approved as a Doctorate Thesis in regard to content and quality by the Jury.

	Title, Name-Surname (Institution)
Chair of the Jury:	Prof. Dr. Gökmen KURT Bezmialem Foundation University
Supervisor:	Prof. Dr. Derya ÇAKAN Yeditepe University
Member/Examiner:	Prof. Dr. Feyza ERAYDIN Gelişim University
Member/Examiner:	Assoc. Prof. Dr. Seden AKAN BAYHAN Yeditepe University
Member/Examiner:	Assist. Prof. Dr. Can ARSLAN Yeditepe University

APPROVAL

This thesis has been deemed by the jury in accordance with the relevant articles of Yeditepe University Graduate Education and Examinations Regulation and has been approved by the Administrative Board of Institute with decision dates .... and numbered ....

Prof. Dr. Bayram YILMAZ

Director of Institute of Health Sciences

DECLARATION

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree except where due acknowledgment has been made in the text.

05.07.2024

Eylül ÖGÜT ÖZUĞUR

ACKNOWLEDGEMENTS

I am deeply grateful to my advisor and the Head of the Orthodontics Department Prof. Dr. Derya Çakan for always being there when I needed her, supporting me throughout my PhD journey, and trusting me in every step. I feel very lucky that I had the privilege to gain a lot from her experience and knowledge. It is a great honor to be her doctorate student.

I am sincerely thankful to Dr. Mustafa Özcan. He was always a support in this thesis, also in profession and life, as being like a real brother and idol to me.

I am grateful to Dr. Javier Lozano Zafra for sharing his experiences and answering my questions when I needed.

I deeply appreciate my partner for life Mr. Cem Özuğur for always encouraging me through my PhD and my career in the Orthodontic field.

I am thankful to my dearest parents, Dt. Tülin Ögüt, Dt. Metin Ögüt and my sister Uzm.Dyt. Deniz Eylem Ögüt for being a great family to me.

TABLE OF CONTENTS

LIST of TABLES

LIST of FIGURES:

LIST OF SYMBOLS AND ABBREVIATIONS

AI: Artificial Int
B: Buccal
BB HIMAME: Bone-Borne Haas-Inspired Miniscrew-Assisted Maxillary Expanders
BTB MARPE: Bone-Tooth-Borne Miniscrew-Assisted Maxillary Expanders
CAT: Clear Aligner Treatment
CBCT: Cone Beam Computed Tomography
CAD: Computer-Aided Design
CAM: Computer Aided Manufacturing
CA: Clear Aligner
GBA: Gingivally Bevelled Attachment
FEM: Finite Element Method
FEA: Finite Element Analysis
HA: Horizontal Attachment
HTL: High Trim Line
Gb: Gigabyte
Ghz: Gigahertz
GBHA: Gingival Bevelled Horizontal Attachment
Ipr: Interproximal Reduction
LRT: Lingual Root Torque
LTL: Low Trim Line
Mag: Magnitude
Mm: Millimeter
MPa: Megapascal
N: Newton
Pmax: Tensile Stress
Pmin: Compression Stress
P: Palatal
PDL: Periodontal Ligament
SS: Stainless Steel
Stl: Stereolithography
TMJ: Temporomandibular Joint

ABSTRACT

ÖGÜT ÖZUĞUR, E. (2024) The Evaluation of the Torque Control Parameters in Incisors with Finite Element Analysis During Posterior Expansion in Clear Aligner Treatments. Yeditepe University, Institute of Health Sciences, Department of Orthodontics, PhD Thesis, İstanbul.

The aims of this study were first to evaluate the effect of the posterior expansion with clear aligner on both posterior and anterior teeth using Finite Element Method (FEM), and then to compare the effectiveness of the attachments or power ridges to prevent torque loss of the anterior teeth during posterior expansion by determining the stress distribution on the teeth and periodontal ligament, and the amount of displacement of the teeth. The study focused solely on dental expansion, utilising cone-beam computed tomography (CBCT) data from a 19-year-old female with median palatal suture fusion. Bone modelling was conducted using 3D Slicer software, including reverse engineering and 3D computer-aided design (CAD) activities. Solid models compatible with analysis environments were generated, and meshing was optimised using ANSYS Workbench software. The LS-DYNA solver was employed to solve finite element models. The aligner thickness was determined as 0.76 mm. Buccal expansion activation was 0.2 mm with 1.5° buccal root torque. In the first phase of the study, Model 1.1 was attachment free model whereas Model 1.2. included gingival beveled horizontal attachments (GBHA) on the posterior teeth. In the second phase of the study, additional 3 models were compared based on Model 1.2; Model 2.1 with labial and palatal power ridges on the central incisor, Model 2.2 with a labial horizontal attachment on the central incisor and Model 2.3 with a labial GBHA on the central incisor. Model 1.2 showed more parallel movement compared to the Model 1.1 attachment free model during posterior expansion with clear aligner. With Model 1.1, a greater expansion was obtained. In both models, incisors showed retroclination during posterior expansion. In Model 2.1, 2.2 and 2.3, adding attachments and power ridges to central incisor prevented retroclination of the incisors. In all the models, the von Mises stresses were higher at the central and lateral incisors compared to the posterior teeth. On the periodontal ligament, main stresses were found to be distributed on the premolars.As a conclusion, this FEM study demonstrated that the use of attachments on the posterior teeth during expansion with clear aligners is effective to prevent buccal tipping of the molars. Furthermore, adding horizontal attachments or double power ridges on the central incisor avoid retroclination of anterior teeth during expansion with aligners.

Keywords: FEM Analysis, Torque Control, Expansion, Clear Aligner Treatment

ÖZET

ÖGÜT ÖZUĞUR, E.(2024) Şeffaf Plak Tedavilerinde Posterior Genişletme Sırasında Kesici Dişlerdeki Tork Kontrol Parametrelerinin Sonlu Eleman Analizi ile Değerlendirilmesi Yeditepe Üniversitesi Sağlık Bilimleri Enstitüsü, Ortodonti ABD., Doktora Tezi. İstanbul.

Çalışmamızın amacı ilk aşamada şeffaf plaklarla posterior genişletme sırasında hem anterior hem posterior dişlerde oluşan etkilerin Sonlu Elemanlar Analizi (FEM) ile değerlendirilmesi, ikinci aşamada ise posterior genişletme sırasında anteriorda oluşan tork kaybının ataşman ve güç çıkıntıları kullanılarak tork kaybını önlemedeki etkinliklerinin dişler ve periodontal ligamentteki stress dağılımı ve dişlerdeki yer değiştime miktarları değerlendirilerek karşılaştırılmasıdır. Bu çalışmada, mediyan palatal sütür füzyonu olan 19 yaşındaki bir kadından alınan konik ışınlı bilgisayarlı tomografi (KIBT) verilerini kullanarak yalnızca dental genişletmeye odaklanıldı. Kemik modelleme, tersine mühendislik ve 3D bilgisayar destekli tasarım (CAD) faaliyetlerini içeren 3D Slicer yazılımı kullanılarak gerçekleştirildi. Analiz ortamlarıyla uyumlu modeller oluşturuldu ve ANSYS Workbench yazılımı kullanılarak birleşmeleri optimize edildi. Sonlu eleman modellerini çözmek için LS-DYNA çözücü kullanıldı. Şeffaf plak kalınlığı 0,76 mm olarak belirlendi. Bukkal genişleme aktivasyonu 1,5° bukkal kök torku ile 0,2 mm idi. Çalışmanın ilk aşamasında Model 1.1 ataşman kullanmadan çalışılan bir model iken Model 1.2. arka dişlerde gingivale eğimli yatay ataşmanları (GBHA) içeriyordu. Çalışmanın ikinci aşamasında Model 1.2 temel alınarak 3 model daha karşılaştırıldı. Bu modeller sırasıyla; santral kesici diş üzerinde labial ve palatal yüzeylerde güç çıkıntıları bulunan Model 2.1, merkezi kesici dişin labial yüzeyinde yatay ataşman bulunan Model 2.2 ve santral kesici diş üzerinde labial yüzeyde gingivale eğimli yatay ataşman bulunan Model 2.3 dir. Model 1.2, şeffaf plaklarla posterior genişletme sırasında ataşmansız olan Model 1.1 e kıyasla daha paralel bir hareket gösterdi. Model 1.1'de daha fazla genişletme elde edildi. Her iki modelde de posterior genişletme sırasında ön kesici dişler retrokline oldular.Model 2.1, 2.2 and 2.3 te santral kesici dişlere ataşman eklenmesi ve güç çıkıntılarının kullanılması ön kesici dişlerin ekspansiyon sırasında palatinale devrilmesini önledi. Çalışmamızdaki tüm modellerde Von Mises Stress değerleri en çok santral ve lateral kesicilerde izlendi. Periodontal ligamentte ise stress dağılımı en çok küçük azı dişlerde gözlendi. Sonlu elemanlar analizi ile gerçekleştirdiğimiz çalışmamızda şeffaf plaklarla posterior genişletme sırasında posterior dişlerde ataşman kullanımının bukkale devrilmeyi önlemede etkili olduğu bulunmuştur. Ek olarak, posterior genişletme sırasında santral kesici dişlerde yatay ataşmanların veya çift güç çıkıntısı kullanımın üst kesici dişlerde palatinale devrilmeyi önlediği sonucuna varılmıştır.

Anahtar Kelimeler: FEM Analizi, Tork Kontrolü, Genişletme, Şeffaf Plak Tedavileri.

1. INTRODUCTION AND PURPOSE

Advancements in technology have made it possible to provide comfortable and esthetic orthodontic treatment options to the patients in recent years. The clear aligners with its removable, plastic, transparent features have a big impact on the orthodontic treatments. Clear aligners fulfil the patient's visual demands while still delivering good treatment outcomes for clinicians**.** Similar to fixed orthodontic treatments, clear aligner treatments are effective for treating different kinds of malocclusions. Initially, clear aligners were exclusively developed to correct small irregularities in the positioning of teeth. While several aligner systems have a specific focus on correcting small positional anomalies, others assert their ability to address more severe malocclusions. [1,7,8] Clear aligners made from plastic materials and cover a majority or whole of the teeth. Its ability mostly comes from the teeth underlying the aligner itself. In the literature, there are many publications showing that many of the tooth movements can be achieved by clear aligners, thus it has been part of orthodontic practices.[1,4,5,7,8]

Posterior dental expansion is commonly performed with clear aligners to solve dental arch crowding or correct mild maxillary dental arch constriction. Aligners have the ability to correct dental crossbites, providing a better arch shape by enhancing the alignment. There are many researches evaluating the effect of the aligners in dental arch expansion, and showing that clear aligners are effective in achieving maxillary transversal expansion. [1,4,5,6,7,8] However, this expansion is mainly dentoalveolar, with the crown of the posterior teeth tipping buccally and leading to a side effect which is an uncontrolled tipping movement.[1,4,5,6,7,8]To prevent this uncontrolled movement, it is suggested that biomechanical measures must be taken such as adding attachments, or power ridges. [6,8 53,66]

In the literature, it has been shown that the anterior area reacts to posterior expansion when clear aligners are used. When the maxillary arch was expanded with clear aligners, the anterior teeth tilted lingually and extruded. [141] This shows a significant torque loss of the anterior teeth during expansion due to the biomechanical effect of the clear aligners. Buccal movement of the posterior ends of the clear aligner during expansion results in a palatal movement of the anterior part of the clear aligner as this is a closed system. As a result of Newton's third law, as clear aligners are a closed system, the expansive effects on the posterior teeth shows the reaction on the anterior area as a retraction effect. [141] There are many expansion studies with clear aligners yet no one demonstrated how to prevent these side effects on the anterior area during posterior expansion. [4,5,6,8]

The Finite Element Method (FEM) can estimate the stresses occurring on the alveolar bone, the periodontal ligament (PDL), and teeth, and can determine the loading and displacement patterns of the studied structures.[9] Therefore (FEM) is a commonly used method to evaluate mechanical behaviours of the orthodontic materials as well as stresses accumulated on the dental tissues and periodontium.

Considering the aforementioned lack of information in the orthodontic literature, in the first phase of our study, our aim was to evaluate the effect of the posterior expansion with clear aligner on both posterior and anterior teeth using FEM. In the second phase of our study, we aimed to compare the effectiveness of different torque control strategies, which is adding attachments or power ridges to prevent torque loss of the anterior teeth during posterior expansion.

2. LITERATURE REVIEW

Adults have increasingly embraced orthodontic treatments due to the enhanced cosmetic characteristics they offer during the treatment process. [1] These advancements have yielded both benefits and drawbacks in terms of the duration and quality of treatment. Patients who were previously hesitant to get treatment owing to concerns about their looks can now choose from many options, such as ceramic brackets, lingual brackets, or orthodontic treatments with clear aligners. [1–3] These advanced treatments cater to the needs of patients with high aesthetic expectations during their treatment. Despite the relatively brief period of treatment with clear aligners, patients express a desire for further reductions in treatment time. From that standpoint, doctors and researchers prioritise further study in the realm of expedited techniques or employing strategies derived from biomechanics in digital treatment planning. The digital planning of aligners is strongly influenced by the order or hierarchy of tooth movements, which in turn impacts the production of aligners. [11]Simultaneously, it is crucial to achieving predictable outcomes to ensure that the treatment strategy meets the expectations of both doctors and patients. As it has been searched in the literature there are many expansion researches as well as anterior torque controls, however, it was obvious that there is a need to address the relationship between these two treatments and a combination of these during clear aligner treatments. [4,5,6,8,9,142] Thus we aim to provide the best treatment protocol to achieve the most desired treatment outcome and reduce the treatment time.

2.1. Aesthetic Approach in Orthodontics

One of the variables that contribute to an improvement in the patients' quality of life is the utilisation of orthodontic treatments. Because of this, the number of people seeking orthodontic treatment is growing on a daily basis. [13] As clinicians, we are able to list the aspects that contribute to an increase in quality of life, including the correction of functional occlusion, the enhancement of self-confidence, and the improvement of social and psychological health. In addition, we can provide a smile that is aesthetically pleasing. On the other hand, in order to fulfil these expectations, the period of fixed treatments often takes between two and three years. [14,15]

People are looking for ways to either reduce the length of this phase or achieve the greatest possible outcomes in orthodontic treatment using procedures that are less noticeable. Because people today care about how their teeth look they prefer orthodontic treatment methods that are removable and can be put in and taken out as needed with clear aligner therapies or lingual orthodontic treatment, in which the brackets are put in through the lingual surface of the teeth. This is in contrast to the braces made of plastic, composite, or ceramic, which are primarily fixed treatment methods. Despite the fact that aesthetic brackets are chosen by patients because they are less noticeable, the treatment process is made more difficult by the increased friction that they generate. [16,17] Even though the brackets are esthetic the wires and the ligatures are still visible and cause the esthetic concerns during the treatment. For this reason, treatments with esthetic brackets are visible and do not fulfil the esthetical needs of patients. Due to the fact that composite brackets experience discolouration over time, they result in patients providing the physician with unfavourable feedback in a short period of time. Ceramic brackets, on the other hand, have a number of drawbacks, including the possibility of the bracket breaking, the fact that there is more friction in the ceramic than there is in the metal in the slot, the possibility of enamel damage occurring during the removal of the braces, and the possibility of abrasion against the teeth that are opposite the brackets. [17]

Lingual orthodontics is an alternative method for patients who have significant aesthetic concerns during orthodontic treatment. This is because the models that are made from the measurements collected on the lingual surface of the teeth of the braces are carefully manufactured in the laboratory for the patients. On the other hand, due to the procedures that are carried out and the requirement for individualised manufacturing or sequencing, it is an alternative that is less affordable. Due to the fact that it is placed on the posterior surface of the teeth, it has the potential to irritate soft tissues like the gingiva and the tongue when it is used in lingual treatment. The need for oral hygiene increases as the patient can not be fully seen and clean the brackets and wire as needed. Once again, the length may be longer than the conventional orthodontic treatment since the biomechanical qualities are different from those of the conventional treatment. [17]

Clear Aligner Treatment is a technique for aligning teeth that involves the use of clear, customised plastic aligners. The aligners exert a mild force on the teeth, gradually shifting them to the intended position. CAT offers several benefits, including its nearly unnoticeable appearance, comfortable fit, and the ability to be easily removed for eating and brushing. Consequently, Clear Aligner Treatment is highly versatile in addressing various orthodontic concerns. [1]

Small tooth movements using thermoforming clear aligners, which began to be utilised in orthodontic tooth movements, were initially published in the literature by Kesling in 1945. [18,19] These movements were performed in addition to the appliances that were previously used for orthodontic treatment. Subsequently, several researchers made modifications to this procedure, and it eventually became the primary way of treatment rather than an adjunctive method in the field of orthodontic treatment. When it comes to the teeth that it comes into contact with, it is not uncommon for the duration of traditional orthodontic treatment to be longer. According to the measurements obtained in 1993 and utilised as a technique of treatment methods, respectively. Based on the findings of the research conducted at the University of Chicago, this system was subsequently digitised using the findings. As a result of digitization, this system has been changed from a two- or three-tray system into a framework that will enable more complex treatments to be performed with a significantly greater number of aligners. This is the outcome of Align Technology's significant investment in this matter, with the company concentrating on the work that will contribute to the system's ongoing improvement through the innovations it has developed and the patents it has successfully obtained. At the present time, it is a treatment approach that is usually favoured by people who have high expectations about their facial appearance. [19]

Patients usually want to have a treatment shorter in terms of length, in addition to the aesthetic standards they have. They want their clinicians to perform to the best of their abilities in this respect as quickly as they can. A number of drawbacks are associated with fixed orthodontic treatments that are either extremely quick or very long-term. The decline in motivation of both the clinician and the patient as a result of the prolonged time, and therefore the formation of caries on the tooth surfaces, the loss of health of the gums, or the increase in the risk of root resorption, are some of the complications that can arise as a result of this. The literature has a number of different approaches that have been explored in order to speed up the movement of teeth, and new approaches are continually being developed. [7,10,20] These days in digital orthodontics many companies also use AI to make the predictable treatment planning to serve better and also reduce the treatment time to the clinicians.

2.1.1. Clear Aligner Systems

The invention of clear aligners has revolutionised orthodontics by enabling individuals with specific professional and social requirements to undergo treatment without visible braces. Requests for clear orthodontic appliances are typically made by adult patients who have frequent interactions with the public, patients in the entertainment industry, or adults who develop late crowding or relapse following conventional orthodontic treatment.

Appearance is also extremely important for teens. Consequently, there is a growing demand to undergo orthodontic treatment that is both aesthetically pleasing and comfortable.

In order to achieve consistent and reliable results with clear aligner treatments, there was a necessity to improve orthodontic appliances. In recent times, numerous companies have emerged and enhanced the materials used in aligners to meet the demands of the industry.

Indeed, there are numerous companies that provide aligner solutions for both doctors and patients, including well-known names such as Invisalign, ClearCorrect, Orthero, Spark, Angel Align and many others. Additionally, there are various software options used for aligner treatment planning, including Nemo, 3 Shape, Orchestrate, and many others. These software platforms offer tools for designing and simulating aligner treatments to achieve optimal results for patients undergoing orthodontic care.

2.1.1.1. History of Clear Aligners

Clear aligners, which are custom-made and often used for cosmetic orthodontic treatment, may appear to be a recent invention. However, its roots can be traced back to

1926 when Orrin Remensnyder created the "Flex-O-Tite" massaging device. Remensnyder manufactured plastic appliances. The objective is to address periodontal problems using the Flex-O-Tite device, which provides comprehensive coverage of both the tooth crown and the marginal gingiva. The device applies stimulating movements to massage the gingiva. Following the application of the appliance, Remensnyder noted an unintended consequence in subsequent years, reporting that certain teeth experienced little movement over the course of the treatment. This finding has introduced the concept that tooth movement may be accomplished using removable appliances, regardless of whether it is for orthodontic purposes or not, into the existing body of literature.[40]

In 1945, Kesling endeavoured to create a straightforward device that would enable the alignment of all teeth to their optimal positions relative to one another, without the reliance on conventional braces. The objective of the Positioner gadget is to remove the intricate process of manually bending the arch wire that doctors often perform during the last phases of therapy. Kesling fabricated the appliance by meticulously shaping dental models, ensuring that the teeth were accurately trimmed and aligned to achieve optimal bite using wax. [41] He determined that this appliance may be used to produce little tooth movements and resolve modest movements following treatment with fixed orthodontic devices. Kesling subsequently determined that for situations necessitating significant tooth adjustments, positioners should be produced in a progressive manner based on the measurements obtained and consecutive wax models. [18] The aforementioned advancements served as the foundation for the concept that orthodontic treatment may be conducted with consecutively detachable equipment, eliminating the need for fixed wires.

In 1959, Nahoum created the first thermoplastic device using materials that can be shaped by heat in the field of dentistry. This achievement was documented by Nahoum in 1964. When it was created, this gadget was specifically referred to as a dental contour device since its sole purpose was to safeguard or adjust the placement of teeth. [42]

A novel mould was made by precisely carving the teeth on the model derived from the measurements acquired from the patient using a jigsaw, and subsequently positioning them on wax. Thanks to the flexibility of the thermoplastic material created from this mould, the movement was achieved thanks to the pressure given by the material until the teeth came to their arrangement in the new mould. Nahoum proposed that the device may be utilised to achieve minimum displacements in orthodontic treatments and to execute tooth movements such as fixing diastemas. He came to the realisation that it was not possible to correct all tooth movements simultaneously. As a result, he developed the concept of progressively conducting the anticipated main tooth movements using appliances, building upon Kesling's approach. [42]

Nahoum proposed utilising acrylic buttons on the device for positioning interarch tires, like contemporary attachment applications, for both upper and lower jaws. [42] Nahoum asserted that following their application, these thermoform appliances may be utilised not only for tooth movement, but also for other objectives such as serving as reinforcing appliances, habit breakers, or interim crowns in the field of dentistry. [43]

The Essix appliance was initially introduced in 1993 by American orthodontist John Joseph Sheridan. It was designed to be easy to apply, clear, and aesthetically pleasing for patients. The Raintree Essix company played a key role in its development. [44] Sheridan states that in order to induce tooth movement, it is necessary to have enough surface area to apply force to the teeth, an ideal amount of force, and enough time for the force to produce an effect.

The Essix technique utilises orthodontic force by strategically producing protrusions and recesses on the appliance using a specialised forceps called Hilliard Thermoplier, developed by Dr. Keith Hilliard from Lakeland, Florida. Alternatively, protrusions can be made on the tooth surface using composite material. Aside from the pressure zones, the diastemas or gaps through which the tooth might shift are formed by intentionally leaving gaps in the aligner or by creating a hole in the aligner using manual instruments. The aligners must be worn continuously in the patient's mouth. [17] By employing this method, it is possible to precisely focus on achieving a movement of one millimetre every month. Once a displacement of 2-3 mm has been attained using a single device, it is necessary to reevaluate the data for a subsequent displacement and fabricate a new appliance. By ensuring accurate adjustments on the model using the Essix appliance, it is possible to accomplish rotation, torque, extrusion, intrusion, and tipping actions.

Tooth movement in the Essix system is accomplished by making changes on the same appliance. [45] Adaptations are achieved by using specialised forceps to create windows or zones of pressure in certain regions of the appliance. These gadgets have dual purposes: to strengthen teeth and to facilitate dynamic tooth movement. A drawback of this technique is that the activation of the appliance only allows for a maximum tooth movement of two or three millimetres. [45] The primary drawback of this is that if there is insufficient room to accommodate adjustments on the appliance, it necessitates the process of gathering measurements and constructing a new device. [46] The benefits of this approach include timesaving by on-site modification of the same appliance without the need for further measurements or modelling. Additionally, it has a cheap production cost and may be readily used in clinical settings. [17]

The creation of clear aligners for tooth movement in CAD-CAM systems is accomplished through the integration of computer-aided design-computer-aided manufacturing technology with laboratory procedures. [47] During the first phase, the manufacturing process of clear aligners relies on Kesling's established technology. Each tooth is individually cut, separated, repositioned, and securely fastened. Nevertheless, the drawback of employing this method is the need to conduct measurements throughout each session, diminishing the comfort experienced by both the patient and the physician. Within CAD-CAM procedures, digital models are first collected. Subsequently, a treatment plan is generated using 3D software programs. Finally, aligners or models are manufactured using 3D printers based on the models gained at each stage. [48] This resolved the drawback of having to build up the model for each session in Kesling's application.

Modern orthodontic treatment systems include clear aligners, enabling fully digital treatment planning. This allows for exact adjustments to the direction and extent of tooth movements on digital models, as well as control over each treatment stage and sequence. Each model in these phases was fabricated using three-dimensional printers, and clear aligners were moulded onto them, ensuring the manufacture of the material necessary to accomplish the whole treatment objective in a single stage. This circumstance has been transformative, as it empowers clinicians to formulate treatment strategies by visualising the prognostications of treatment outcomes and presenting them to the patient at the outset of the therapy.

2.1.1.2. Biomechanical Analysis of Clear Aligners and Its Comparison with Fixed Orthodontic Devices

In 2008, Brezniak examined the biomechanical evaluation of tooth movements using clear aligners, distinguishing between possible and impossible movements. [11,12,47,49–51] According to Brezniak, the placement of clear aligners in the mouth results in the exertion of force on the teeth, causing them to shift as a result of their elastic qualities. This phenomenon has been designated as the "watermelon seed effect" due to its resemblance to the ejection of a watermelon seed when it is squeezed between the thumb and index finger. Due to the watermelon seed effect, the appliance shifts away from the dental arch and exerts pressure on the tooth while chewing, resulting in an unwanted intrusive movement. This effect is comparable to the bite-block effect. When an aligner is displaced from the dental arch, it recedes from the tooth surface, making it challenging for mass movement to take place. To mitigate this impact in clear aligner treatment, it is advisable to fabricate auxiliaries such as attachments. These attachments, made from composite material matching the tooth colour, are affixed to the tooth surface. Attachments enhance retention by augmenting the contact surface area and assisting movements of the crown and root.

The objective of optimal orthodontic treatments is to provide perfect pressure that will induce maximal tooth displacement while minimising tissue injury. The pressures exerted by the flexible appliance throughout its travel to the ultimate position on the dental arch are effective in achieving tooth movement with clear aligners. Hence, the durability characteristics of these devices are crucial for achieving optimal targeted tooth displacement. The magnitude of force exerted by clear appliances is limited upon the level of activation incorporated in digital planning, as well as the resilience characteristic of the aligner. The activation levels differ across different clear aligner manufacturing businesses at each stage. Furthermore, practitioners and organisations may differ in several factors, including aligner material, thickness, marginal trim line, number of attachments, features of the attachments utilised, and duration of usage. [11,12,47,50,51]

Clear aligners allow for easy attainment of tilting, intrusion, and relative extrusion movements. However, achieving rotation, parallel movement, and pure extrusion movements is more challenging as compared to using fixed conventional devices.

In conventional orthodontic treatment procedures, tooth movement is accomplished by the application of a force that pulls the teeth. In contrast, tooth movement is induced by the 'push' force in clear aligner treatments. In static mechanics, the force exerted on the tooth is determined by the wire's flexibility and the extent of its elastic deformation during the application of force to the tooth. The material's elastic deformation property allows it to exert a force on the tooth, actively attempting to restore it to its target position. This force is generated by the material's tensile strength as it strives to revert back to its original shape. Conversely, in clear aligner treatments, there are negligible disparities between the immediate activation of force when the appliance is inserted into the mouth and the locations of the teeth in both the intraoral and clear aligner. When the clear aligner is positioned over the teeth, it undergoes deformation and, due to the ability the adaptation of the material, exerts a propulsive force on the teeth, guiding them towards the intended alignment. [52]

Djeu et al.'s research demonstrated that both the Invisalign and braces groups achieved similar ratings in the marginal ridge category, demonstrating that Invisalign is capable of aligning arches as effectively as fixed appliances. The unexpected achievement of favourable root angulation was equally remarkable. In general, removable aligners have a tendency to tip crowns but are unable to tip roots due to the limited ability to control tooth movement, particularly when it comes to translating roots through bone. The findings of this investigation, however, revealed that there was no statistically significant disparity between the two groups. This finding could be attributed to the exclusion of extraction patients in the sample. The majority of malocclusions typically begin with roots that are rather well-aligned. Root angulation becomes a significant concern primarily when dealing with the closure of extensive gaps, such as in situations involving tooth extraction. Including premolar extraction patients in the study would likely have resulted in Invisalign cases receiving a higher score reduction for root angulation compared to braces cases. When extracting teeth, clinicians often utilise skeletal anchorage to enhance the effectiveness of bodily movement. [29]

In the context of bonding, fixed orthodontic devices utilise composite adhesives to bind the brackets to the tooth. This is achieved by bonding the etched surface of the tooth to the 80 mesh spiral on the back surface of the brackets. Brackets are positioned on the teeth in three spatial planes: sagittal, vertical, and transverse. The specific location of this position may differ based on factors such as the manufacturer, treatment approach, or the optimal point chosen to address the needs of the clinician and patient. Upon completion of the treatment, arch wires or segmental arch wires are inserted and attached to the brackets in order to align the teeth to the correct position. [52] Adequate space on the tooth surface is necessary for the connection of the braces, allowing the brackets' table surface to be put securely. It has no impact on the connection between the bracket and the tooth, or the connection between the arch wire and the bracket. In fixed orthodontic treatment, the efficacy of wire retention and tooth grip is directly proportional to the thickness of the wire inserted into the slot of the brackets. The treatment often starts with the use of very versatile, round, and slender nickel titanium wires to rectify teeth that deviate significantly from their optimal alignment. The term used to describe this procedure is levelling. After aligning the teeth, they are then transitioned to rectangular, rigid wires with the goal of achieving root movements.

In clear aligner treatments, the aligner attaches to the teeth by enveloping or covering them. The coverage of the tooth's surface leads to an increase in retention. Retention and tooth movement pose challenges when dealing with teeth that have short clinical crowns or are incompletely erupted with tiny surface areas. However, tooth movement becomes more predictable when working with teeth that have lengthy clinical crowns and wide surfaces, as a stronger connection may be established.

Attachments can be employed in clear aligner treatments to augment the surface area and enhance friction, hence facilitating the intended tooth movement on places with limited surface space. By enlarging the contact surface between the clear aligner and the tooth, friction regions are formed where the aligner may exert force on the tooth. Modifications to the form, location, and size of the attachments can be implemented based on factors such as the direction of tooth movement, the type of movement, and their role in retaining. Treatment plans created using clear aligners are customised to each patient's particular movements, taking into account the cumulative effect of these movements. [52]

When considering anchoring in fixed devices, Newton's third rule, known as the 'rule of Action-Reaction', states that a reaction force is generated in the opposite direction and with equal magnitude to the force applied to an item in a certain direction in space. Fixed orthodontic treatments provide mechanical pulling pressures that cause teeth to move. This movement occurs as a result of the force exerted by neighbouring teeth or a skeletal anchoring unit. To generate force outside of wires, one can utilise supplementary mechanisms such as elastic chains, elastic threads, coils for closing and opening, fixed functional appliances, screws and expansion devices. These devices can be employed to induce tooth movement or orthodontic/orthopaedic force. It is important to remember that mechanics involving pushing forces can generate reverse movements that need control, similar to mechanics involving pulling forces. For instance, when open coils are used, applying a pushing force to the space in the arch can result in the movement of a tooth and the creation of a new space in the area where the spring is placed. Additionally, if the arch wire lacks sufficient rigidity, it can lead to tooth movement in various directions, such as tipping.

Clear aligner treatments sometimes offer more convenient methods for achieving anchorage control compared to fixed approaches. A benefit of the procedure is that the teeth forming the anchor segment can be immobilised and changed at various stages. For instance, when distalization is intended, the second molar teeth are initially moved towards the distal of its previous position. The teeth located between the right first molar and the left first molar remain stationary throughout the first phase and function as units for providing support. Then, when distalization of the second molars is completed they serve as the stable support for the rest of the teeth in the dental arch in further steps The procedure of using a clear aligner to execute this task is referred to as sequencing (phasing). During the process of sequencing, auxiliary force components, such as intermaxillary elastics, are employed to mitigate any adverse effects or enhance the force exerted as the values of the moving segments and the teeth acting as anchor units become closer to each other. [52]

Attachments are another component employed to enhance the impact of movements. Attachment applications are variously shaped or sized pieces that are put on the tooth's surface. Their purpose is to enhance the grip of the clear aligners, alter the direction of the applied force, and facilitate particular tooth movements. During the initial phase of the procedure, the guide aligners are positioned on the teeth by applying composite material to the specified attachment locations.

Clear aligners exert stress on the teeth, allowing for various tooth movements, including proclination, without the need for attachments. Nevertheless, achieving complex tooth movements and rotations in the majority of teeth is challenging in the absence of attachments. [53]

The clear aligner technique has evolved significantly since its inception, now enabling the treatment of more complex malocclusions. This advancement is primarily due to the introduction of bonded attachments, which facilitate the locational alignment of the tooth crown. Additionally, continuous innovations are being incorporated into the technique on an annual basis.

2.1.1.3. Orthodontic Movements Performed with Clear Aligners

2.1.1.3.1. Extrusion

Clear aligners allow for comparatively simple relative extrusion, but pure extrusion is a challenging process with an efficiency of just 29.6%. [47,53] To facilitate the extrusion movement, a gap is intentionally created between the aligner and the tooth to allow for the tooth to naturally erupt. Alternatively, attachments can be placed on the tooth to induce the extrusion movement. [56] However, if there is not enough space in the back area owing to occlusal pressures, the opposite movement may occur, causing intrusion as a result of the thickness of the aligner.

Attachments can assist in achieving a limited degree of incisor extrusion in most instances. Prior to initiating extrusion, it is crucial to ensure that there is sufficient space available, particularly in instances where there are tight interproximal contacts or notable crowding, regardless of the absence of crowding. [53] Incisors and canines often have a narrow form near the gums and broaden as they move toward the biting edge. In such instances, it is futile to anticipate the initiation of movement without first ensuring an adequate amount of space for extrusion.

Simultaneously, it is particularly challenging to achieve extrusion movement in teeth with limited clinical crown lengths due to the tiny grip area and teeth with a narrow force application area accompanied by clear aligners. In such instances, attachments with an angled active surface towards the gingiva are affixed to the teeth. Subsequently, a clear aligner is applied, exerting an extrusion force on the tooth surface. Extrusion attachments are necessary for the treatment of open bite in order to facilitate the extrusion of all incisors. These attachments are placed on the front teeth as a standard procedure. [57]

2.1.1.3.2. Intrusion

Although intrusion is generally considered unfavourable to tooth movement because it leads to increased aligner thickness, particularly at the posterior region, it can be beneficial in situations where molar intrusion is necessary. If the goal is to correct the intrusion of a single tooth or tooth segments, it may be essential to undertake additional procedures throughout the treatment using clear aligners. In situations of deep bite, incisors can be intruded by applying intrusive force and using attachments on premolar and molar teeth for anchorage reasons. Anterior intrusion refers to the process of moving the front teeth downwards. Companies often propose a set of protocols, also known as the frog protocol, which involves a certain sequence of moving the incisors and canines. This sequence helps improve the accuracy of these movements.

The duration and efficacy of performing the invasive movement with clear aligners are still unknown. Hence, in certain instances, it enhances the viability of skeletal anchoring applications, namely, mechanics supported by mini-screws.

The presence of clear aligners, because of their thickness and ability to avoid contact with the occlusal surface, is known to provide a bite-block effect. This effect leads to incursion in areas where the clear aligner comes into touch with the force exerted by the chewing muscles. This technique has been proven to be efficacious in diminishing the extent of challenging movement of extrusion. Hence, it is evident that clear aligners offer significant benefits in situations when open-bite cases need the intrusion of posterior teeth.[58] Posterior intrusion has the benefit of reducing the necessity for incisor extrusion to create overbite. The presence of a bite block effect poses challenges in treating deep bite patients with clear aligners. In order to reduce this phenomenon, if one wishes to achieve posterior extrusion, the aligner can be precisely incised in that specific region, allowing for sufficient room for extrusion. Applying posterior extrusion mechanics is essential to prevent the development of an open bite in the posterior area at the conclusion of the therapy.

Hence, further therapeutic measures such as overtreatment, button-elastic use, and bite-ramp application might be employed. Bite-ramps are specifically engineered to prevent backward movement and apply downward force to the lower front teeth using the natural biting action. It assists in the alignment of the buccal segments and promotes effective movement of posterior teeth out of the jaw. The bite-ramp location is automatically modified to provide continuous frontal contact during the whole treatment process. Nevertheless, it is important to acknowledge that there will be a reduction in torque due to the decrease in grip.[59]

2.1.1.3.3. Rotation

Rotation refers to the act or process of turning or spinning around a central axis. Performing rotational movements with clear aligners, particularly in a circular shape, is exceedingly challenging owing to tooth anatomy. Aligning teeth, particularly premolars or canines with a round form or teeth that are rotated more than 45 degrees, is a challenging task that typically requires the use of rotating attachments on the teeth.[56]

The inclusion of attachments enhances the management of rotational movements and improves the predictability of executing these movements to a small extent. Research has indicated that the rotating movement is least successful in the lower canine teeth, with a rate of 29.1%. Conversely, the maximum efficiency rate of 54.2% is observed in the upper central teeth.[47]

If a tooth that has been rotated during treatment cannot be fully fixed, it may need further correction or the use of extra mechanical methods to achieve its desired position.

To achieve the optimal position, it is beneficial to employ overcorrection and a 1.5-degree correction per aligner during rotational movements. [57]

To obtain the appropriate rotational movement, the physician may need to employ techniques beyond attachment and aligner force. To initiate the intended rotational movement, one can begin by establishing a gap of 0.25-0.5 mm in the neighbouring regions of the target tooth. Alternatively, IPR can be employed to minimise the force that the tooth would otherwise lose as a result of friction. [60] This approach is also beneficial for enhancing aligner retention. In cases of extreme rotations, the problem may not be resolved just with the use of attachments and aligners. It may be beneficial to seek assistance from other mechanical resources. Prior to or during the process of clear aligner treatment, it is advisable to enhance the treatment by utilising buttons and elastics, mini-screws, and even fixed devices. [60] Currently, in standard treatment approaches, rotation correction has emerged as a commonly favoured technique for including supplementary mechanical adjustments that are separate from the aligner and attachment, both prior to and during the treatment.

2.1.1.3.4. Torque

Torque refers to the measure of the force that can cause an object to rotate around an axis. Clear aligners, while they cover a significant portion of the tooth's surface area, have certain limitations in terms of their ability to bind with the teeth when compared to permanent systems. According to Castroflorio et al., it is more challenging to achieve torque movement in clear aligner treatments compared to other forms of tooth movement. [61]

To provide the rotational force, the power ridge is either included into the aligners during their manufacturing or added afterwards using specialised pliers. It is commonly used to generate a rotating force couple around the gingival line on the outside surface and at the top section on the inner surface. Nevertheless, because of the flexible composition of the clear aligner and the challenge of relocating the roots within the bone by gripping them far from the centre of resistance, it is advisable to use overcorrection in order to get the intended outcome. Furthermore, it is important to note that due to the increased forces exerted on the occlusal edge, the clear aligner may detach from the teeth, resulting in reduced grip and a tendency to shift towards the occlusal surface. This can weaken the connection between the clear aligner and the tooth. [53]

The en-masse retraction of the incisors, commonly used in extraction situations, is an intricate dental procedure that necessitates precise management of incisor intrusion and torque control. [62] If torque control is not given, lingual tilting, extrusion and clockwise moment of the incisors, dubbed the roller-coaster effect, occur. Particularly at this time, the problem, which is being attempted to be managed by immobilisation in a fixed treatment, proves to be quite challenging to regulate using aligners. [63]

The roller-coaster effect is characterised by an increase in the depth of the bite, the occurrence of early contacts in the anterior teeth, and the presence of an open bite in the posterior teeth, which are commonly observed in traditional fixed orthodontic treatments. However, in contrast to fixed treatments, the lack of rigidity in clear aligner materials aggravates their inclination to tilt and intensifies the roller-coaster effect. [64]

Dai et al.[65] revealed in their investigation that clear aligners could only accomplish 42% of the root torque and intrusion of the incisor teeth. [65] To enhance the reliability of tooth movement, it is advisable to incorporate extra root torque and intrusion of the incisor teeth into the treatment plan for overtreatment. Nevertheless, the impact of excessive correction on the rotation and downward movement of the anterior teeth remains mainly uncertain. [66]

The efficacy of root torque control and intrusion was observed to be lower for lateral incisors compared to central incisors. Given that the force exerted by clear aligners is contingent upon the surface area, it is crucial for the clear aligner-tooth surface to be extensive in order to provide a substantial gripping effect and apply enough force. Given the lesser size of the lateral incisors and their reduced crown surface area, overtreatment has been seen to be less successful in comparison to the central incisors. Overtreatment may result in the lateral incisors not aligning properly with the clear aligner, causing tooth movements to deviate. [67]

2.1.1.3.5. Tipping and Parallel Movement

Clear aligners may effectively execute controlled and uncontrolled tipping movements by biomechanically engaging and pushing. According to Kravitz et al.[47], the intentional tipping movement in the direction from the front to the back of the teeth was found to be highly predictable and successful in 41% of cases. [47] In the same study, it was also revealed that the labiolingual tipping action is extremely predictable. Although a clear aligner may readily manipulate the top portion of the tooth, the inability to move the roots at the same level is a significant drawback.

Attaining simultaneous tooth movement using clear aligners is improbable since the force is transmitted above the centre of resistance. Simultaneously, when considering the watermelon seed effect on tooth movement, studies indicate that tooth movement often occurs as uncontrolled tipping, even if parallel movement is intended during treatment planning. This is because it is challenging to apply force to the teeth from the gingiva. [55] Simon et al. found that the distalization of upper molar teeth showed a significant increase in parallel movement when attachments were used for support.

Upon examining the literature, many investigations yield different findings about parallel movement using clear aligners. The primary factor contributing to the occurrence of this circumstance is the challenging application of force couples on clear aligners. To enhance the management of root movements, it is necessary to develop various aligners and attachments in digital planning and assess them with studies.

2.1.1.4. Attachments and Auxiliaries on Aligners

2.1.1.4.1. Attachments

2.1.1.4.1.1. Conventional attachments

Conventional attachments are passive devices designed to enhance the grip of aligners on teeth, serving as handles for moving teeth. They can be added to the treatment plan either by written request to the technician or by using the drag-and-drop feature in the 3D controls. [68]

There are three main types of conventional attachments:

2.1.1.4.1.1.1. Ellipsoid attachments: These attachments are utilised for retention or anchorage purposes, particularly in cases where the tooth surface area is limited. They are often used for teeth with unusual shapes, such as peg-shaped lateral incisors, or on the lingual surface of mandibular second molars with lingual inclination.

2.1.1.4.1.1.2. Rectangular attachments: Rectangular attachments can be either vertical or horizontal and are primarily passive in function. By default, they are positioned in the centre of the tooth crown but can be repositioned as needed to facilitate the planned mechanics for the case.

2.1.1.4.1.1.2.1. Horizontal attachments: These are useful for controlling root movement, particularly for achieving labial root torque on molars. They may also be employed in cases with short crowns to enhance aligner retention, which is standard in protocols for patients undergoing interventions like mandibular advancement. In cases of unilateral crossbites, horizontal rectangular attachments are placed on the non-crossbite side to provide anchorage for correcting the unilateral posterior crossbite on the opposite side. Additionally, they aid in controlling root torque to achieve a comprehensive movement involving not just the crown but the entire tooth body.

2.1.1.4.1.1.2.2. Vertical attachments: These attachments are utilised for root control in cases where the software cannot optimise root control attachments, such as mandibular incisors in cases involving the extraction of a lower incisor.

2.1.1.4.1.1.3. Bevelled attachments: Both horizontal and vertical rectangular attachments can be bevelled.

- Horizontal attachments can be bevelled either towards the occlusal or gingival direction to assist with intrusion or extrusion movements:

For extrusive movements of posterior molars, a horizontal attachment bevelled towards the gingival can be utilised.

To achieve intrusion, a horizontal attachment bevelled towards the occlusal can be applied on the teeth adjacent to the one requiring intrusion.

- Vertical attachments can be bevelled either towards the mesial or distal direction.

They are particularly useful for rotation movements in cases where the software hasn't positioned optimised rotation attachments, such as correcting first molar rotation.

The active surface is the bevelled one, as it provides a flat surface for the aligner to exert pressure against, facilitating the intended tooth movement.

Conventional and optimised attachments may serve similar purposes:

- Double root control attachment: This function can be fulfilled by the conventional rectangular vertical attachment.
- Optimised rotation attachment: The conventional rectangular vertical attachment, bevelled to mesial or distal, can function similarly to optimised rotation attachments.
- Optimised extrusion attachment: The conventional horizontal attachment, bevelled to gingival can serve as an alternative to optimised extrusion attachments.

2.1.1.4.1.2. Optimised attachments:

Optimised attachments differ from conventional attachments in several ways:

They are designed to deliver optimal force for achieving more predictable tooth movement. Each attachment is customised according to the width, long axis, and contour of the tooth. The positioning of optimised attachments is precise to ensure effective force delivery while eliminating any interferences. These characteristics are determined by the ClinCheck software and cannot be altered by the practitioner, although this feature may change in the future.

Optimised attachments offer SmartForces tailored to the specific needs of each tooth, ensuring the ideal movement with the right amount of force. Here are some key features:

Automatically placed by the software based on predefined thresholds of tooth movement, ensuring precise control over the application point, direction, and force magnitude.

Customised to fit the unique morphology of each tooth, with an active surface designed to interact with the aligner.

The aligner is designed at a sharper angle than the attachment's active surface, enabling it to exert force on the attachment and guide the tooth movement effectively.

The size of the attachment on the tooth may differ from the space allocated in the aligner (reservoirs) for attachment.

If replacement of an optimised attachment is necessary during treatment, the clinician will use the attachment template to re-bond the attachment rather than relying on the last aligner.

In the past, practitioners were unable to request the placement of optimised attachments directly, but they could request specific movements that would prompt the software to place them accordingly. For instance, if an optimised extrusion attachment was needed on a particular tooth, the practitioner could request more than 0.5 mm of extrusion for that tooth, prompting the software to place the attachment accordingly. However, it is now possible to request optimised attachments even for movements that are not expected to occur or are below the threshold, which could be beneficial for certain situations, such as using lower premolar anchorage to level the lower Spee curve by incisor intrusion. It's important to note the following:

Optimised attachments are customised for each tooth and the specific movement required for that tooth.

- Their position, shape, or size cannot be altered.
- They cannot be placed lingually.
- They are not compatible with other lingual attachments or SmartForces.
- Currently available optimised attachments include:
- Optimised rotation attachment can be used for rotational movements in canines and premolars
- Optimised extrusion attachment can be used for extrusion movements in incisors, canines, and premolar
- Optimised root control attachment can be used for root control in incisors, canines, and premolars
- Optimised attachment for upper lateral incisors.

2.1.1.4.2. Power Ridges:

These can be placed independently and are not compatible with attachments. They typically establish a force couple, particularly useful for incisor torque adjustments.

If only the buccal aspects are to be considered, then:

- Found on both upper and lower incisors.
- Generate lingual root torque.
- Placement is triggered when a threshold of 3 degrees LRT is reached.
- Adjustment rate is set at 1 degree per aligner.

If both buccal and lingual aspects are to be considered, then:

- Found on upper incisors.
- They induce both LRT and incisor retraction.
- Placement is initiated when a threshold of 3 degrees LRT plus anterior retraction is reached.
- Adjustment rate is set at 1 degree per aligner plus 0.25 mm of retraction.

2.2. Expansion in Orthodontics

Several factors are crucial during the treatment of transversal insufficiency in the maxilla. These include the patient's age, the level of cooperation from the patient and their family, the severity of the crossbite, the possibility of eliminating the underlying cause, the potential for natural recovery, and the choice of appliance. These factors significantly influence the treatment outcome. [69]

Researchers have divergent views on the management of posterior crossbite. Although some studies assert that this problem is often not capable of being fixed spontaneously [70] , there are others who contend that this condition may be spontaneously fixed throughout the deciduous and early mixed dentition phase. [71]

Orthodontic treatment is recommended for patients with a small maxilla and a broad mandible, who do not have a functional crossbite that may be corrected by abrasion or tuberoplasty. In such circumstances, maxillary expansion should be used.

The disparity in skeletal structure and the alignment of teeth in the back region are significant factors in determining the appropriate appliance for addressing crossbite conditions. [72]

During the early mixed dentition era, there were two treatment options available based on the underlying causes:

1. Surgical procedure to open the median palatal suture and laterally expand the maxillary bases to correct skeletal crossbites.
2. Dental crossbites may be caused by lateral tilting and/or parallel movement of the teeth.

Dental tilting and/or parallel movement are often used to correct transversal malocclusions measuring up to 4-5 mm. Nevertheless, skeletal adjustments are essential when there is a growing disparity. [72]

When the transversal disparity is caused by the maxilla, the upper dental arch and apical bone base should be enlarged simultaneously. [73,74] Posterior crossbite is treated with either fixed or removable appliances. [69]

The common skeletal problem of maxillary deficiency or narrowness in the transverse direction can manifest as horizontal deficiency at both dental and skeletal levels, frequently resulting in a posterior crossbite. [75,76]

Crossbite can vary from affecting single teeth to multiple or all teeth, arising from either skeletal or dentoalveolar factors and occurring more commonly during deciduous and mixed dentition periods. [77]

Transverse expansion techniques can be employed in both the maxilla and mandible to address posterior crossbites and moderate incisor discrepancies. Mandibular transverse expansion occurs earlier than maxillary expansion.

A critical aspect is that the inter-canine distance in the mandible remains constant after permanent canines erupt. Any transverse increase in the intercanine distance after permanent canine eruption is temporary and may regress. In the maxilla, transverse expansion can be extended over a longer period due to continued growth and development. [78]

Both fixed and removable appliances are utilised in crossbite correction, and maxillary expansion procedures can be applied slowly, semi-rapidly, or rapidly. [69,78]

Mc Inaney et al. [79] found that early expansion eliminates the need for extracting deciduous canines and premolars. [79] While skeletal effects are achieved by mid-palatal suture separation during early stages like the mixed dentition period, orthodontic effects involve inducing alveolar and dental tipping in adulthood. [80–83] A study comparing slow, semi-rapid, and rapid expansion protocols with different appliances during the mixed dentition period concluded that early expansion resulted in both skeletal and dental effects across all groups. [82]

Proffit[69] advises against rapid expansion with heavy force during the deciduous and early mixed dentition periods due to adverse effects on the nasal shape, potential swelling in the paranasal region, and a nasal hump. [69]

Removable expansion appliances serve for gradual expansion in both the maxilla and mandible, particularly in minimal constrictions of less than 4-5 mm. Their low retention necessitates low-force application, predominantly creating dental effects, with patient cooperation being pivotal for treatment success. [69,73,74,84,85]

2.2.1 Skeletal Expansion

2.2.1.1. Rapid Maxillary Expansion

Skeletal expansion is an expansion that has effects both on skeletal structures and dental tissues. In early ages, the most used technique is Rapid Maxillary Expansion which has been used for a considerable duration in the management of maxillary transversal insufficiency. [86]

RME is the process of widening the midpalatal suture by exerting a stress in the lateral direction on the maxillary teeth, palatal bone, and/or alveolar tissues that exceed physiological limitations. [87]

The force generated during expansion is first transmitted to the teeth and subsequently to the periodontal ligament and alveolar bone. The procedure involves the opening of the midpalatal suture and the observation of the buccal tilting of the teeth. [76]

RME therapy involves the application of periodic force. The maximum force applied during the first rotation of the screw is reset and remains inactive until the next activation.

RME is easily and successfully applied in adolescents and children before fusion of the midpalatal suture. Nevertheless, studies have shown that the efficacy of maxillary expansion diminishes in teenagers and young adults who have completed their development, mostly because of suture closure. [86]

There are limitations of the application of RME. In adults, it is not planned without skeletal anchorage or surgical interventions. If a skeletal expansion is required in adults patients need to undergo these treatments. If the crowding or crossbite is at dental levels, dental expansion can be suggested.

2.2.2. Dental Expansion

Orthodontic or dental expansion is achieved by the use of different removable expansion appliances and conventional fixed appliances. By expanding the arch, crowding can be resolved, dento-alveolar crossbite can be corrected, or the arch shape can be altered.

In the slow maxillary expansion method, gentle and continuous forces are utilised to achieve adequate widening of the upper jaw. This involves applying forces ranging from 450 to 900 grams to the posterior teeth over a period of around 2–6 months while maintaining the integrity of the midpalatal suture. [83,90,91]

When administered to patients at an early stage, slow expansion can lead to midpalatal suture opening and demonstrate orthopaedic effects, minimising pain and discomfort by allowing the regeneration of the midpalatal suture area. [85,90–92,95,96]

The forces applied in the slow expansion protocol result in less accumulation of residual stress in the maxillary and craniofacial structures, promoting healthier tissue adaptation without exceeding physiological limits. Consequently, since tissue integrity remains intact in the slow expansion protocol, a lower rate of relapse may occur. It has been reported that the expansion amount ranging from 0.5 to 1 mm per week is more suitable for midpalatal suture and surrounding tissue adaptation. [90–92]

Several studies have shown that slow maxillary expansion equally impacts dental and skeletal structures, with the skeletal effect varying between 16% and 30%. [85,93]

When performing slow expansion in adults, it must be known that the effect is dental and the expansion will not show a skeletal effect. In order to accomplish dental expansion, the crown demonstrates buccal tipping, while the roots display lingual tipping. One of the most important things to keep in mind is to make the necessary evaluations to avoid gingival recession during dental expansion. While performing the tipping movement, sagging of the cusp tops of the crown due to the side effects of tipping can be encountered in treatments with both fixed and removable appliances. In order to maintain the integrity of both retention and periodontal tissues at the end of treatment, bodily movement should be the main goal and vertical dimension control should be ensured by checking regularly during treatment.

2.2.2.1. Dental Expansion with Clear Aligner Systems

The development of arch width through different orthodontic methods has been extensively researched. Dentoalveolar expansion can be achieved using fixed appliances like the quadhelix device or broader archwires with self-ligating and conventional bracket systems. [7,97–100]

In non-extraction treatment, managing moderate crowding and constricted maxillary arches involves increasing arch perimeter through transverse expansion and proclination of the incisors. Attaining a stable and functional upper transverse dimension is a primary goal in orthodontic treatment, ensuring occlusal stability and aesthetic results. Studies on fixed appliance effects generally show more pronounced expansion in the premolar region and less increase in intermolar width. [100–103]

Innovations in orthodontics aim to enhance patient comfort, reduce treatment time, improve oral hygiene, and increase patient acceptance. Clear aligner treatment (CAT) has emerged as an aesthetic alternative to traditional orthodontics, capable of correcting dentoalveolar crossbite and achieving interarch transverse coordination. Unlike conventional fixed appliances, CAT allows digital planning of upper arch expansion through a combination of buccal dental tipping and bodily translation of posterior teeth. However, some authors note a clinical observation of more dental tipping than bodily translation, raising questions about the predictability of clear aligners in complex movements. [4,5,104–107]

Galluccio et al. indicated an average efficacy accuracy of 70.88%. There were no statistically significant differences in predictability among the various vestibular measurements (intercanine, inter-premolar, and intermolar), but there were significant differences in gingival measurements. The overall accuracy of the expansion treatment was 70%, irrespective of the tooth type. [109]

The predictability of expansion, which assesses the ability to anticipate final outcomes at the start of Clear aligner treatment, can be evaluated by comparing the virtual post-treatment digital model simulated on virtual digital software with the actual digital model obtained through scanning the post-treatment model. This predictability is also referred to as the efficiency or accuracy of arch expansion. The average expansion differed significantly from the predicted expansion for each type of tooth in both the maxilla and mandible, with instances of both under-expansion and overexpansion observed. [108,110–117]

However, Lione's study did not find statistically significant differences between the software-planned treatment and the post-treatment outcome measures on the models. [108]

Notably, Zhou's study revealed the efficacy of crown expansion movement in the upper arch for the canine, first premolar, second premolar, and first molar to be 79.75%, 76.10%, 73.27%, and 68.31%, respectively. [118]

Prior studies have indicated that clear aligner therapy is successful in managing posterior buccolingual inclination, but it may not be as effective in controlling anterior buccolingual inclination. Moreover, it has been found to effectively manage upper molar body movements, with an average displacement of approximately 1.5 mm. [1]

2.3. Finite Element Analysis

The 3D finite element method (FEM) is a computer-based technique used to simulate the distribution of stress in the periodontal ligament (PDL) and alveolar bone when loads are applied to simulate tooth movement. This method has been widely employed in the orthodontics profession to enhance comprehension of the biomechanics associated with orthodontic movement and to offer direction for clinical procedures.

The present work employed the Finite Element Method (FEM) to examine the biomechanics of expanding the maxillary arch and to explore the optimal stride length and torque compensation. Subsequently, this data was utilised to direct the therapeutic application of clear aligners to find the best treatment protocols of torque control on anterior incisors while expanding the upper dental arch.[9]

2.3.1. Basic Concepts Related to Finite Element Analysis

2.3.1.1. Force

The interaction between two objects in the form of pressing or pulling constitutes force. Forces can exist between bodies in contact or at a specific distance; examples include electromagnetism and gravity. Force is a vector quantity denoted by a magnitude and a direction, both of which are expressed in Newton units (N). [119]

2.3.1.2. Tension (Stress)

Internal resistance to a deforming force is generated when an external force is applied to an object. Stress refers to this internal resistance that is of the same magnitude as the applied force but acts in the opposite direction. The unit of measurement is frequently Pascal.

Due to the fact that both internal resistance and applied external force are distributed across a specific surface area of the object, tension and external pressure are also quantified in terms of force per unit area. In essence, stress can be described as the external force exerted on a mass per unit area, which the object resists. It is visually represented by the notation 'S' or 'σ'. [120]

Stress is calculated by the following formula;

$\text{Stress}(\sigma) = \text{Force}(F) / \text{Area} = N / mm2 = MPa$

The object can be subjected to a force that can originate from any direction and angle. These impacts frequently merge to generate intricate strains within the framework. There are primarily three fundamental types of stress that occur:

Tensile stress arises when a body is subjected to two forces acting on the same line but in different directions, causing the molecules of the body to move apart from each other.

Compressive stress refers to the situation where two forces act on a body in the same direction but in different directions, causing the molecules of the body to come closer together.

Shear stress is the result of two opposing forces acting on a body, causing the molecules within the body to slide against each other in a parallel direction to the surface. [121,122]

Normal stresses, which are denoted by the symbol "σ", refer to both tensile and compressive stresses. The symbol "τ" represents shear stresses. Applying a uniform type of stress to items in life is challenging. Compound stress situations, characterised by the simultaneous occurrence of tensile, compressive, and shear stresses, can be observed in loaded objects. [123]

2.3.1.3. The Principal Stress

Principal stresses refer to stresses that solely consist of normal stresses that are perpendicular to the region, with zero shear stresses in all planes. The primary stressors can be classified into three categories: highest, middle, and minimal. [122]

The greatest primary stress refers to the highest magnitude of stress experienced in a material. The maximum primary stresses are positive and indicate the highest levels of tensile stress. The least primary stress refers to the lowest value of stress experienced by a material. The minimum primary stresses are negative and indicate the maximum compressive stresses.

The analytical results show that positive values imply tensile stresses, whereas negative values indicate compressive stresses (compression). The effective stress at a nodal point is determined by the stress with the bigger absolute value. [124,125]

2.3.1.4. Von Mises Stress (Equivalent Stress)

Von Mises stress is a measure used to depict the distribution of stress within a body subjected to a specific force. Von Mises stress is a criterion derived from the notion that if the internal energy in a certain region of a structure exceeds a particular threshold, the structure will deform at that location. This is the point at which ductile materials start to undergo deformation. The Von Mises stress values can be analysed to gather overall information regarding the stress distribution and areas of concentration. [122,126]

2.3.1.5. Strain

Strain refers to the alteration in the form of an object's unit dimension caused by the application of a specific force. When a force is exerted on an item, it generates both stress and strain. Strain can be quantified by measuring the displacement of atoms. The forces that oppose displacement between atoms are referred to as tension, whereas the resistance of atoms to displacement is known as strain. There is a lack of a standardised unit of measurement. Tension is a vector quantity that has both magnitude and direction, whereas strain is a scalar quantity that simply has magnitude. Hooke's Law states that the stress in a body will increase in direct proportion to the strain, as long as specified limits are not exceeded. [123,125,126]

The strain (ε) is defined as the ratio of the deformation (ΔL) to the original length ($L0$) of an object.
There are two distinct ways in which bodies undergo changes in shape when force is applied. [122]

Elastic deformation refers to the object's ability to revert back to its original state once the force acting upon it is no longer there.

Plastic deformation refers to the phenomenon when an object does not revert to its original state after the applied force is eliminated.

2.3.1.6. Modulus of Elasticity (Young Modulus)

The Modulus of Elasticity, often known as Young's Modulus, is a measure of a material's stiffness. The modulus of elasticity, defined as the stress-to-strain ratio, is a coefficient that quantifies the resilience of an item within its elastic limits. As the modulus of elasticity increases, the object's stiffness also increases proportionally. According to Şeker[127], a body with a high modulus of elasticity experiences less deformation compared to a body with a low modulus of elasticity when subjected to the same force. [127]

The modulus of elasticity (E) is equal to the stress (σ) divided by the strain (ε).

2.3.1.7. Poisson's Ratio

The term "Poisson's ratio" refers to the ratio of the change in width to the change in length of a body within its elastic limit when subjected to tensile or compressive pressures. Poisson's ratio, ranging from 0 to 0.5, is a characteristic attribute of a material, similar to the modulus of elasticity. For instance, when a tensile tension is exerted on an item, it causes the object to elongate in the direction of the force, while simultaneously causing a reduction in length in other dimensions perpendicular to the force. [125,127]

Poisson's Ratio (V) is defined as the ratio of lateral strain to axial strain. It can also be expressed as the ratio of unit elongation in width to unit elongation in length.

2.3.1.8. Proportional Limit

The proportional limit is defined as the highest stress at which the ratio of stress to strain remains constant without any alteration. When forces are applied to a material below its proportionate limit, the material does not experience permanent deformation. Instead, it recovers to its former shape once the force is no longer applied. [127]

The elastic limit refers to the maximum stress that a material can withstand without undergoing permanent deformation. The elastic limit refers to the greatest stress that a material can withstand without experiencing any irreversible deformation. [127]

2.3.1.8.1. Uniform Substance

These are homogeneous bodies, where the elastic characteristics remain constant at every place in the body. [128]

Linear elastic body refers to a material or object that exhibits linear behaviour when subjected to external forces, meaning its deformation is directly proportional to the applied force. The assumption is made that there is a straight proportionality between voltage and elongation, and this connection may be represented in a simple manner. This assumption holds true only within a specific threshold of stress. While this limit is suitable for bone, it is insufficient for soft tissue, leading to significant calculation errors beyond this threshold. [129,130]

2.3.1.9. The Concept of Isotropy and Anisotropy

Isotropy refers to the uniformity of elastic characteristics in all directions of a body. Isotropic bodies exhibit uniform elasticity in response to tensile, compressive, and shear loads exerted from all directions. Anisotropic bodies exhibit varying modulus of elasticity. [128,130,131]

2.3.1.10. Element

The finite element method involves partitioning the system's defining region into basic geometric entities known as elements. These elements are represented as unknown values at specific sites known as nodes. By integrating the components, including boundary conditions, a series of linear or nonlinear algebraic equations is derived, and solving these equations reveals the accurate behaviour of the system. Increasing the number of elements in the model leads to more accurate and lifelike outcomes. Elements are categorised based on their geometric shape (such as triangle, parallelepiped, quadrilateral), size (one-dimensional, two-dimensional, three-dimensional), and the number of nodes they have. [128,131]

2.3.1.11. Node

In the context of finite element analysis, the models are divided into a finite number of elements, which are then joined at specific positions known as nodes. The displacements in each element of the models are directly correlated with the displacements at the nodes. In the context of finite element analysis, it is necessary to establish fixed connections between these nodes at certain locations. [131]

2.3.1.12. Constructing a Mesh Framework

The network structure generates the coordinates of the nodes and elements. Network generation can be automated by programs or users have the option to manually generate a network. When designing a network structure, it is more efficient to place a greater number of elements per unit area in regions that exhibit or can be anticipated to have significant fluctuations within their boundaries. The crucial aspect is determining the most effective method to decompose the model into smaller components. Following the completion of the mesh generation procedure, the boundary conditions are established to indicate the locations where the body is immobilised and where the force is exerted. The approach can be replicated by augmenting the number of components, altering the sort of elements, modifying the method of mesh formation, and reconfiguring the mesh. [123,132]

2.3.1.13. Boundary Conditions

Boundary conditions encompass the manifestations of stresses and displacements at the boundaries. It indicates the location of the body's fixation point and the point at which the force is exerted. The boundary conditions are established based on the specific location of the analysed body where the force would be exerted. [123,132]

3. MATERIAL AND METHOD

3.1. Sample

In our study, cone beam volumetric computerized tomography data of a 19-year-old female, obtained from the archives of Yeditepe University Dental Faculty Department of Orthodontics, was used (Figure 3.1). Inclusion criteria were as follows; adult patient with midpalatal suture fusion, no missing maxillary teeth or periodontal problems, minimal dental crowding, no transversal discrepancy. This study was approved by Yeditepe University Faculty of Medicine Non-Interventional Research Ethics Committee (Decision no: 2023120500, Date: 27/09/2018).

3.2. Method

This study was conducted in collaboration with Yeditepe University Faculty of Dentistry and Tinus Technologies.

Performing the organisation of the three-dimensional mesh structure and conversion of the mathematically appropriate solid mesh structure, as well as creating three-dimensional finite element analysis models and conducting finite element stress analysis, were tasks carried out on high-performance workstations equipped with INTEL Xeon E-2286 processors running at a clock speed of 2.40 GHz and 64 GB ECC memory.

The bone model was generated using the 3DSlicer software as shown in Figure 3.2.

The STL model was acquired from tomography data in 3DSlicer software. Activities involving reverse engineering and three-dimensional CAD were carried out using ANSYS SpaceClaim software (SpaceClaim Corporation, Concord, Massachusetts, 2007). Solid models were created to be compatible with the analysis environment, and meshing activities were optimised using ANSYS Workbench software(SpaceClaim Corporation, Concord, Massachusetts, 2007). The LS-DYNA solver was utilised to discrete the finite element models.

Figure 3.1. CBCT

3.3. Modelling of Bone, Teeth and Periodontal Ligaments

For the creation of the maxillary bone and tooth model, the CBCT data used was taken with iCAT. The tomography data was reconstructed with a section thickness of 0.1 mm. The tomography data obtained as a result of reconstruction were transferred to 3DSlicer software in DICOM (.dcm) format. The CT data in DICOM format were segmented according to the appropriate Hounsfield values in 3DSlicer software and converted into three-dimensional models by the segmentation process. The models were exported in .stl format.

The three-dimensional model was transferred to ANSYS SpaceClaim software where the maxillary bone and teeth were modelled as shown in Figure 3.3.

The mucosa was designed with respect to the outer surface of the maxillary bone.

For the reference, the outer surface of the teeth was used, and a slight outward offset of 0.2 mm was applied to model the periodontal ligaments.

All prepared models were accurately positioned in the appropriate coordinates within the 3D space using ANSYS SpaceClaim software, completing the modelling process.

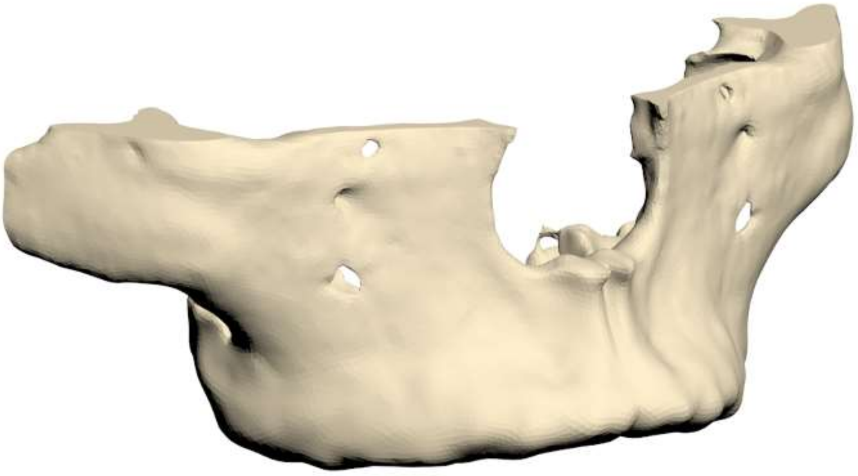


Figure 3.2. Bone Segmentation from CBCT

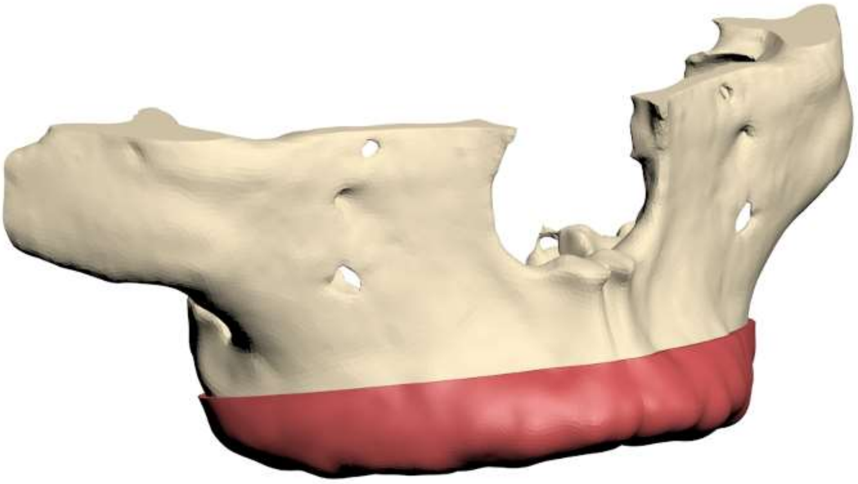


Figure 3.3. Model of Mucosa with Bone

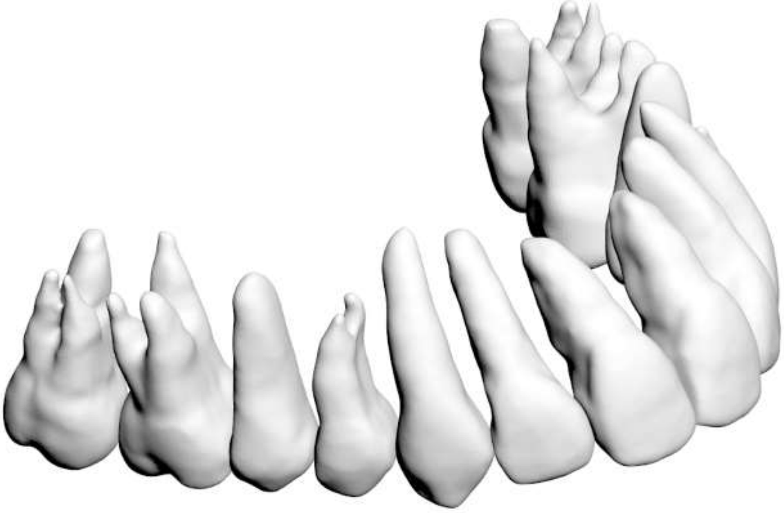


Figure 3.4. Teeth Segmentation from CBCT

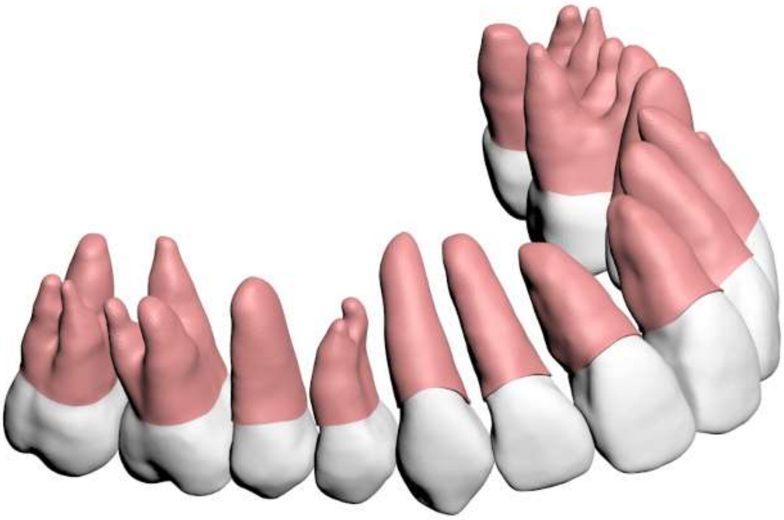


Figure 3.5. Model with Periodontal Ligaments

3.4. Generating Models and Performing Modelling of Attachments and Clear Aligners

3.4.1. First Phase

Two main models were created in the initial stage of the study: Model 1.1 served as a control group without any attachment and Model 1.2 with gingival bevelled horizontal attachments (GBHA) on molars and premolars.

The GBHA was modelled in ANSYS SpaceClaim software with dimensions of 4 mm in length, 2 mm in width, and 1 mm in thickness with 60 degrees of gingival bevel.[19] The ANSYS Spaceclaim software was used to model clear aligners that are 0.76 mm thick. The aligners were modelled without any attachments initially, and for the second group, the attachments were placed.

Table 1. Definition table of Model 1.1 and 1.2 at Phase 1.

PHASE 1							
	Central Incisors	**Lateral Incisors**	**Canines**	**First Premolars**	**Second Premolars**	**First Molars**	**Second Molars**
Model 1.1	No Attachment	No Attachment	No Attachment	No Attachment	No Attachment	No Attachment	No Attachment
Model 1.2	No Attachment	No Attachment	No Attachment	GBHA	GBHA	GBHA	GBHA

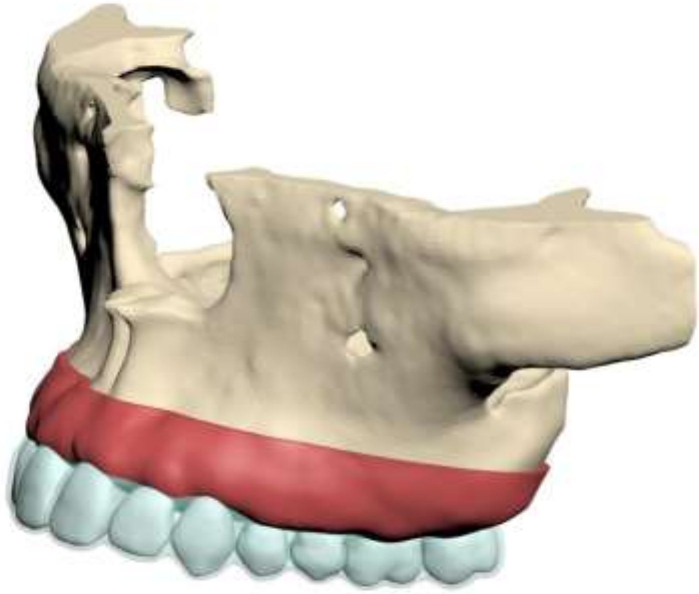


Figure 3.6: Low Trim Line Clear Aligner Border

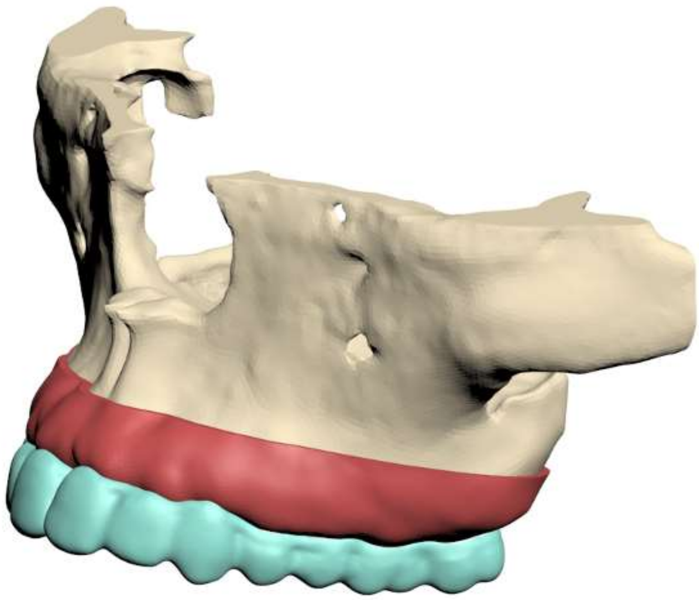


Figure 3.7. Phase 1 Model 1: Bone with Mucosa, Teeth and Low Trimmed Line Clear Aligner

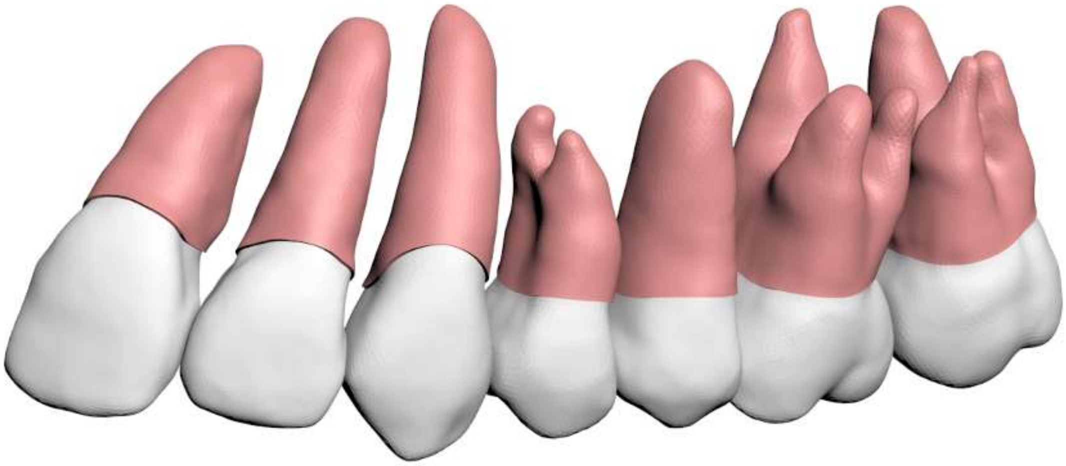


Figure 3.8. Phase 1 Model 1.1: Segmented teeth from CBCT with Periodontal Ligaments

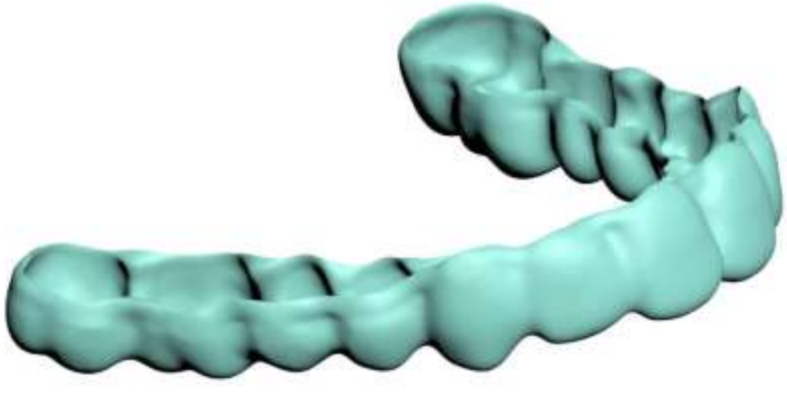


Figure 3.9: Clear Aligner without Attachment

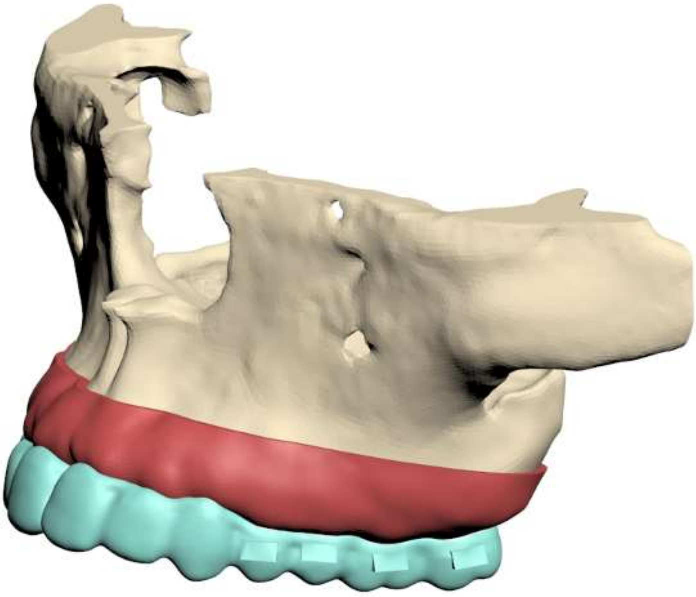


Figure 3.10. Phase 1 Model 1.2: Bone with Mucosa, Gingival Bevelled Horizontal Attachments and Low Trim Line Clear Aligner

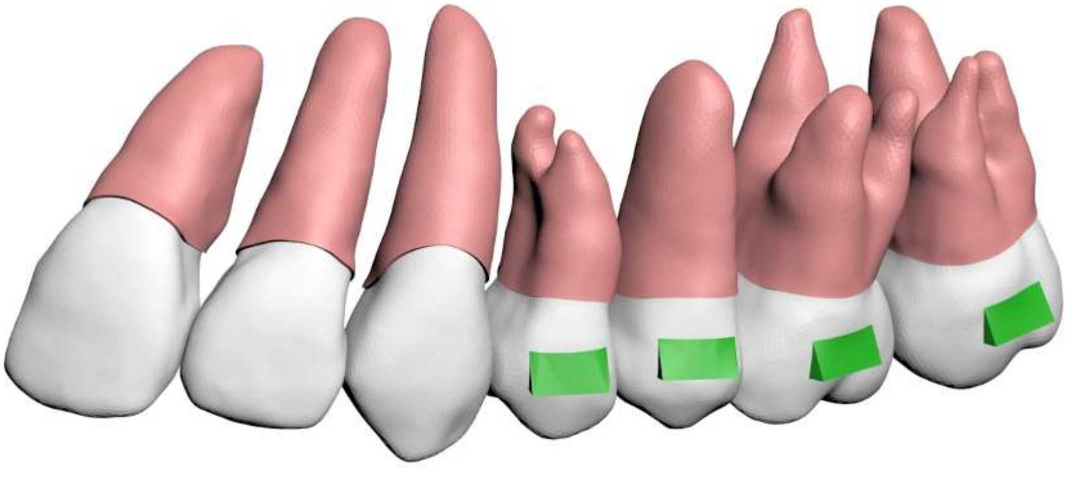


Figure 3.11. Phase 1 Model 2: Segmented teeth from CBCT with Periodontal Ligaments, Horizontal Gingival Bevelled Attachments on Molars and Premolars

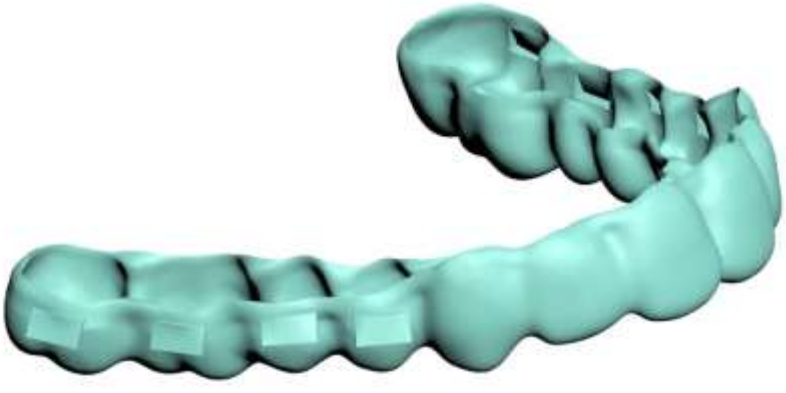


Figure 3.12. Low Trim Line Clear Aligner with Gingival Bevelled Horizontal Attachments on Molars and Premolars

3.4.2. Second Phase

Continuing from the first phase, the study progressed to the second phase with the most successful model in terms of posterior torque control during expansion, which was Model 1.2.

At this point, three models were developed.

The clear aligners, with a thickness of 0.76 mm, were created using ANSYS SpaceClaim software with low trim line (0 mm).

Model 2.1 included the power ridge in the central incisor region of the clear aligner, on both buccal, at the gingival third, and the palatal side, at the incisal third,

In Model 2.2, the horizontal attachment (HA) was positioned on the central incisors, measuring 4 mm in length, 2 mm in width, and 1 mm in thickness.

In Model 2.3, the horizontal attachment was positioned on the central incisors, measuring 4 mm in length, 2 mm in width, and 1 mm in thickness, and 60-degree of gingival bevel.

Table 2. Definition table of models in Phase 2

PHASE 2							
	Central Incisors	**Lateral Incisors**	**Canines**	**First Premolars**	**Second Premolars**	**First Molars**	**Second Molars**
Model 2.1	Power Ridge	No Attachment	No Attachment	GBHA	GBHA	GBHA	GBHA
Model 2.2	HA	No Attachment	No Attachment	GBHA	GBHA	GBHA	GBHA
Model 2.3	GBHA	No Attachment	No Attachment	GBHA	GBHA	GBHA	GBHA

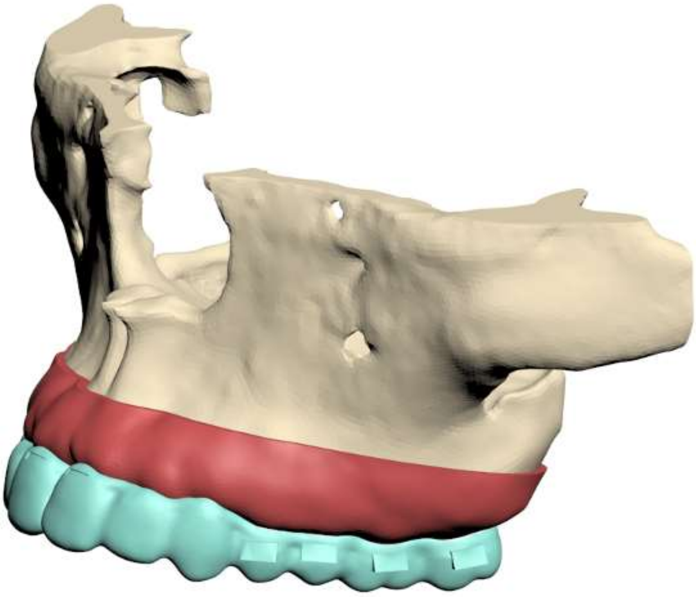


Figure 3.13. Phase 2 Model 1: Bone with Gingiva, Gingival Bevelled Horizontal Attachments on Molars and Premolars, Power Ridges on Vestibular side at Gingival ⅓ with Low Trim Line Clear Aligner

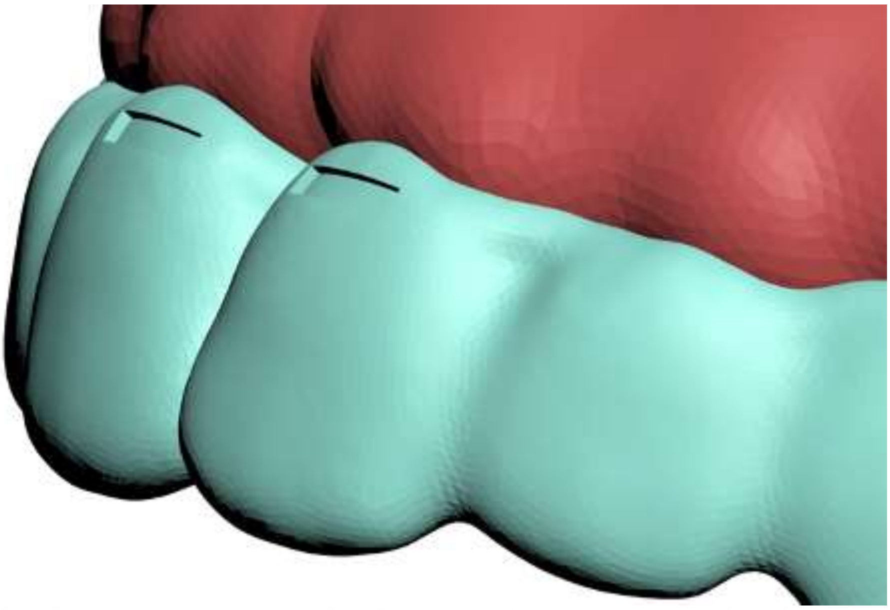


Figure 3.14. Phase 2 Model 1: Low Trim Line Clear Aligner with Power Ridges on Vestibular side at Gingival ⅓

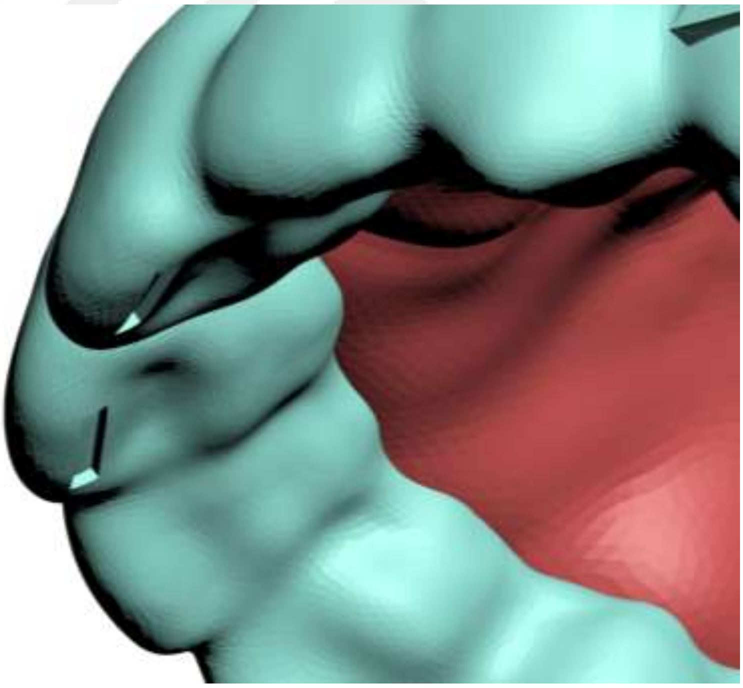


Figure 3.15. Phase 2 Model 1: Low Trim Line Clear Aligner with Power Ridges on Palatal side at Incisal ⅓

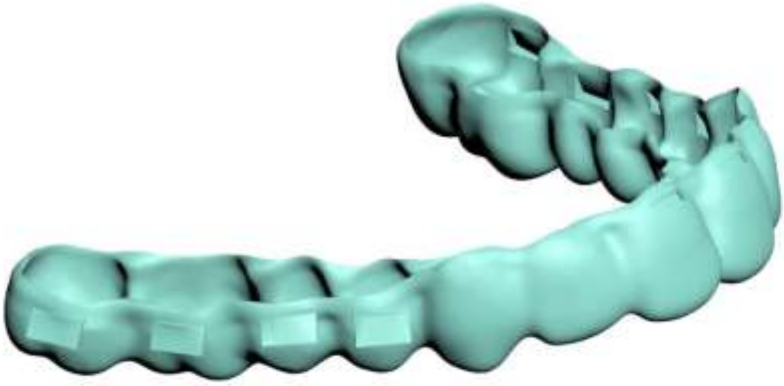


Figure 3.16. Low Trim Line Clear Aligner with Gingival Bevelled Horizontal Attachments on Molars and Premolars, Power Ridges on Incisors

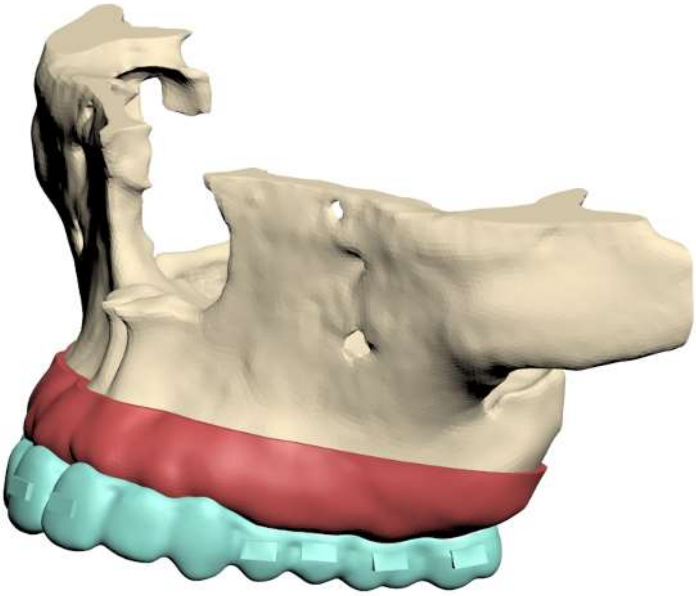


Figure 3.17. Phase 2 Model 2: Bone with Gingiva, Gingival Bevelled Horizontal Attachments on Molars and Premolars, Horizontal Attachments on Incisors Middle ⅓ with Low Trim Line Clear Aligners

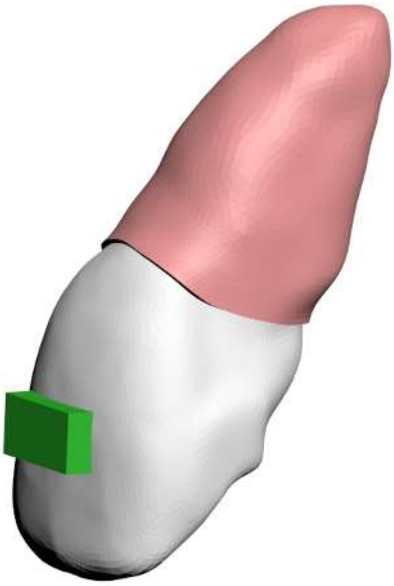


Figure 3.18. Phase 2 Model 2: Segmented Teeth from CBCT with Periodontal Ligaments, Horizontal Attachment on Middle ⅓

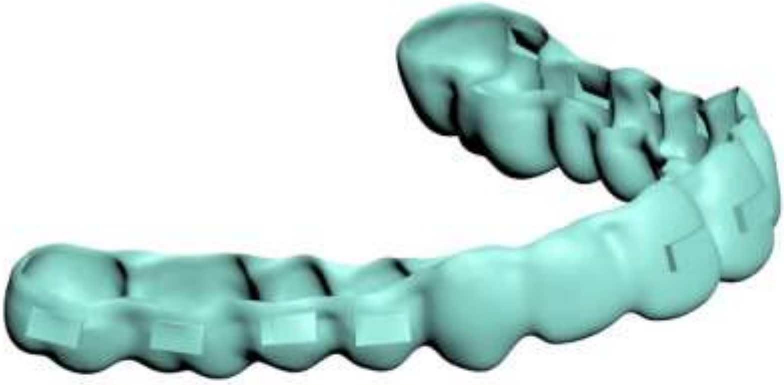


Figure 3.19. Low Trim Line Clear Aligners with Gingival Bevelled Horizontal Attachments on Molars and Premolars, Horizontal Attachments on Incisors

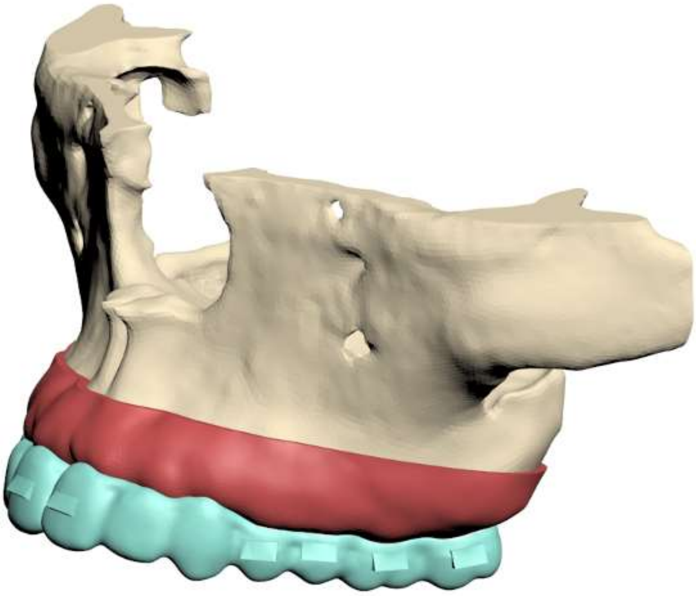


Figure 3.20. Phase 2 Model 3: Bone with Gingiva, Gingival Bevelled Horizontal Attachments on Molars, Premolars and Incisors Middle ⅓, Low Trimmed Line Clear Aligner

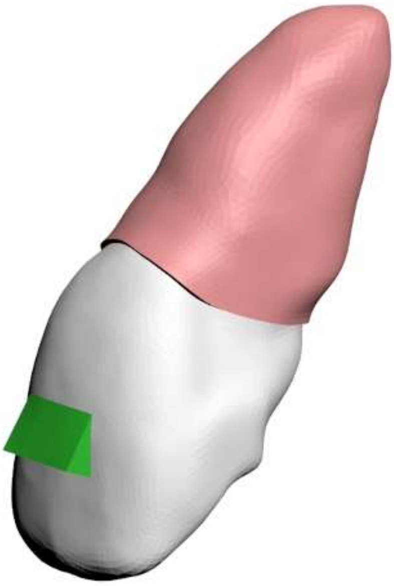


Figure 3.21. Phase 2 Model 3: Segmented Teeth from CBCT with Periodontal Ligament, Gingival Bevelled Horizontal Attachment on Middle ⅓

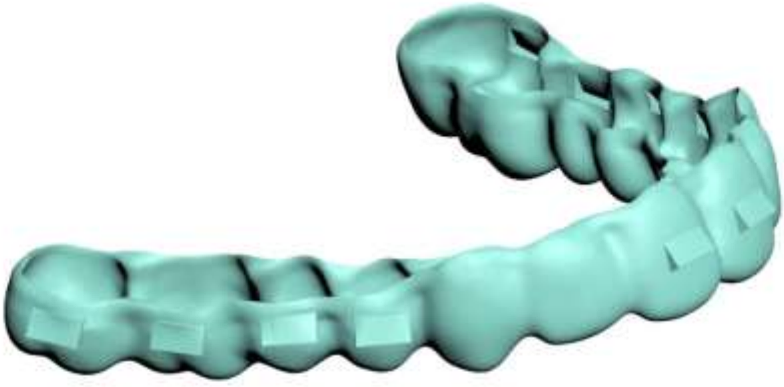


Figure 3.22. Low Trimmed Line Clear Aligner, Gingival Bevelled Horizontal Attachments on Molars, Premolars and Incisors Middle ⅓

3.5. Steps of Obtaining Mathematical Models

Mathematical models were formed by dividing geometric models into simple and small parts called mesh. After the modelling process was completed in ANSYS Spaceclaim software, the models were created mathematically with ANSYS Workbench software and made ready for analysis. The ANSYS Spaceclaim software can be used for creating geometric models. This software divided complex geometries into simple and small parts, creating a structure known as "mesh," which forms the basis for the subsequent mathematical expressions needed for analysis. Subsequently, using the ANSYS Workbench software, these geometric models were prepared to be mathematically ready for analysis. During this process, information about material properties, boundary conditions, and other parameters related to the system were changed into mathematical expressions.

Finally, the mathematical models are transferred to the LS-DYNA solver. LS-DYNA is commonly used for dynamic analysis and modelling complex physical behaviours. By transferring the mathematical model to the solver, it becomes ready for analysis. Throughout this process, it is important to carefully verify and validate the accuracy of the mathematical models. Additionally, accuracy and validation steps are crucial to ensuring that the analysis results align with real-world conditions. (Figure 3.23)

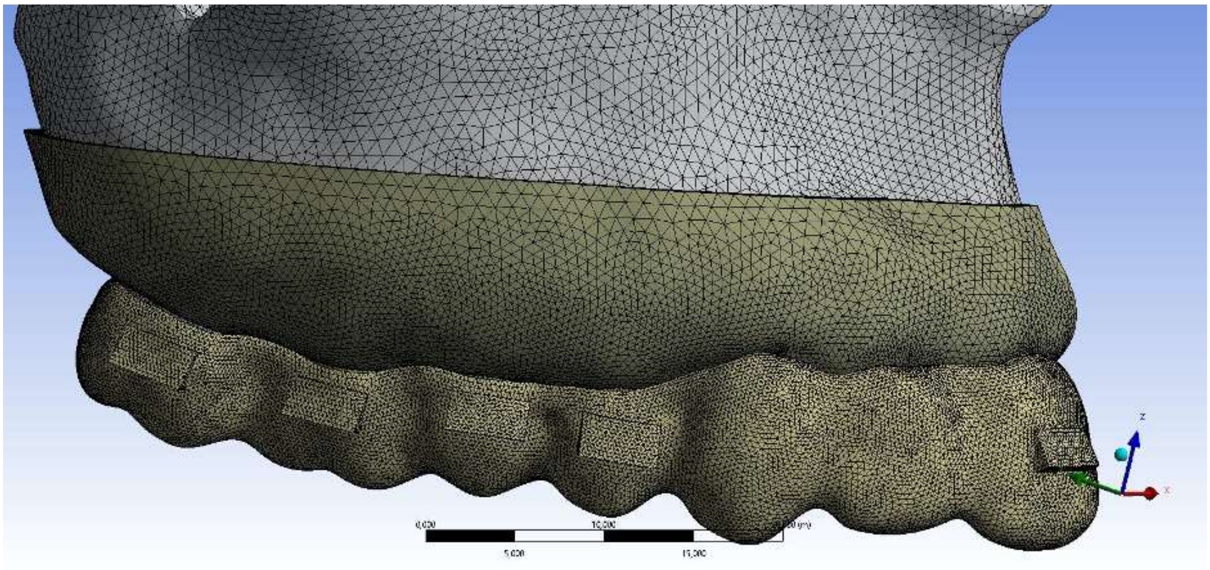
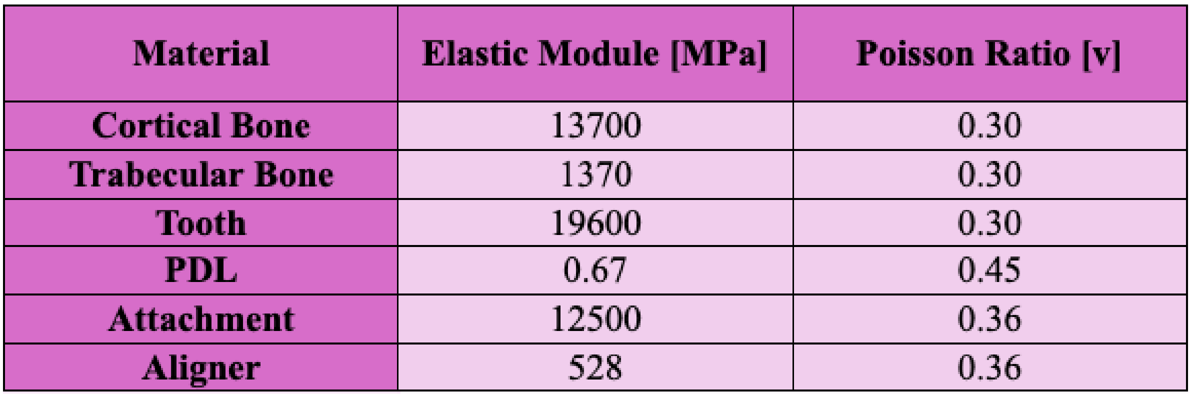


Figure 3.23. STL File of the Model

3.6. Material Definitions

Linear material properties of the materials given elastic modulus and Poisson's ratio were used in the analyses. The material properties of the analysed models were defined numerically in Table 3.

Table 3: Table of Materials, Elastic Modulus and Poisson Ratio



Material	Elastic Module [MPa]	Poisson Ratio [v]
Cortical Bone	13700	0.30
Trabecular Bone	1370	0.30
Tooth	19600	0.30
PDL	0.67	0.45
Attachment	12500	0.36
Aligner	528	0.36

3.7. Loading Scenarios and Boundary Conditions

3.7.1. Phase 1

A 0.2 mm expansion activation force was applied to the active surfaces of the clear aligner on the first premolars, second premolars, first molars, and second molars in all models. The effect of the force showed expansion movement in all the models.

In addition to the aligner activation force, a 1.5° buccal root torque has been added to the premolars and molars from the attachment points in all study models, and the models were analyzed.

3.7.2. Phase 2

In addition to the activation force applied in Phase 1 and the buccal root torque, a 0.2 mm activation force has been applied through the power ridges and attachments on the central incisor area of the clear aligner.

All independent variables have been limited from the nodal points located in the superior region of the bone in a manner that prevents movement along all three axes.

A boundary condition has been provided to all parts in the model, such that they are symmetric with respect to the Y-Z plane normal to the X-axis.

Under the specified forces and boundary conditions, a total of 5 nonlinear static analyses have been conducted for 5 models in both Phase 1 and Phase 2.

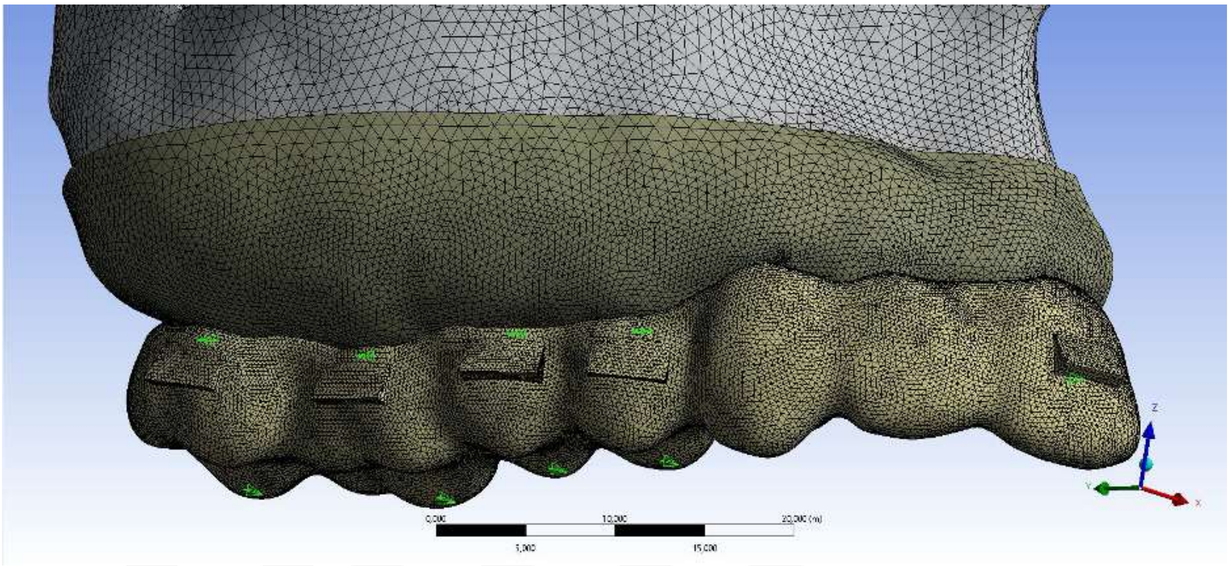


Figure 3.24. Activation Force Areas (Green)

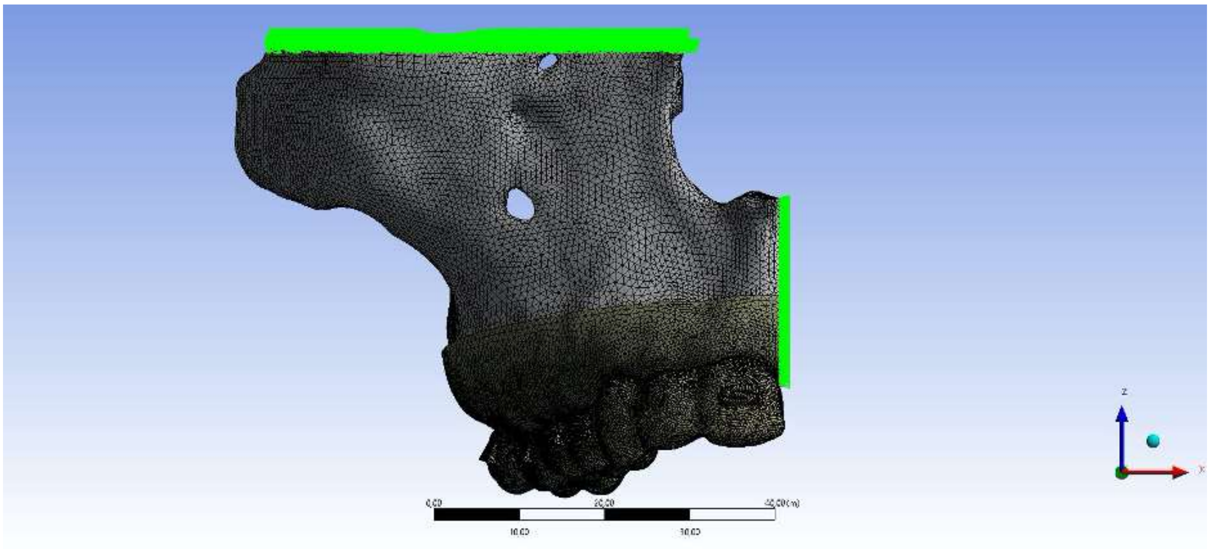
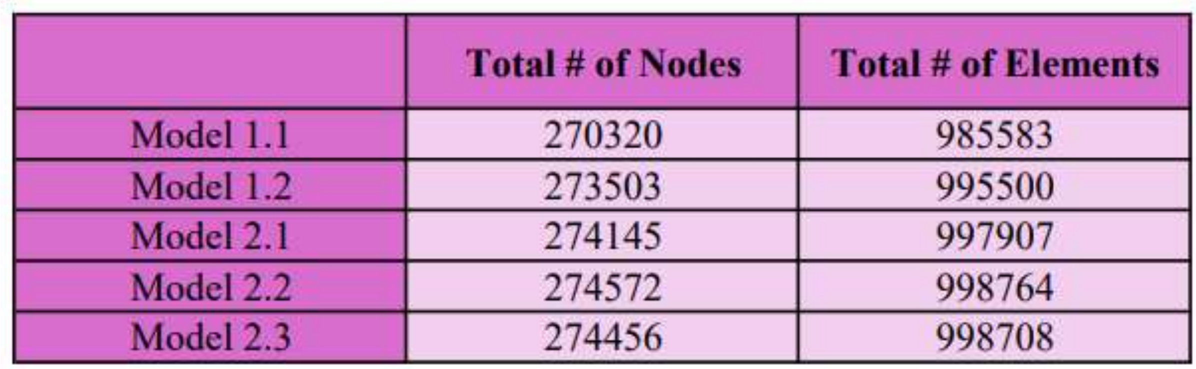


Figure 3.25. Border Conditions of the Model (Green)

3.8. Quantitative Model Information

Information for the 5 analysis models created is shared in Table 4.

Table 4: Quantitative Model Information



	Total # of Nodes	Total # of Elements
Model 1.1	270320	985583
Model 1.2	273503	995500
Model 2.1	274145	997907
Model 2.2	274572	998764
Model 2.3	274456	998708

3.9. Integration of Systems and Inter-Part Connections

For all models, nonlinear frictional contact with a coefficient of $\mu=0.2$ was defined at the interfaces between Aligner - Tooth and Aligner - Attachment surfaces.

A bonded-type contact definition was implemented for various contacting components. This technique is predicated on the basis that the components move in full correlation throughout their motion.

4. RESULTS

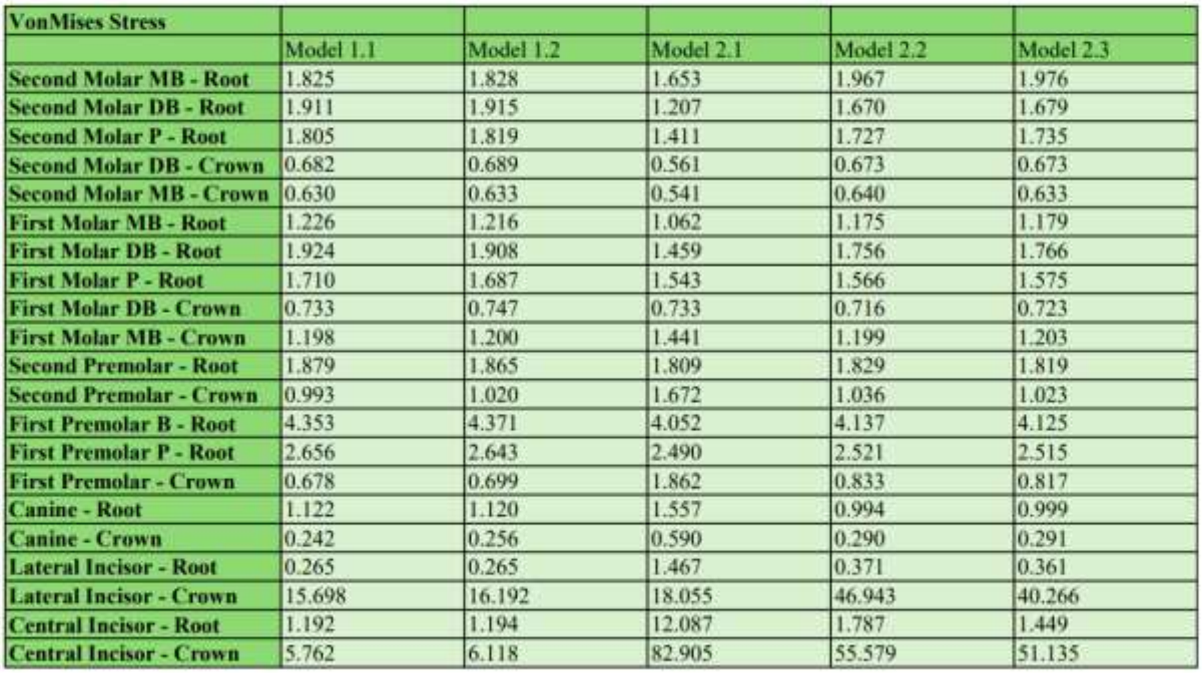
The first phase of our study examined the impact of posterior expansion on the incisors in clear aligner treatments. In the second phase, we tried to control any negative effects on the incisors by using attachments and power ridges during expansion. The cumulative displacement in 5 scenarios during phase 1 and phase 2, as well as the displacement in the transversal, sagittal, and vertical planes, and the Von Mises stresses, maximum principle (Pmax), and minimum principle (Pmin) stresses in the periodontal ligament were measured. The X-axis represents the buccolingual direction for posterior segment teeth, the Y-axis represents the buccolingual direction for the anterior segment, and the Z-axis represents the gingivoocclusal direction on the vertical axis. The values we compared in our study using the finite element method correspond to the measurements taken at the start of the study when the force is first applied to the tooth by the clear aligner.

Our study established a colour scale to indicate the areas where displacement, Von Mises stress, maximum principal stress, and minimum principal stress. The red areas in the figures represent locations of the highest Von Mises stress, whereas the dark blue portions represent regions of lowest Von Mises stress values. The red areas represented in the figures indicate regions where the maximum primary stress value (Pmax - maximum tensile stress - maximum tensile stress) is concentrated, indicating areas of high tensile stress. In the figures displaying the minimal primary stress (Pmin - the highest compressive stress - maximum compression -) value, the dark blue patches indicate the regions where the compressive stresses are concentrated. The figures also display the extent of movement in the transversal, sagittal, and vertical directions. The red areas represent the regions with the greatest amount of displacement along the associated axis, while the dark blue areas indicate the regions with the most displacement in the opposite direction to the examined direction. The study reports the values of Pmin, Pmax, and Von Mises in units of 'MPa', whereas the displacement quantities are expressed in 'mm'.

4.1. Von Mises Stress

In Table 5, the numerical values of the tooth-specific and region-specific regional variations in Von Mises Stress for all teeth were given.

Table 5: Von Mises Stress Table for All Phases and Models



VonMises Stress					
	Model 1.1	Model 1.2	Model 2.1	Model 2.2	Model 2.3
Second Molar MB - Root	1.825	1.828	1.653	1.967	1.976
Second Molar DB - Root	1.911	1.915	1.207	1.670	1.679
Second Molar P - Root	1.805	1.819	1.411	1.727	1.735
Second Molar DB - Crown	0.682	0.689	0.561	0.673	0.673
Second Molar MB - Crown	0.630	0.633	0.541	0.640	0.633
First Molar MB - Root	1.226	1.216	1.062	1.175	1.179
First Molar DB - Root	1.924	1.908	1.459	1.756	1.766
First Molar P - Root	1.710	1.687	1.543	1.566	1.575
First Molar DB - Crown	0.733	0.747	0.733	0.716	0.723
First Molar MB - Crown	1.198	1.200	1.441	1.199	1.203
Second Premolar - Root	1.879	1.865	1.809	1.829	1.819
Second Premolar - Crown	0.993	1.020	1.672	1.036	1.023
First Premolar B - Root	4.353	4.371	4.052	4.137	4.125
First Premolar P - Root	2.656	2.643	2.490	2.521	2.515
First Premolar - Crown	0.678	0.699	1.862	0.833	0.817
Canine - Root	1.122	1.120	1.557	0.994	0.999
Canine - Crown	0.242	0.256	0.590	0.290	0.291
Lateral Incisor - Root	0.265	0.265	1.467	0.371	0.361
Lateral Incisor - Crown	15.698	16.192	18.055	46.943	40.266
Central Incisor - Root	1.192	1.194	12.087	1.787	1.449
Central Incisor - Crown	5.762	6.118	82.905	55.579	51.135

4.1.1. Phase 1 Model 1

Figure 4.1 represents Model 1.1. Maximum Von Mises Stress value was detected on the incisal edge of the lateral incisor (15.698 MPa), then on the central incisor (5762 MPa). In the posterior area, it was observed that cervical ⅓ of the roots of premolars showed a significant stress accumulation.

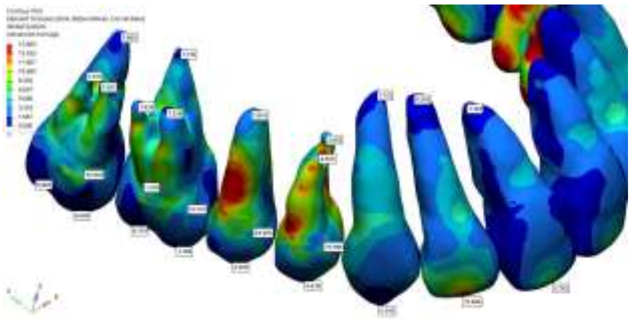


Figure 4.1. Von Mises Stress Distribution of Model 1.1

Figure 4.2. represents Von Mises stress distribution on PDL of Model 1.1. The maximum Von Mises Stress occurring on PDL was on the first premolar(2.461 MPa), and the minimum value was on the lateral incisor(0.923 MPa). The maximum Von Mises Stress on the PDL was observed on the first premolar (2.556 MPa), followed by the second premolar and molars.

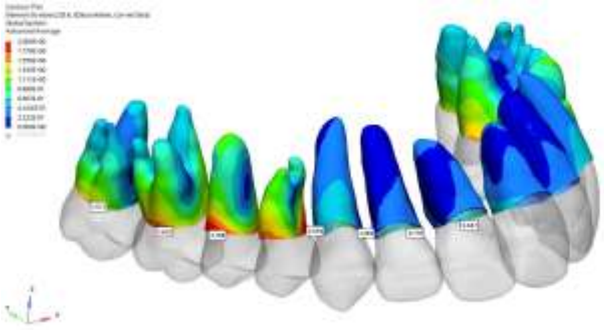


Figure 4.2. Von Mises Stress Distribution Colour Map PDL Model 1.1

4.1.2. Phase 1 Model 2

Figure 4.3. represents Model 1.2. The maximum Von Mises Stress value was detected on the incisal edge of the lateral incisor (16.192 MPa), then on the central incisor (6.118

MPa). The minimum stress was on the canine (0.256 MPa). In the posterior area, it was observed that the cervical ⅓ of the roots of premolars showed a significant stress accumulation in this model. The Von Mises Stresses were slightly higher in the Model 1.2 compared to the Model 1.1.

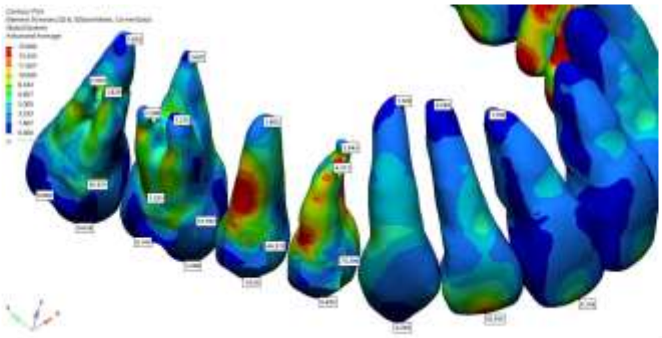


Figure 4.3. Von Mises Stress Distribution of Model 1.2

Figure 4.4. represents Von Mises stress distribution on PDL of Model 1.2. The maximum Von Mises Stress occurring on PDL was on the first premolar(2.461 MPa), and the minimum value was on the lateral incisor(0.923 MPa). The maximum Von Mises Stress value on PDL was observed on the first premolar (2.541 MPa). In comparison between Model 1.1 and Model 1.2, Model 1.1 showed more Von Mises Stress accumulation on posterior teeth.

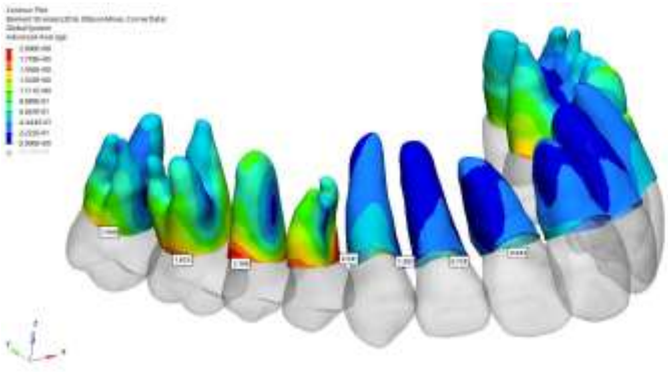


Figure 4.4. Von Mises Stress Distribution Colour Map PDL Model 1.2

4.1.3. Phase 2 Model 1

Figure 4.5. represents Von Mises Stress of Model 2.1 (Power ridges on Central Incisor). The maximum Von Mises Stress value was on the incisal and the cervical area of the central incisor (82.905 MPa). The placement of power ridges on incisal ⅓ on the palatal surface of the central incisor and gingival ⅓ buccal surface increased the stress level on the central incisor. The minimum Von Mises Stress value was on the second molar (0.541 MPa).

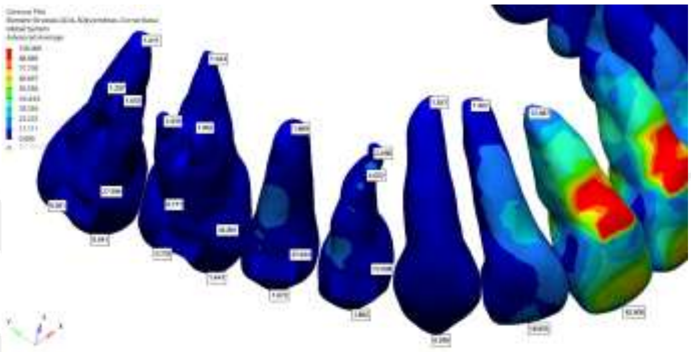


Figure 4.5. Von Mises Stress Distribution of Model 2.1

Figure 4.6. represents Von Mises stress distribution on PDL of Model 2.1.The maximum Von Mises Stress value observed on PDL was on the central incisor (7.379 MPa), and the minimum Von Mises Stress was on the canine (0.945 MPa).

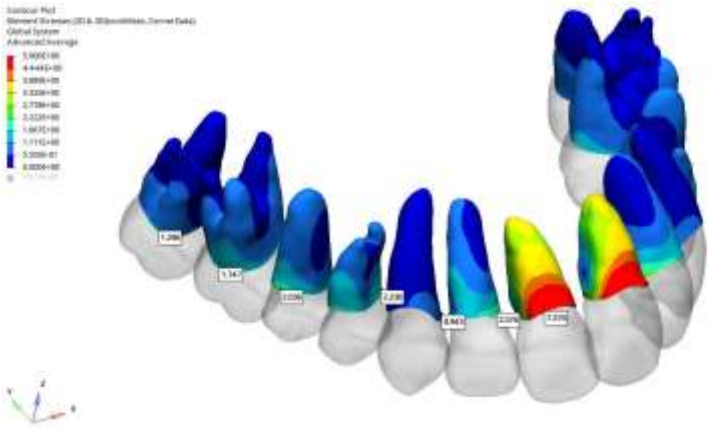


Figure 4.6. Von Mises Stress Distribution Colour Map PDL Phase 2 Model 1

4.1.4. Phase 2 Model 2

Figure 4.7 represents Model 2.2 (HA on Central Incisor), in which the central incisors have horizontal attachments on the buccal surface. The maximum Von Mises Stress value was on the incisal edge of central incisors (55.579 MPa) then on the lateral incisor (46.943 MPa) and the minimum value was on the canine (0.290 MPa). Central incisor showed a lower stress value than Model 2.1.

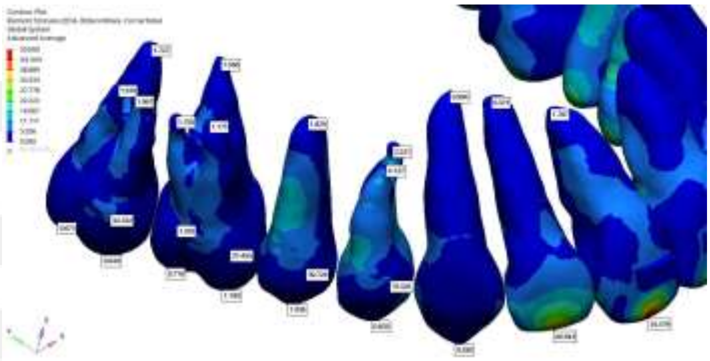


Figure 4.7. Von Mises Stress Distribution of Model 2.2

Figure 4.8. represents Von Mises stress distribution on PDL of Model 2.2. The maximum Von Mises Stress occurring on PDL was on the first premolar (2.461 MPa), and the minimum value was on the lateral incisor (0.923 MPa). Model 2.2 The maximum Von Mises Stress value on PDL was on the first premolar (2.455 MPa), the minimum value was (0.927 MPa) on the lateral incisor (0.927 MPa).

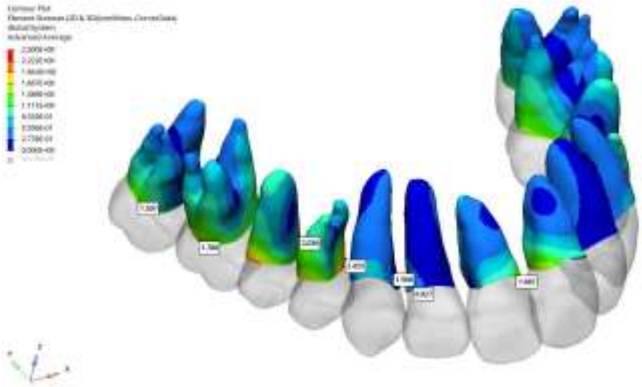


Figure 4.8. Von Mises Stress Distribution Colour Map PDL Phase 2 Model 2

4.1.5. Phase 2 Model 3

Figure 4.9 represents Model 2.3 (GBHA on Central Incisor). The maximum Von Mises Stress value was on the central incisor (51.135 MPa) followed by the lateral incisor (40.266 MPa). Central incisor showed a lower stress value than Model 2.1 and Model 2.2.

Figure 4.9. Von Mises Stress Distribution of Model 2.3

Figure 4.10. represents Von Mises Stress distribution on PDL of Model 2.3. The maximum Von Mises Stress occurring on PDL was on the first premolar (2.461 MPa), and the minimum value was on the lateral incisor (0.923 MPa).

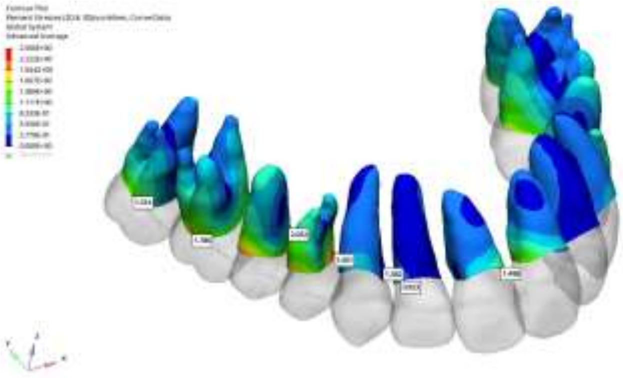


Figure 4.10. Von Mises Stress Distribution Colour Map PDL Phase 2 Model 3

4.1.6. Comparison of Von Mises Stress In All Models

In Figure 4.11 and Table 5, comparing Model 1.1 and Model 1.2 the buccal surface of the roots of premolars showed increased Von Mises Stress values. In the incisors region, the significant differences were observed in the crowns of the central and lateral incisors on incisal edges.

In the first molars, Von Mises Stresses were higher on the apex of the root in the attachment-free model (Model 1.1) compared to Model 1.2, while on the crown, Von Mises stresses of the Model 1.2 were higher.

In the second premolars, Von Mises Stresses were higher on the apex of the root in the attachment-free model (Model 1.1) compared to Model 1.2, while on the crown, Von Mises stresses of the Model 1.2 were higher.

In the first premolars, Von Mises stresses of the Model 1.2 were higher than Model 1.1 on the crown and the apex.

While the stress on the root and the values of the lateral incisor are the same in Model 1.1 and Model 1.2, there is a significant difference in the crown, with higher stress in Model 1.2 (the attachment model).

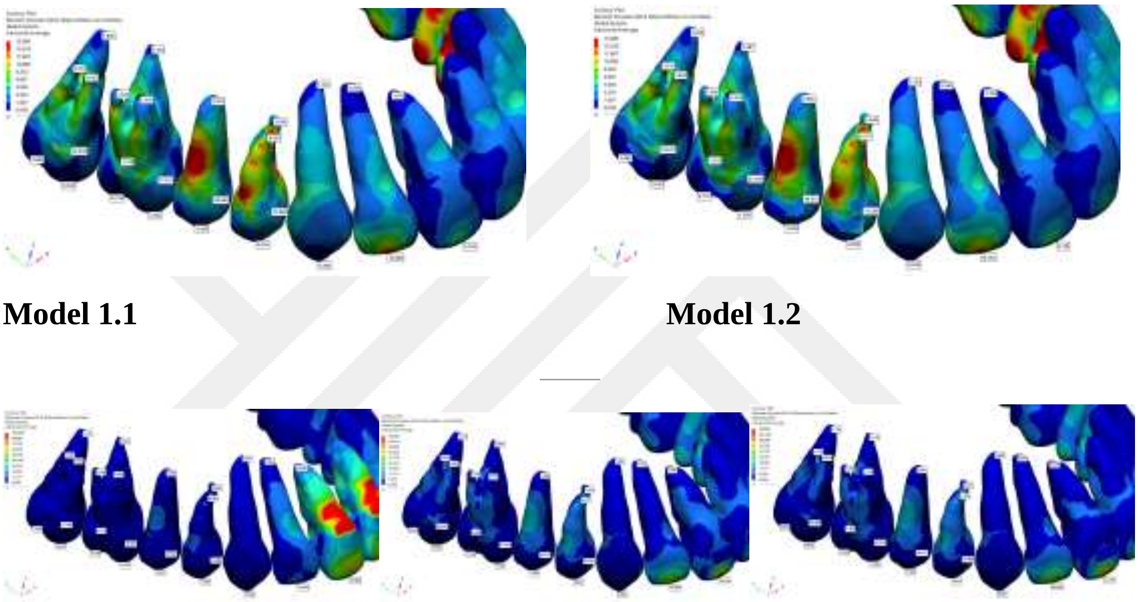
In the central incisor, the stress shown on the crown and the apex was higher in the Model 1.2.

The results of Phase 2 are as follows:
For the first molars, Von Mises Stresses in Model 2.1 showed the highest stress value on the crown, while Model 2.2 has the lowest value. Comparing the Von Mises Stresses of apex of the roots, Model 2.3 has the highest value, Model 2.1 has the lowest value.

For the first premolar roots, Model 2.2 has the highest stress value, Model 2.1 has the lowest value. For the crown, Model 2.1 has the highest stress value, while Model 2.2 has the lowest.

For the lateral incisors, Model 2.1 showed the highest Von Mises Stress value on the apex, while Model 2.1 showed the lowest stress in the crown in all the models. Model 2.3 has the lowest stress on the root, while Model 2.1 has the highest in the crown.

For the central incisors, both in the crown and root, Model 2.1 had the highest stress value, while Model 2.3 had the lowest. For the PDL, Model 2.1 showed the highest stress value and Model 2.3 showed the lowest value.



Model 1.1 **Model 1.2**

Model 2.1 **Model 2.2** **Model 2.3**

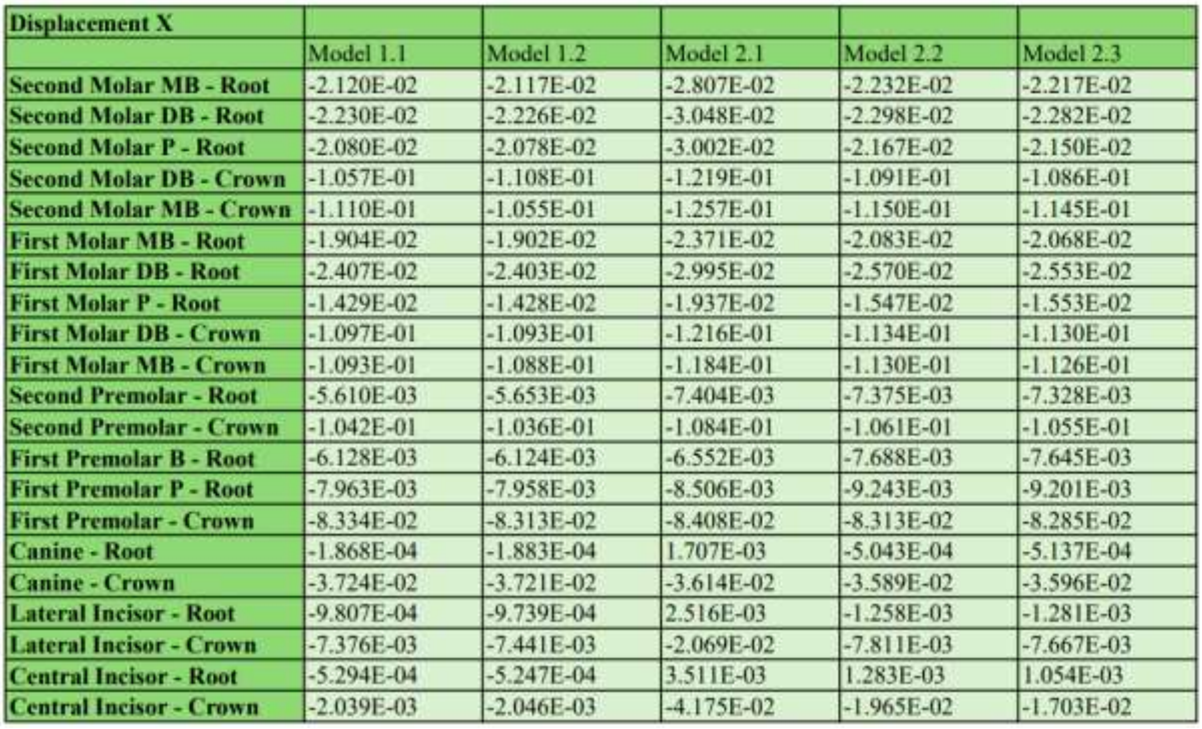
Figure 4.11. Comparative Von Mises Stress distribution in all Models

4.2. Displacement X

Based on the data in Table 6, the total values of crown and root were taken and the difference between them was obtained, and the displacement values according to the X plane were calculated. According to these values coming from Table 6, a separate table of values in the X plane was also created as Table 7.

X plane provided the expansion values on posterior. For this reason, only posterior teeth were analysed in numbers.

Table 6. Displacement X Table for All Phases and Models



Displacement X					
	Model 1.1	Model 1.2	Model 2.1	Model 2.2	Model 2:3
Second Molar MB - Root	-2.120E-02	-2.117E-02	-2.807E-02	-2.232E-02	-2.217E-02
Second Molar DB - Root	-2.230E-02	-2.226E-02	-3.048E-02	-2.298E-02	-2.282E-02
Second Molar P - Root	-2.080E-02	-2.078E-02	-3.002E-02	-2.167E-02	-2.150E-02
Second Molar DB - Crown	-1.057E-01	-1.108E-01	-1.219E-01	-1.091E-01	-1.086E-01
Second Molar MB - Crown	-1.110E-01	-1.055E-01	-1.257E-01	-1.150E-01	-1.145E-01
First Molar MB - Root	-1.904E-02	-1.902E-02	-2.371E-02	-2.083E-02	-2.068E-02
First Molar DB - Root	-2.407E-02	-2.403E-02	-2.995E-02	-2.570E-02	-2.553E-02
First Molar P - Root	-1.429E-02	-1.428E-02	-1.937E-02	-1.547E-02	-1.553E-02
First Molar DB - Crown	-1.097E-01	-1.093E-01	-1.216E-01	-1.134E-01	-1.130E-01
First Molar MB - Crown	-1.093E-01	-1.088E-01	-1.184E-01	-1.130E-01	-1.126E-01
Second Premolar - Root	-5.610E-03	-5.653E-03	-7.404E-03	-7.375E-03	-7.328E-03
Second Premolar - Crown	-1.042E-01	-1.036E-01	-1.084E-01	-1.061E-01	-1.055E-01
First Premolar B - Root	-6.128E-03	-6.124E-03	-6.552E-03	-7.688E-03	-7.645E-03
First Premolar P - Root	-7.963E-03	-7.958E-03	-8.506E-03	-9.243E-03	-9.201E-03
First Premolar - Crown	-8.334E-02	-8.313E-02	-8.408E-02	-8.313E-02	-8.285E-02
Canine - Root	-1.868E-04	-1.883E-04	1.707E-03	-5.043E-04	-5.137E-04
Canine - Crown	-3.724E-02	-3.721E-02	-3.614E-02	-3.589E-02	-3.596E-02
Lateral Incisor - Root	-9.807E-04	-9.739E-04	2.516E-03	-1.258E-03	-1.281E-03
Lateral Incisor - Crown	-7.376E-03	-7.441E-03	-2.069E-02	-7.811E-03	-7.667E-03
Central Incisor - Root	-5.294E-04	-5.247E-04	3.511E-03	1.283E-03	1.054E-03
Central Incisor - Crown	-2.039E-03	-2.046E-03	-4.175E-02	-1.965E-02	-1.703E-02

The values in Table 7 reflected the individual tipping values in the teeth, depending on the situation.

The expansion assessment in the X plane was explained only for the second molar, first molar, first premolar, and second premolar located posteriorly.

Table 7. The Difference Between Crown and Root Displacement on Posterior Region

Displacement X					
	Model 1.1	Model 1.2	Model 2.1	Model 2.2	Model 2.3
Second Molar	0,17320	0,17287	0,18905	0,17880	0,17811
First Molar	0,175890	0,175050	0,186340	0,179870	0,179390
Second Premolar	0,098590	0,097947	0,100996	0,098725	0,098172
First Premolar	0,0772120	0,0770060	0,0775280	0,0754420	0,0752050

4.2.1. Phase 1 Model 1

Table 7 showed buccal movement of premolars and molars. Figure 4.12. represented Model 1.1, The expansion movement occurred on each tooth were in order: first molar (0.175890 mm), the second molar (0.17320 mm), the second premolar has a value of (0.098590 mm), and the first premolar has a value of (0.0772120 mm). Buccal tipping on the posterior area and palatal tipping of incisors were shown in Figure 4.12.

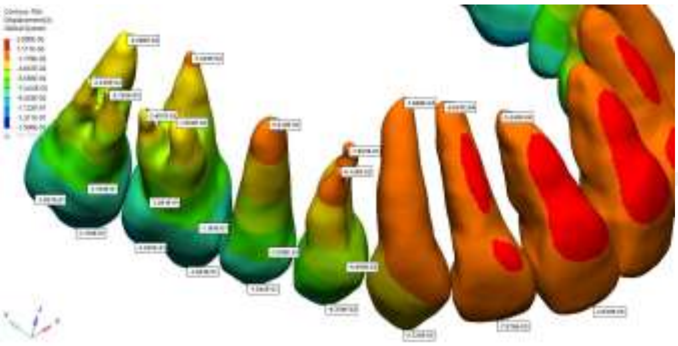


Figure 4.12 Displacement on X plane of Model 1.1

4.2.2. Phase 1 Model 2

Table 7 showed buccal movement of premolars and molars. Figure 4.13. represented Model 1.2, The expansion movement occurred on each tooth were in order: the first molar (0.175050 mm), the second molar (0.17287 mm), the second premolar (0.097947 mm) and the first premolar (0.0770060 mm). Buccal tipping on the posterior area and palatal tipping of incisors are shown. When comparing the results of Model 1.1 and Model 1.2, Model 1.2 showed more bodily movement than Model 1.1.

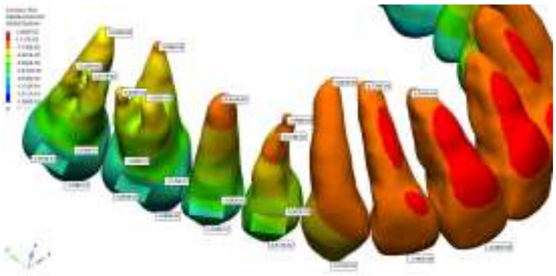


Figure 4.13. Displacement on X plane of Model 1.2

4.2.3. Phase 2 Model 1

Table 7. showed buccal movement of premolars and molars. Figure 4.14. represented Model 2.1(Power ridges on Central Incisor). The expansion movement occurred on each tooth were in order: the second molar(0.18905 mm), the first molar (0.186340 mm), the second premolar (0.100996 mm), and the first premolar (0.0775280 mm).

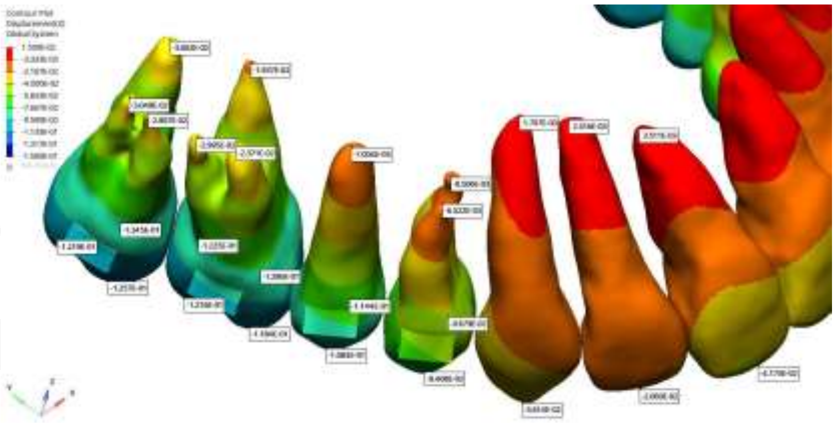


Figure 4.14. Displacement on X plane of Model 2.1

4.2.4. Phase 2 Model 2

Table 7. showed buccal movement of premolars and molars. Figure 4.15. represented Model 2.2.(HA on Central Incisor) The expansion movement occurred on each tooth were in order: the first molar (0.179870 mm),the second molar(0.17880 mm), the second premolar(0.098725 mm), and the first premolar (0.0754420 mm).

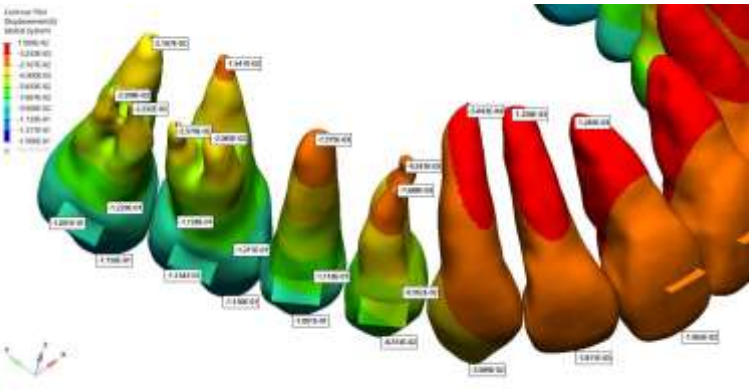


Figure 4.15. Displacement on X plane of Model 2.2

4.2.5. Phase 2 Model 3

Table 7. showed buccal movement of premolars and molars. Figure 4.16. represented Model 2.3.(GBHA on Central Incisor) The expansion movement occurred on each tooth were in order: the first molar(0.179390 mm) the second molar (0.17811 mm), the second premolar (0.098172 mm), and the first premolar (0.0752050 mm).

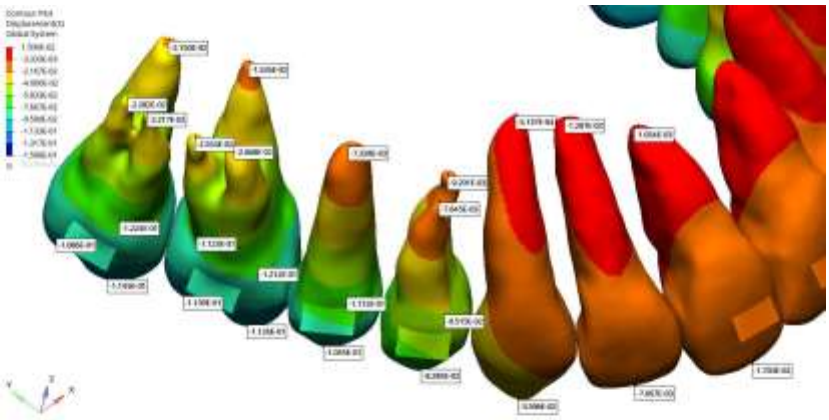


Figure 4.16. Displacement on X plane of Model 2.3

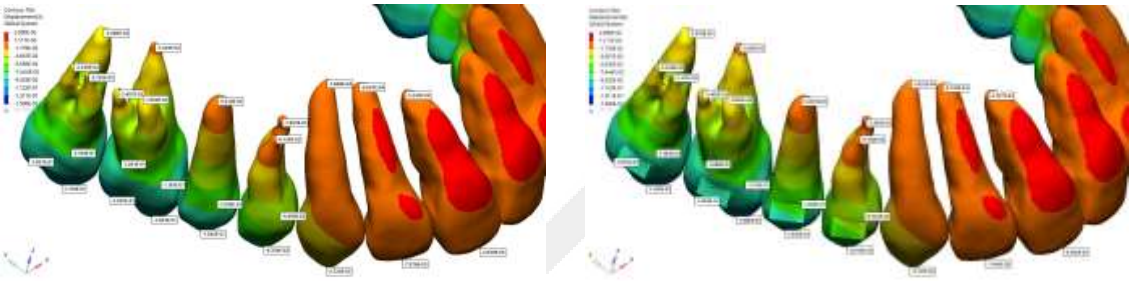
4.2.6. Results of Displacement X In All Models

In the X dimension, both Model 1.1 and Model 1.2 showed buccal tipping of the crowns and palatally tipping of the roots. When comparing Model 1.1 and Model 1.2, Model 1.2 showed more bodily movement than Model 1.1. The only difference between these two models was posterior gingival bevel attachment.

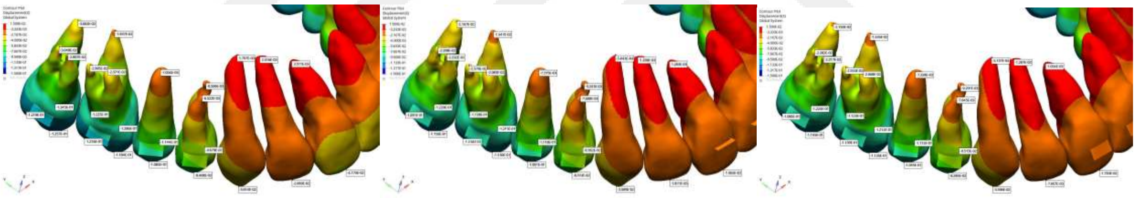
In phase 2, the evaluations were made on the X plane, both for the first and second molars: Model 2.1 has the highest value of buccal tipping, while Model 2.3 has the lowest for both crown and the roots.

For the second premolars, Model 2.1 showed the highest value of root tipping in the palatal direction, and Model 2.3 has the lowest. Additionally, in the crowns, the lowest value of tipping to buccal direction was observed in Model 2.3, while the highest was in Model 2.1.

For the first premolars, roots showed the highest value of tipping in Model 2.2, lowest value of tipping in Model 2.1 For the crowns, the highest value of the buccal tipping was in Model 2.1, while the lowest was in Model 2.3. (Figure 4.17)



Model 1.1 **Model 1.2**



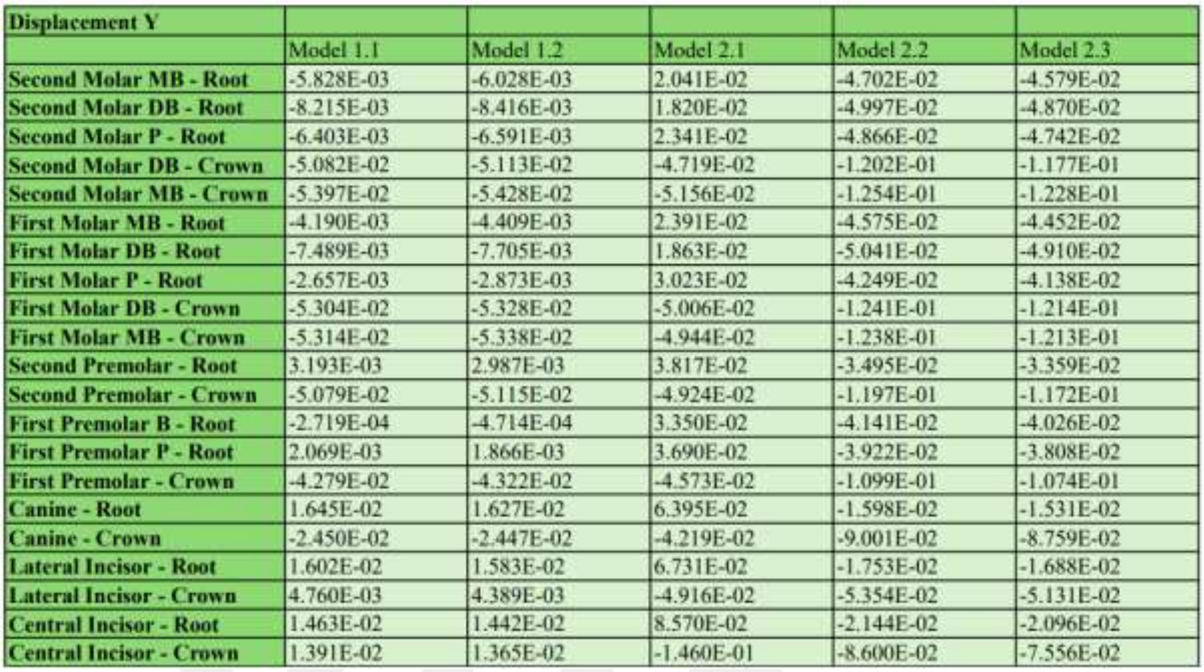
Model 2.1 **Model 2.2** **Model 2.3**

Figure 4.17. Comparative X plane distribution in all Models

4.3. Displacement Y

Based on the data in Table 8, the total values of crown and root were taken and the difference between them was obtained, and the change values according to the Y plane were calculated. According to these values coming from Table 8, a separate table of values in the Y plane was also created as Table 9.

Table 8: Displacement Y for All Phases and Models



Displacement Y					
	Model 1.1	Model 1.2	Model 2.1	Model 2.2	Model 2.3
Second Molar MB - Root	-5.828E-03	-6.028E-03	2.041E-02	-4.702E-02	-4.579E-02
Second Molar DB - Root	-8.215E-03	-8.416E-03	1.820E-02	-4.997E-02	-4.870E-02
Second Molar P - Root	-6.403E-03	-6.591E-03	2.341E-02	-4.866E-02	-4.742E-02
Second Molar DB - Crown	-5.082E-02	-5.113E-02	-4.719E-02	-1.202E-01	-1.177E-01
Second Molar MB - Crown	-5.397E-02	-5.428E-02	-5.156E-02	-1.254E-01	-1.228E-01
First Molar MB - Root	-4.190E-03	-4.409E-03	2.391E-02	-4.575E-02	-4.452E-02
First Molar DB - Root	-7.489E-03	-7.705E-03	1.863E-02	-5.041E-02	-4.910E-02
First Molar P - Root	-2.657E-03	-2.873E-03	3.023E-02	-4.249E-02	-4.138E-02
First Molar DB - Crown	-5.304E-02	-5.328E-02	-5.006E-02	-1.241E-01	-1.214E-01
First Molar MB - Crown	-5.314E-02	-5.338E-02	-4.944E-02	-1.238E-01	-1.213E-01
Second Premolar - Root	3.193E-03	2.987E-03	3.817E-02	-3.495E-02	-3.359E-02
Second Premolar - Crown	-5.079E-02	-5.115E-02	-4.924E-02	-1.197E-01	-1.172E-01
First Premolar B - Root	-2.719E-04	-4.714E-04	3.350E-02	-4.141E-02	-4.026E-02
First Premolar P - Root	2.069E-03	1.866E-03	3.690E-02	-3.922E-02	-3.808E-02
First Premolar - Crown	-4.279E-02	-4.322E-02	-4.573E-02	-1.099E-01	-1.074E-01
Canine - Root	1.645E-02	1.627E-02	6.395E-02	-1.598E-02	-1.531E-02
Canine - Crown	-2.450E-02	-2.447E-02	-4.219E-02	-9.001E-02	-8.759E-02
Lateral Incisor - Root	1.602E-02	1.583E-02	6.731E-02	-1.753E-02	-1.688E-02
Lateral Incisor - Crown	4.760E-03	4.389E-03	-4.916E-02	-5.354E-02	-5.131E-02
Central Incisor - Root	1.463E-02	1.442E-02	8.570E-02	-2.144E-02	-2.096E-02
Central Incisor - Crown	1.391E-02	1.365E-02	-1.460E-01	-8.600E-02	-7.556E-02

The values in Table 9 reflect the individual values of the incisors, depending on the movement.

The expansion assessment in the Y plane was analysed only for the central and lateral incisors.

Table 9. The Difference Between Crown and Root Displacement on the Anterior Region

Displacement Y					
	Model 1.1	Model 1.2	Model 2.1	Model 2.2	Model 2.3
Lateral Incisor	-0.01126	-0.011441	-0.01815	0.03601	0.03443
Central Incisor	-0.00072	-0.00077	0.0603	0.06456	0.0546

4.3.1. Phase 1 Model 1

Table 9. showed the buccal movement of central incisors and lateral incisors. Figure 4.18. represented Model 1.1. The movement shown on the lateral incisor (-0.01126 mm) and the central incisor (-0.00072 mm).

With a negative outcome in Table 9 for Model 1.1, central incisors and lateral incisors showed an uncontrolled tipping with the crowns moving in palatal direction and the apexes showed a buccal movement.

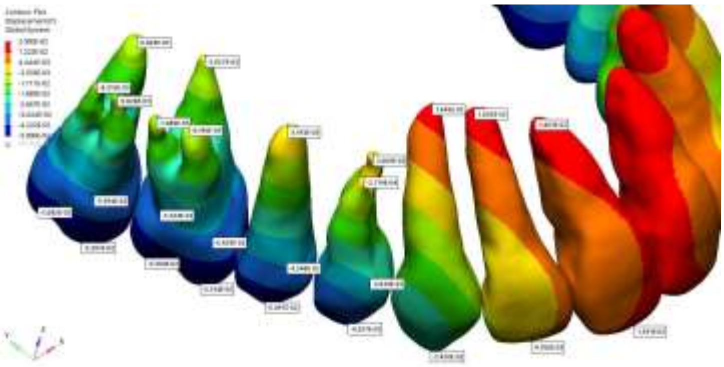


Figure 4.18. Displacement on Y plane of Model 1.1

4.3.2. Phase 1 Model 2

Table 9. showed the buccal movement of central incisors and lateral incisors. Figure 4.19. represented Model 1.2. The movement shown on the lateral incisor (-0.011441 mm) and the central incisor (-0.00077 mm). With a negative outcome in Table 9. for Model 1.2, central incisors and lateral incisors showed an uncontrolled tipping with the crowns moving in palatal direction and the apexes showed a buccal movement.

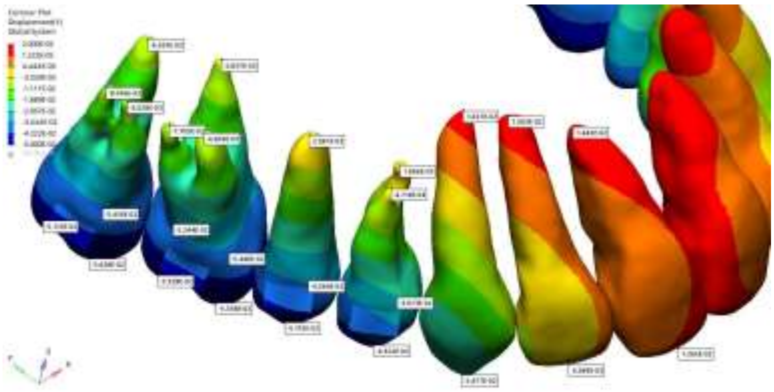


Figure 4.19. Displacement on the Y plane of Model 1. 2

4.3.3. Phase 2 Model 1

Table 9. showed the buccal movement of central incisors and lateral incisors. Figure 4.20. represented Model 2.1(Power ridges on Central Incisor). The movement shown on the lateral incisor (-0.01815 mm) and the central incisor (0.0603 mm).

The crowns of central incisors move buccally while lateral incisors have an uncontrolled tipping with the apex moving more palatally.

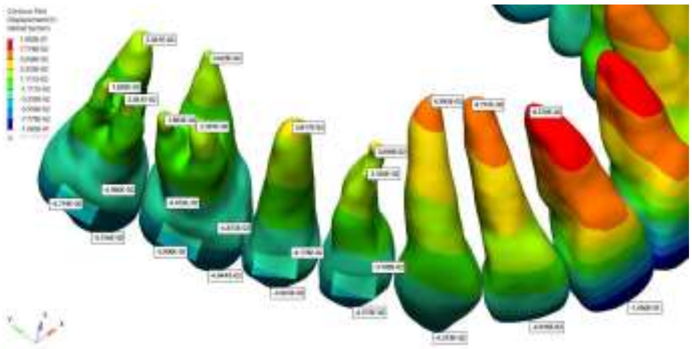


Figure 4.20. Displacement on the Y plane of Model 2.1

4.3.4. Phase 2 Model 2

Table 9. showed the buccal movement of central incisors and lateral incisors. Figure 4.21. represented Model 2.2(HA on Central Incisor). The movement shown on the lateral incisor (0.03601 mm) and the central incisor (0.06456 mm).
Both the crowns of central and lateral incisors move buccally.

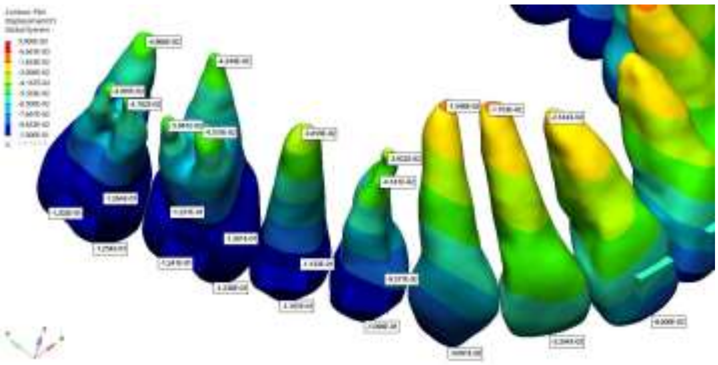


Figure 4.21. Displacement on the Y plane of Model 2.2

4.3.5. Phase 2 Model 3

Table 9. showed the buccal movement of central incisors and lateral incisors. Figure 4.22. represented Model 2.3(GBHA on Central Incisor). The movement shown on the lateral incisor (0.03443 mm) and the central incisor (0.0546 mm).
Both the crowns of central and lateral incisors move buccally.

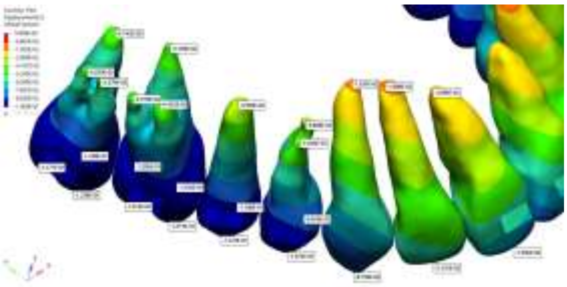


Figure 4.22. Displacement on Y plane of Model 2.3

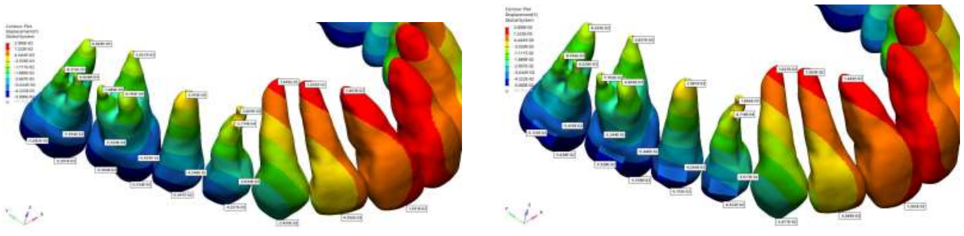
4.3.6. Results of Displacement Y In All Models

Movements occurring in the Y dimension indicated palatal movement if positive and buccal movement if negative.

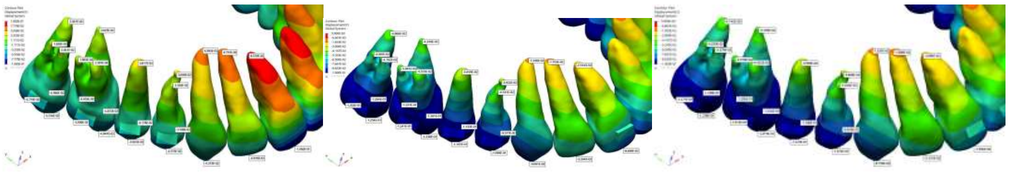
Model 1.1 and Model 1.2 showed palatal crown tipping due to the expansion of molars and premolars. The expansion on the posterior caused anterior retraction on incisors.

For the crown of the lateral incisor which showed negative results and moved buccal direction. In Table 9 it is shown that laterals have been uprighted in Model 2.2 and Model 2.3 but in Model 2.1 lateral incisors showed uncontrolled tipping.

For the crown evaluation of the central incisor which showed negative results and moved buccally, while the Model 2.1 showed uncontrolled tipping as the root of central incisor moved palatally and the crown moved buccally, in Model 2.2 and Model 2.3 the central incisors moved buccally.



Model 1.1 **Model 1.2**



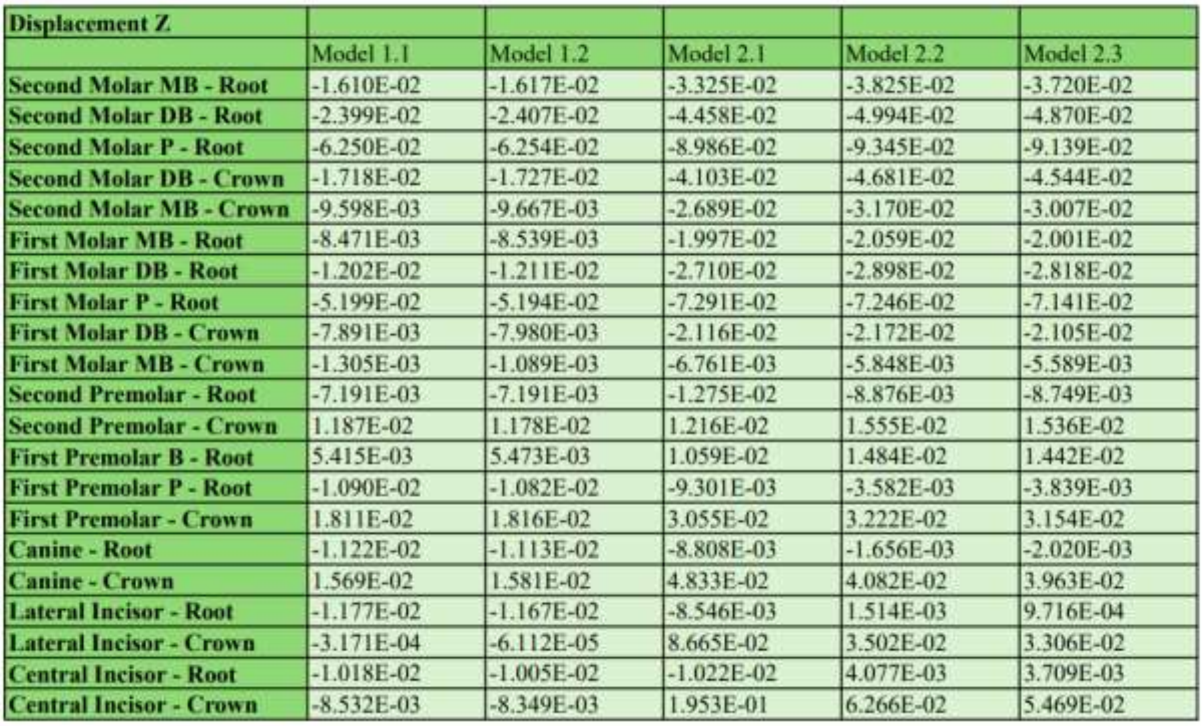
Model 2.1 **Model 2.2** **Model 2.3**

Figure 4.23. Comparative Y plane distribution in all Models

4.4. Displacement Z

The values in Table 10. reflect the individual intrusion or extrusion values observed on the Z plane.

Table 10. Intrusion and Extrusion Movements Z plane



Displacement Z					
	Model 1.1	Model 1.2	Model 2.1	Model 2.2	Model 2.3
Second Molar MB - Root	-1.610E-02	-1.617E-02	-3.325E-02	-3.825E-02	-3.720E-02
Second Molar DB - Root	-2.399E-02	-2.407E-02	-4.458E-02	-4.994E-02	-4.870E-02
Second Molar P - Root	-6.250E-02	-6.254E-02	-8.986E-02	-9.345E-02	-9.139E-02
Second Molar DB - Crown	-1.718E-02	-1.727E-02	-4.103E-02	-4.681E-02	-4.544E-02
Second Molar MB - Crown	-9.598E-03	-9.667E-03	-2.689E-02	-3.170E-02	-3.007E-02
First Molar MB - Root	-8.471E-03	-8.539E-03	-1.997E-02	-2.059E-02	-2.001E-02
First Molar DB - Root	-1.202E-02	-1.211E-02	-2.710E-02	-2.898E-02	-2.818E-02
First Molar P - Root	-5.199E-02	-5.194E-02	-7.291E-02	-7.246E-02	-7.141E-02
First Molar DB - Crown	-7.891E-03	-7.980E-03	-2.116E-02	-2.172E-02	-2.105E-02
First Molar MB - Crown	-1.305E-03	-1.089E-03	-6.761E-03	-5.848E-03	-5.589E-03
Second Premolar - Root	-7.191E-03	-7.191E-03	-1.275E-02	-8.876E-03	-8.749E-03
Second Premolar - Crown	1.187E-02	1.178E-02	1.216E-02	1.555E-02	1.536E-02
First Premolar B - Root	5.415E-03	5.473E-03	1.059E-02	1.484E-02	1.442E-02
First Premolar P - Root	-1.090E-02	-1.082E-02	-9.301E-03	-3.582E-03	-3.839E-03
First Premolar - Crown	1.811E-02	1.816E-02	3.055E-02	3.222E-02	3.154E-02
Canine - Root	-1.122E-02	-1.113E-02	-8.808E-03	-1.656E-03	-2.020E-03
Canine - Crown	1.569E-02	1.581E-02	4.833E-02	4.082E-02	3.963E-02
Lateral Incisor - Root	-1.177E-02	-1.167E-02	-8.546E-03	1.514E-03	9.716E-04
Lateral Incisor - Crown	-3.171E-04	-6.112E-05	8.665E-02	3.502E-02	3.306E-02
Central Incisor - Root	-1.018E-02	-1.005E-02	-1.022E-02	4.077E-03	3.709E-03
Central Incisor - Crown	-8.532E-03	-8.349E-03	1.953E-01	6.266E-02	5.469E-02

4.4.1. Phase 1 Model 1

The total displacement observed on the Z plane, values of second molar was 0.013312, first molar 0,011295, second premolar 0,019061, first premolar 0,012695, canine 0,02691, lateral incisor 0,0114529 and central incisor 0,001648. (Figure 4.24.)

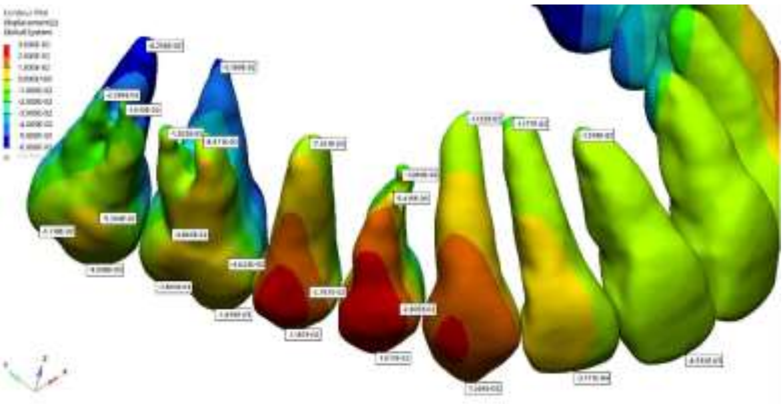


Figure 4.24. Displacement on Z plane of Model 1.1

4.4.2. Phase 1 Model 2

The total displacement observed on the Z plane, values of second molar is 0.013303, first molar 0,01158, second premolar 0,018971, first premolar 0,012687, canine 0,02694, lateral incisor 0,0116089 and central incisor 0,001701. (Figure 4.25.)

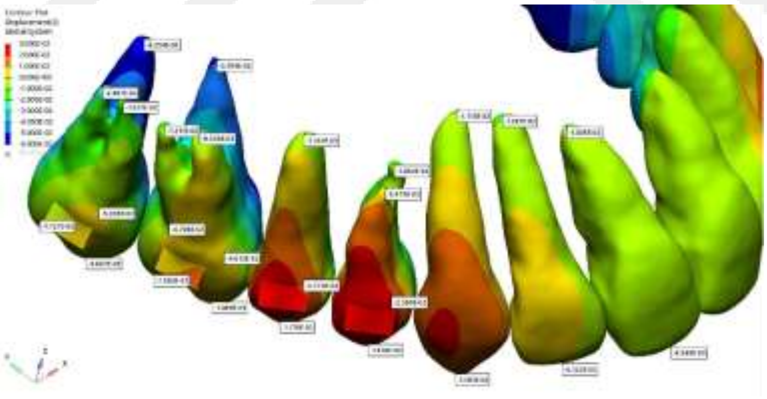


Figure 4.25. Displacement on Z plane of Model 1.2

4.4.3. Phase 2 Model 1

The total displacement observed on the Z plane, values for the second molar was 0.00991, first molar 0,019149, second premolar 0,02491, first premolar 0,01996, canine 0,057138, lateral incisor 0,095196 and central incisor 0,20552. (Figure 4.26.)

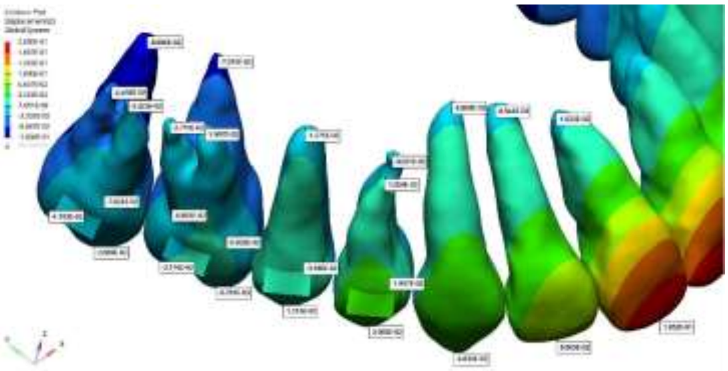


Figure 4.26. Displacement on Z plane of Model 2.1

4.4.4. Phase 2 Model 2

The total displacement observed on the Z plane, values for second molar was 0.00968, first molar 0,022002, second premolar 0,024426 first premolar 0,01738, canine 0,042476, lateral incisor 0,033506 and central incisor 0,058583. (Figure 4.27.)

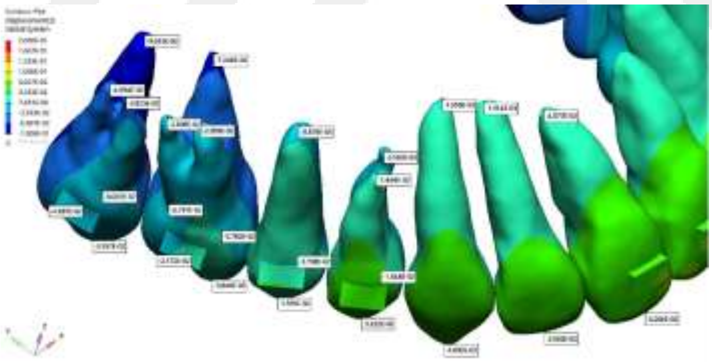


Figure 4.27. Displacement on Z plane of Model 2.2

4.4.5. Phase 2 Model 3

The total displacement observed on the Z plane, values of the second molar was 0.001039 mm, first molar 0,021551 mm, second premolar 0,024109, first premolar 0,01712 mm, canine 0,04165 mm, lateral incisor 0,0320884 mm and central incisor 0,050981 mm. (Figure 4.28.)

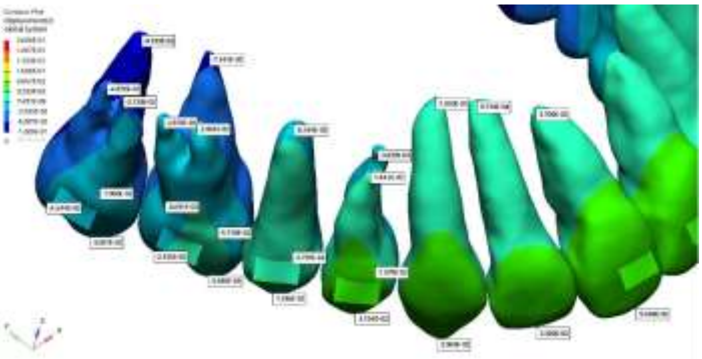
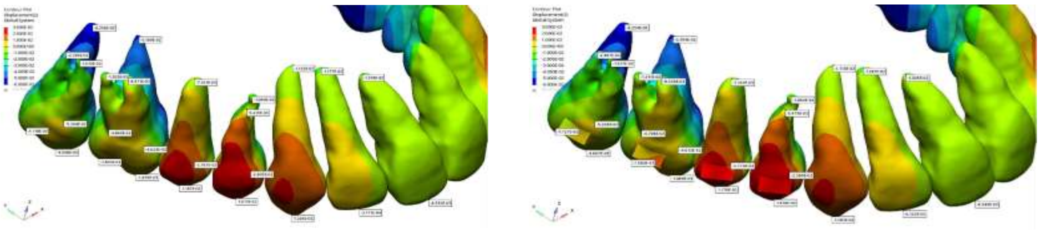


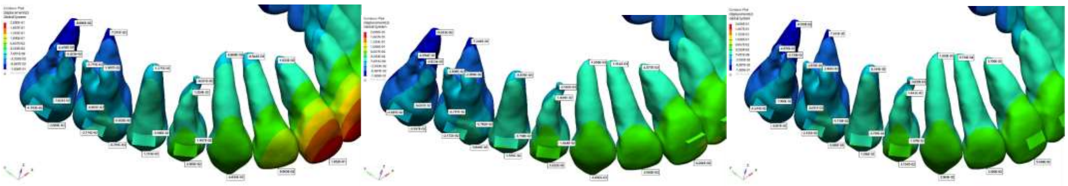
Figure 4.28. Displacement on Z plane of Model 2.3

The displacement on the Z plane was shown with all the study models in Figure 4.29. When evaluating the first and second molars, both Model 1.1 and Model 1.2 showed negative values, indicating extrusion. On the lateral and central incisors, both Model 1.1 and Model 1.2 showed both crown and root extrusion, with the extrusion was greater in Model 1.1.

For the central incisors, Model 2.1 has the highest value for the crown and roots, which is negative, Model 2.2 and Model 2.3 have positive values. (Figure 4.29.)



Model 1.1 **Model 1.2**



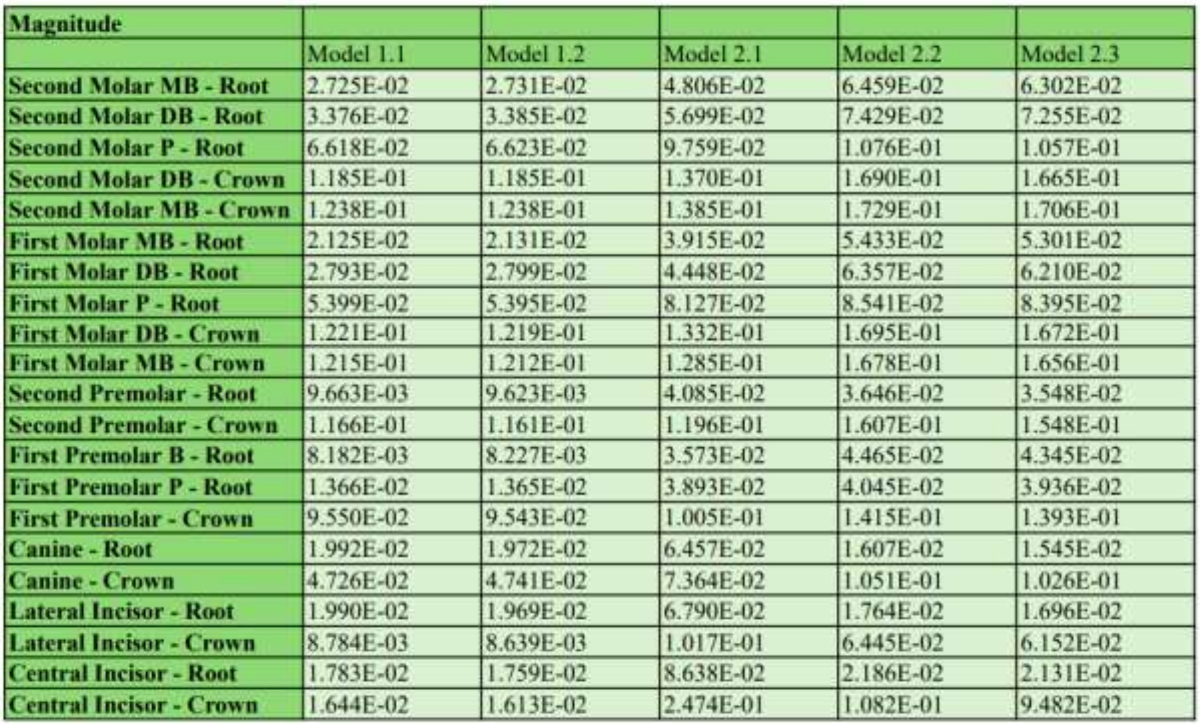
Model 2.1 **Model 2.2** **Model 2.3**

Figure 4.29. Comparative Z plane distribution in all Models

4.5. Magnitude

Table 11. shows the total displacement values for each tooth, including crown, root, and regional displacements.

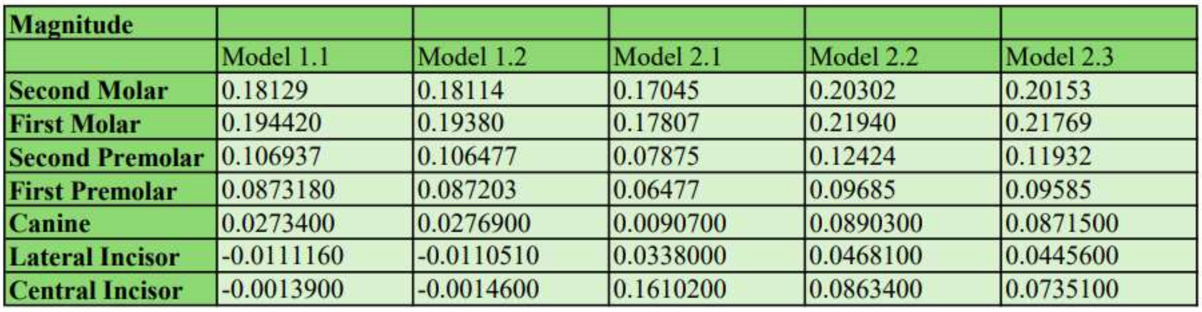
Table 11. Magnitude for All Phases and Models



Magnitude					
	Model 1.1	Model 1.2	Model 2.1	Model 2.2	Model 2.3
Second Molar MB - Root	2.725E-02	2.731E-02	4.806E-02	6.459E-02	6.302E-02
Second Molar DB - Root	3.376E-02	3.385E-02	5.699E-02	7.429E-02	7.255E-02
Second Molar P - Root	6.618E-02	6.623E-02	9.759E-02	1.076E-01	1.057E-01
Second Molar DB - Crown	1.185E-01	1.185E-01	1.370E-01	1.690E-01	1.665E-01
Second Molar MB - Crown	1.238E-01	1.238E-01	1.385E-01	1.729E-01	1.706E-01
First Molar MB - Root	2.125E-02	2.131E-02	3.915E-02	5.433E-02	5.301E-02
First Molar DB - Root	2.793E-02	2.799E-02	4.448E-02	6.357E-02	6.210E-02
First Molar P - Root	5.399E-02	5.395E-02	8.127E-02	8.541E-02	8.395E-02
First Molar DB - Crown	1.221E-01	1.219E-01	1.332E-01	1.695E-01	1.672E-01
First Molar MB - Crown	1.215E-01	1.212E-01	1.285E-01	1.678E-01	1.656E-01
Second Premolar - Root	9.663E-03	9.623E-03	4.085E-02	3.646E-02	3.548E-02
Second Premolar - Crown	1.166E-01	1.161E-01	1.196E-01	1.607E-01	1.548E-01
First Premolar B - Root	8.182E-03	8.227E-03	3.573E-02	4.465E-02	4.345E-02
First Premolar P - Root	1.366E-02	1.365E-02	3.893E-02	4.045E-02	3.936E-02
First Premolar - Crown	9.550E-02	9.543E-02	1.005E-01	1.415E-01	1.393E-01
Canine - Root	1.992E-02	1.972E-02	6.457E-02	1.607E-02	1.545E-02
Canine - Crown	4.726E-02	4.741E-02	7.364E-02	1.051E-01	1.026E-01
Lateral Incisor - Root	1.990E-02	1.969E-02	6.790E-02	1.764E-02	1.696E-02
Lateral Incisor - Crown	8.784E-03	8.639E-03	1.017E-01	6.445E-02	6.152E-02
Central Incisor - Root	1.783E-02	1.759E-02	8.638E-02	2.186E-02	2.131E-02
Central Incisor - Crown	1.644E-02	1.613E-02	2.474E-01	1.082E-01	9.482E-02

Table 12. displays the values obtained by taking the difference between the crown and root values of the teeth, representing the total dental displacement.

Table 12. Total Displacements for Each Tooth



Magnitude					
	Model 1.1	Model 1.2	Model 2.1	Model 2.2	Model 2.3
Second Molar	0.18129	0.18114	0.17045	0.20302	0.20153
First Molar	0.194420	0.19380	0.17807	0.21940	0.21769
Second Premolar	0.106937	0.106477	0.07875	0.12424	0.11932
First Premolar	0.0873180	0.087203	0.06477	0.09685	0.09585
Canine	0.0273400	0.0276900	0.0090700	0.0890300	0.0871500
Lateral Incisor	-0.0111160	-0.0110510	0.0338000	0.0468100	0.0445600
Central Incisor	-0.0013900	-0.0014600	0.1610200	0.0863400	0.0735100

As a result of Figure 4.30, Figure 4.31, Figure 4.32, Figure 4.33, Figure 4.34, Figure 4.35, Figure 4.36, Figure 4.37, Figure 4.38 and Figure 4.39 total displacement on Model 1.1 and Model 1.2 showed expansion on posterior teeth and retraction on lateral and central incisors.

4.5.1. Phase 1 Model 1

The total magnitude values for second molar were 0.18129 mm, first molar 0,194420 mm, second premolar 0,106937 mm, first premolar 0,0873180 mm, canine 0,0273400 mm, lateral incisor -0,0111160 mm and central incisor -0,0013900 mm. Molars and premolars showed buccal crown tipping while the anterior area was retracted.

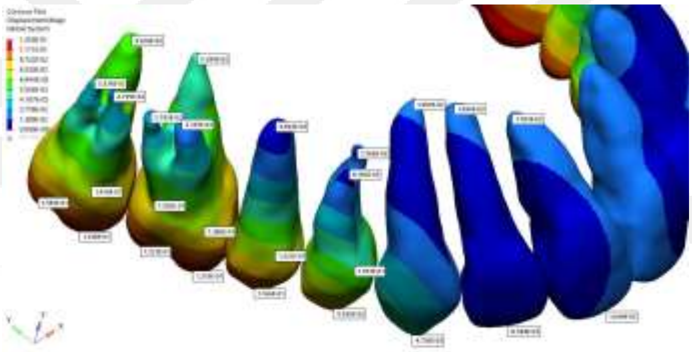


Figure 4.30. Magnitude Distribution of Model 1.1

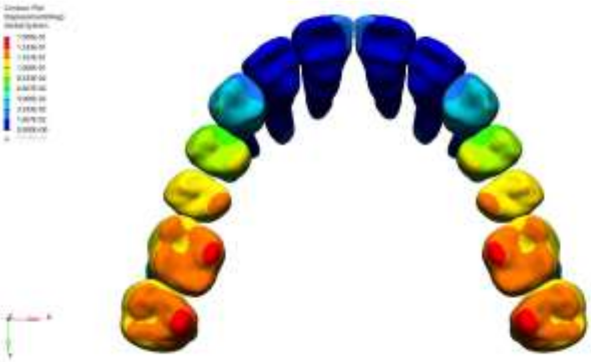


Figure 4.31. Magnitude Colour Map from Occlusal View

Figure 4.32. Magnitude Initial Position

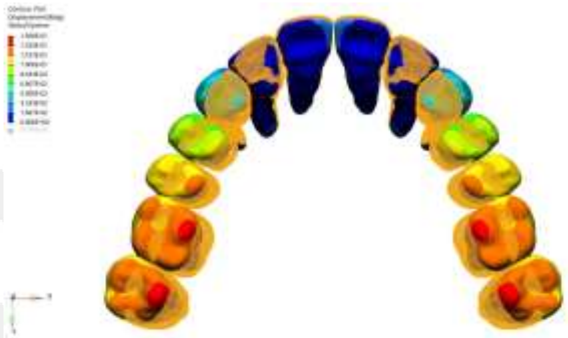


Figure 4.33. Magnitude Superimposition from Occlusal View

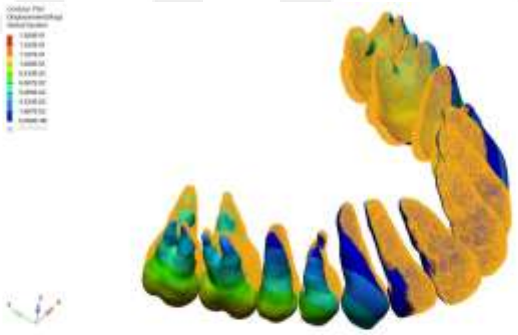


Figure 4.34. Magnitude Colour Map Superimposition

4.5.2. Phase 1 Model 2

The total magnitude values for the second molar were 0.18114 mm, the first molar 0,19380 mm, the second premolar 0,106477 mm, the first premolar 0,087203 mm, the canine 0,0276900mm, the lateral incisor -0,0110510 mm and the central incisor -0,0014600 mm. Buccal movement of molars and premolars and palatal movement of incisors were the most significant results. Extrusion of first and second molars palatal cups and retraction on the anterior area are shown.

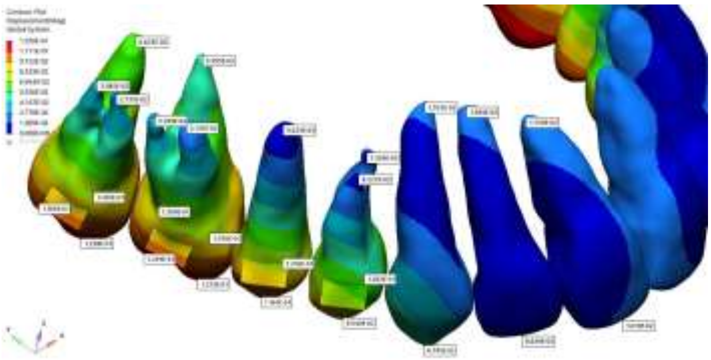


Figure 4.35. Magnitude Distribution of Model 1.2

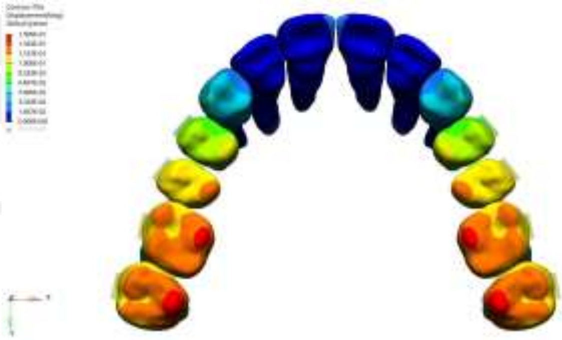


Figure 4.36. Magnitude Colour Map From Occlusal View

Figure 4.37. Magnitude Initial Position

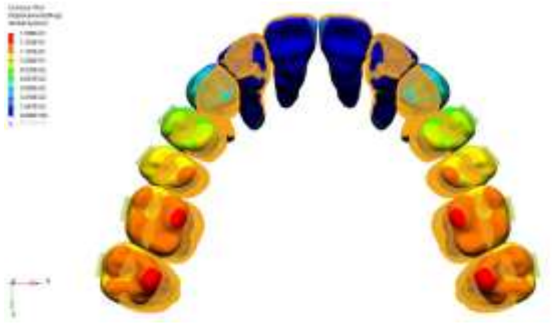


Figure 4.38. Magnitude Superimposition from Occlusal View

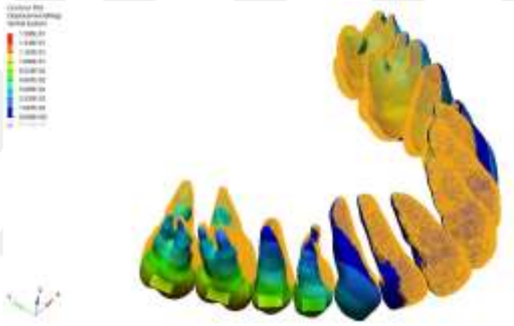


Figure 4.39. Magnitude Colour Map Superimposition

4.5.3. Phase 2 Model 1

The total magnitude values for the second molar were 0.17045 mm, the first molar 0,17807 mm, the second premolar 0,07875 mm, the first premolar 0,06477mm, the canine 0,0090700 mm, the lateral incisor 0,0338000 mm and the central incisor 0,1610200 mm. The central incisors are extruded and the canine-canine area shows palatally tilted roots on the anterior area.

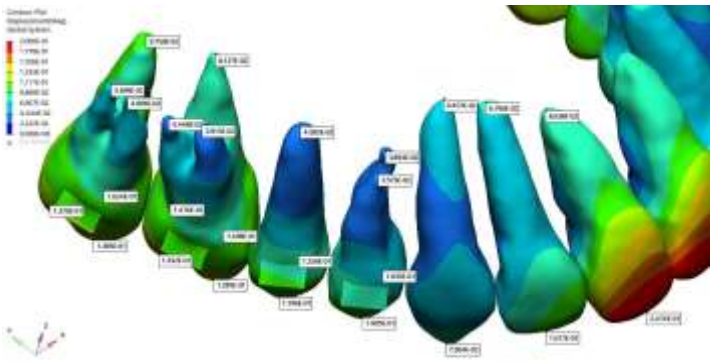


Figure 4.40. Magnitude Distribution of Model 2.1

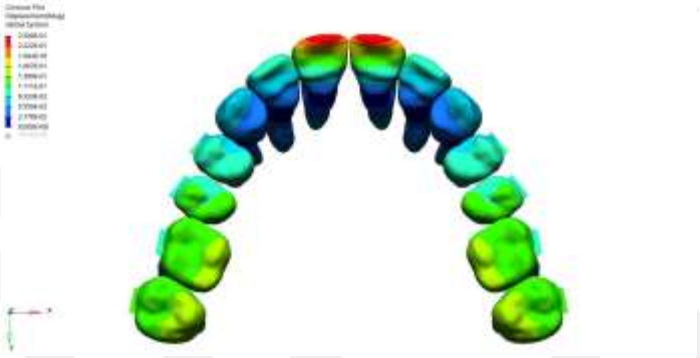


Figure 4.41. Magnitude Colour Map From Occlusal View

Figure 4.42. Magnitude Initial Position

Figure 4.43. Magnitude Superimposition from Occlusal View

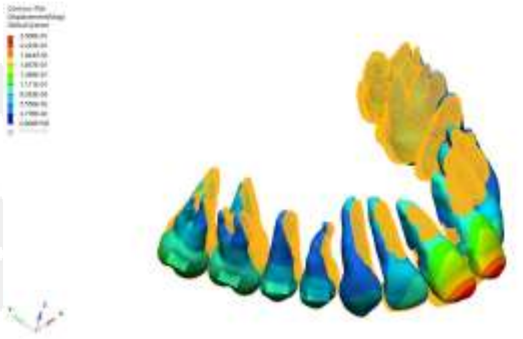


Figure 4.44. Magnitude Colour Map Superimposition

4.5.4. Phase 2 Model 2

The total magnitude values for the second molar were 0.20302 mm, the first molar 0,21940 mm, the second premolar 0,12424mm, the first premolar 0,9685 mm, the canine 0,0890300 mm, the lateral incisor 0,0468100 mm and the central incisor 0,0863400 mm. Molars and premolars showed buccal crown tipping while incisors moved more parallel in buccal direction.

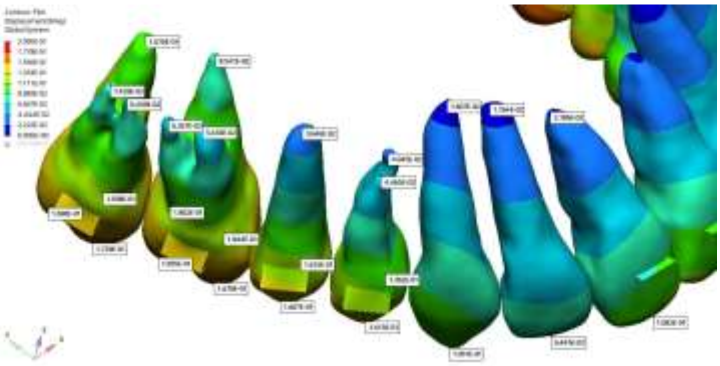


Figure 4.45. Magnitude Distribution of Model 2.2

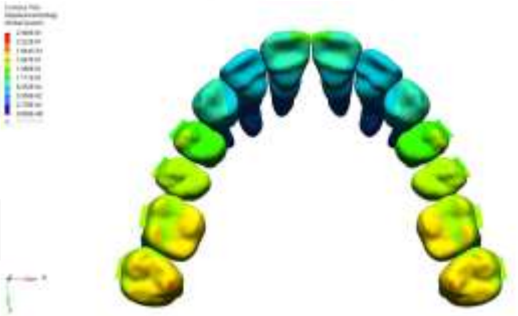


Figure 4.46. Magnitude Colour Map from Occlusal View

Figure 4.47. Magnitude Initial Position

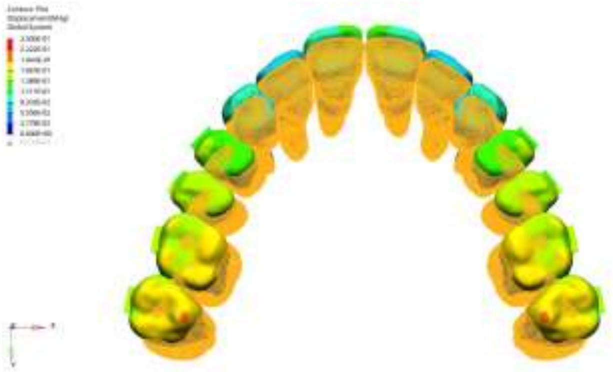


Figure 4.48. Magnitude Superimposition from Occlusal View

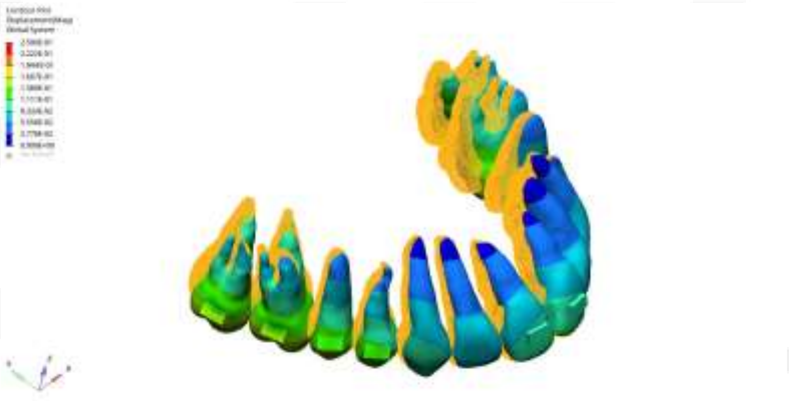


Figure 4.49. Magnitude Colour Map Superimposition

4.5.5. Phase 2 Model 3

The total magnitude values for the second molar were 0.20153 mm, the first molar 0,21769 mm, the second premolar 0,11932 mm, the first premolar 0,09585 mm, the canine 0,0871500 mm, the lateral incisor 0,0445600 mm and the central incisor 0,0735100 mm. Molars and premolars showed buccal crown tipping while incisors moved more parallel in buccal direction.

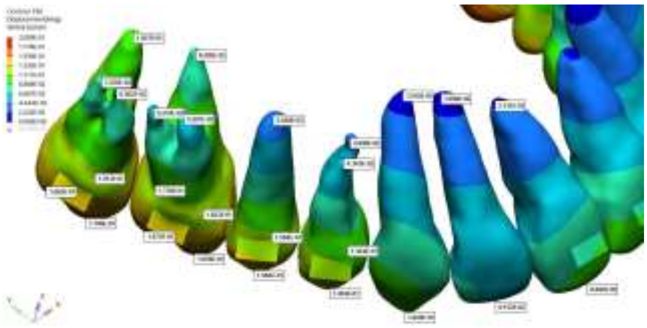


Figure 4.50. Magnitude Distribution of Model 2.3

Figure 4.51. Magnitude Colour Map From Occlusal View

Figure 4.52. Magnitude Initial Position

Figure 4.53. Magnitude Superimposition from Occlusal View

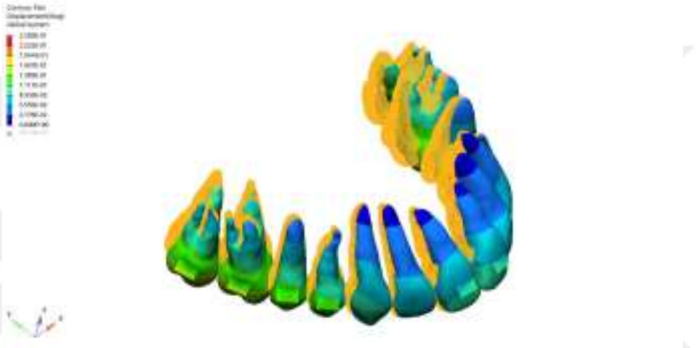


Figure 4.54. Magnitude Colour Map Superimposition

In Model 2.2, Model 2.3, molars and premolars showed buccal crown tipping and incisors showed more bodily translation in buccal direction while in Model 2.1 incisors showed uncontrolled tipping with their apexes moved palatally and crowns moved buccally.

5. DISCUSSION

5.1. Discussion of Purpose

Transversal problems are one of the most common orthodontic malocclusions. Conventional dentoalveolar expansion devices primarily achieve upper arch expansion through bone remodelling, which is achieved by increasing posterior buccal tipping with broadened arches or by repeatedly activating an expansion appliance. With the improvement in digital orthodontics, treatments of transversal problems can be solved by clear aligners. When designing a digital setup for transverse expansion with clear aligner treatment, both dental tipping and physiological translation of posterior teeth are expected. The predicted values for this procedure can vary significantly, contingent upon the specific teeth that are involved. [133,134]

In the literature, many studies showed that clear aligner treatment is effective in achieving maxillary transverse expansion. According to the retrospective studies [112,118], the primary factor contributing to the expansion effect of the dental arch is the transverse width variation resulting from the tipping movement of teeth. Furthermore, Duncan et al. noted that one of the efficient way to resolving dental constriction is the arch expansion accomplished by the buccal crown tipping movement of teeth, which is a type of transversal movement.[4,5,29,107,109,112,116,118]
In order to encourage bodily translation rather than tipping, Zhou and Guo [118] suggested that palatal crown torque to be incorporated into the extension movement. Despite the inclusion of this torque, buccal tilting was still observed in all teeth as reported by Lione et al. [137].

When expanding an arch it has shown that pure expansion can not be achieved, unplanned intrusion, extrusion, mesiodistal or buccolingual movements are likely to be observed after posterior expansion movements. The most prevalent concern throughout the history of clear aligner treatments has been the unpredictability of tooth movement. 57% of the predicted tooth movement could be accomplished with treatment utilising clear aligners, according to Chisari et al. [138] Previous researches have primarily focused on two key aspects: only expansion and the integration of torque control mechanisms in expansion.[4,5,29,109,112,116,,118] While these studies have contributed valuable insights, there remains a gap in the literature concerning the combined evaluation of expansion and torque control and their respective impacts on treatment outcomes. In the literature it has been shown that more expression of expansion is found at the cusp tips rather than gingival margins, indicating some tipping over bodily translation.[76] Yao et al. [66] suggested that torque control mechanism should be added to enhance torque control in arch expansion in clear aligner treatments. Lozano and Palma[68] suggested that gingival bevelled horizontal attachment can be used on posterior teeth during posterior expansion.[68] Zhou and Guo[118] proposed the addition of palatal crown torque in the expansion movement. Even when this torque was included, Lione et al.[137] still observed buccal tilting in all teeth.

In their study, Zhang et al.[141] explained that the CAT procedure resulted in buccal and distal tipping of the posterior teeth, lingual tipping of the anterior teeth, and extrusion of the incisors, along with maxillary arch expansion without torque compensation. However, these patterns of dental tipping might potentially lead to an occlusal problem and a clockwise rotation of the lower jaw, which can have a negative impact on the facial profile of individuals with a backward movement of the lower jaw. To avoid the aforementioned negative consequences, orthodontists prefer to improve the torque compensation during the expansion of the maxillary arch. Preserving the torque of anterior teeth is also an important factor to achieve a predictable outcome in posterior expansion cases. Therefore integrating auxiliary features, such as power ridges and attachments, can enhance the anterior root torque.[6,37,152] Mehmedali et al.[142] showed that the gingivally bevelled rectangular attachment can be used for torque control if any specific movement is not desired in the anterior region.

In light of the already mentioned lack of information in the orthodontic literature, our initial objective in the first part of our study was to assess the impact of posterior expansion using clear aligners on both posterior and anterior teeth using Finite Element Method (FEM). In the second phase of our study, our objective was to assess the efficacy of various torque control methods, including the use of attachments and power ridges, in preventing torque loss of the anterior teeth during posterior expansion.

5.2. Discussion of Methods

The Finite Element Method is a commonly used method to evaluate mechanical behaviors of the orthodontic materials as well as stresses accumulated on the dental tissues and periodontium. There are numerous finite element studies on expansion, torque control, as well as various aspects like distalization and mesialization.[63,66,67,128,130,132,147,151]Therefore, it is considered as a suitable method for this purpose.[63,66,67,128,130,132,147,151]

Zhang et al.[141] and Yao et al.[66] suggested that, if maxillary arch expansion is needed, a stride length of 0.2 mm and a torque compensation of 1.5° should be used. They also suggested adjusting the torque compensation of the anterior teeth to prevent unanticipated tooth displacement. In accordance with their suggestions, in our study, we have also added a torque compensation of 1.5° and used a stride length of 0.2 mm to the posterior teeth.

Attachments are the units which transfer the forces to the teeth in clear aligner treatments. There are different designs of attachments regarding their purpose. In general, horizontal attachments are used to control buccolingual tooth movements. In the first phase of our study, because our aim was to determine the group showing more bodily translation movement during expansion, two models, with and without posterior attachments, were evaluated. In the first model of the first phase, there were no attachments. An expansion force with torque compensation was applied on the posterior teeth via the clear aligner. In Model 1.2 gingivally bevelled horizontal attachments (GBHA) , as recommended by Lozano and Palma, were added on the posterior teeth in addition to expansion with torque compensation. [68] Furthermore, although different sizes of attachments are available, we used an attachment with 4 mm of length. The literature shows that 4 mm attachments are more effective in terms of torque control during expansion. [19,68]

Karslı et al.[19] also found that a larger attachment size increases the surface area over which force was exerted on the tooth, resulting in more effective control of tooth movement.

In contrast to our findings, Karslı et al.[19] reported that the crown measurement points of maxillary molars exhibited buccal displacement along the X-axis while the root measurement points displayed palatal displacement in their attachment-free clear aligner expansion model. However, in our study, we observed buccal displacement of both the crown and the roots.

The differences between studies may be due to the torque compensation activation of our models. Studies indicated that the torque compensation during posterior expansion is significant in achieving bodily movement. As a result of this torque compensation, we have achieved the buccal movement of both root and crown compared to other FEM studies.

Comparing the activation force used in the studies, Karslı et al[19] used 0.3mm activation force per aligner, we used 0.2mm activation force in all our models.

In the second phase, based on the data obtained from the first phase, GBHA was used in all models on the posterior teeth. The aim of the second phase was to obtain the most accurate combination for addressing the side effects occurring in the anterior teeth during expansion. As well as attachments, power ridges, positioned on the buccal aspect of the tooth, are advised to improve torque expression[140]. Hence, we evaluated the impact of power ridges placed on the labial and palatal surfaces of the central incisors. [140] Lozano et al.[68] observed that a single buccal or palatal power ridge caused disinsertion of the aligner from the tooth, while double power ridges created torque properly. Accordingly, in Model 2.1, in addition to GBHA in the premolar and molar teeth, power ridges were added on the aligner surface in buccogingival and palato-incisal positions of the central teeth.In Model 2.2, in addition to GBHA in premolar and molar teeth, a horizontal attachment was added to the middle ⅓ of the central teeth. In Model 2.3, GBHA was placed in the middle ⅓ of the central teeth, in addition to GBHA in premolar and molar teeth.Mehmedali et al suggested GBHA for anterior torque control as in our study however she found that in total displacement ellipsoid attachment showed maximum displacement but we found that horizontal attachment showed maximum displacement. On the other hand, attachments were not placed on lateral incisor and canine in any of these phases to simplify the models and observe the effect on central incisor.

5.3. Discussion of Results

During expansion of the posterior teeth, greater stress was observed mostly on lateral incisors and central incisors compared to the molars in the first phase, at both Model 1.1 and Model 1.2. This may be due to the forces acting on the anterior teeth during expansion in a closed system. Buccal movement of the posterior ends of the clear aligner leads to a straightening effect on the middle part of the aligner, which corresponds to the anterior teeth. Therefore, it generates palatally directed forces on the anterior teeth, thus leading to stress accumulation. Since the dimensions of the anterior teeth are smaller than the posterior teeth more stress was observed on the crowns of anterior teeth, mainly on the incisal edges.

With attachments on posterior teeth during expansion, it was observed that the Von Mises Stress was slightly higher on incisors in Model 1.2. This might be due to the increased stress values on the crowns of the posterior teeth due to the addition of the attachments, which may result in more stress accumulation on the incisors as previously explained.

When comparing Phase 1 and Phase 2, lateral incisors showed maximum stress accumulation on model 2.2 (horizontal attachment), central incisors showed the maximum stress levels on model 2.1 (power ridge) at the crown level. However, both central incisors and lateral incisors were affected the most in model 2.1 when observing stress at the apical level. It is evident that the power ridges exert extra forces on the central incisors as well as on the lateral incisors, which is not a surprising finding since in the clinical situation torque control causes stress on the root of the tooth. Therefore, if the root of the lateral incisors are small, the clinician should be careful to add power ridges on the anterior teeth in order to increase torque control for avoiding root resorption.

When the accumulated stress on the periodontal ligament (PDL) was evaluated, the teeth with the highest stress accumulation are the first premolars and second premolars, with values significantly higher than those of the other teeth. A possible explanation might be the smaller surface area of the premolar roots compared to the molars. Similarly, Zang et al.[141] found that when looking at the von Mises values on the PDL, the accumulation amount is higher in premolars in the cervical region, which is consistent with our study. Another explanation may be that the premolar area appears to be a transitional region where forces on the posterior and anterior area coincide, leading to higher stress accumulation on the periodontal ligament.

When observing the X plane, in our study, the negative results of the X plane show the buccal movement of the posterior teeth. When focusing on tipping and parallel movements, we noted that Model 1.2 showed more parallel and controlled buccal movement compared to Model 1.1. during expansion although Model 1.1. showed more buccal displacement with tipping movement. Considering these findings, the use of an attachment-free expansion protocol may be recommended when uncontrolled tipping is desired clinically. For cases requiring translational movement, the use of GBHA may offer greater accuracy. Similar to our findings, Karslı et al.[19] also found that a larger attachment size (4 mm) increases the surface area over which force was exerted on the tooth, resulting in more effective control of tooth movement.

In Model 1.1, the crown and the apex of the molars buccally displaced, with less displacement in the apical area. One might expect buccal displacement of the crown with palatal displacement of the root with a model of expansion without any attachments on the posterior teeth. In contrast to our findings, Karslı et al.[19] reported that the crown measurement points of maxillary molars exhibited buccal displacement along the X-axis while the root measurement points displayed palatal displacement in their attachment free clear aligner expansion model. However in our study we observed buccal displacement of both the crown and the roots.. The same difference also applied to the Model 1.2 of our study and other models with posterior attachments from the study of Karslı et al.[19] The differences between studies may be due to the torque compensation activation of our models. Studies indicated that the torque compensation during posterior expansion is very important to achieve bodily movement [66,76,118,137]. We have added 1.5° torque compensation on posterior teeth during posterior expansion in all the models. As a result of this torque compensation, we have achieved the buccal movement of both root and crown compared to other FEM studies.[19,141]

In our study, the greatest displacement in posterior teeth was found to be in the first molars where the highest magnitude value was observed as well, showing compatibility with Zang’s study [141]. Their findings are similar to our study in terms of buccolingual movement. Since no attachments were used in their study, comparing our Model 1.1

values shows similar effects on molars; however, we found the least expansive movements on premolars. Lozano and Palma[68] explained that if the premolars and molars are expanded (opening the pearl necklace in the posterior zone), the incisors will automatically naturally move backward into a more retroclined position. This movement is called as the pearl necklace effect and Zhang et al.[141] showed lingual tipping of the anterior teeth when the maxillary arch is expanded

Y plane shows the buccopalatal movement of anterior teeth and if the result is negative, it shows the retraction. In our study, during the posterior expansion, anterior teeth moved palatally in Model 1.1 and Model 1.2. When the aligner expands at the posterior ends, the middle part exerts palatally directed forces on the anterior teeth leading to retraction and palatal tipping of the incisors with torque loss. Supporting our findings, Zhang et al.[141] also showed lingual tipping of the anterior teeth when the maxillary arch is expanded using clear aligners in a FEM study. Furthermore, as the expansion movement on the posterior teeth increased from 0.1 to 0.3 mm, the retrusion effect on the incisors increased as well.

Whether this side effect on the anterior can be controlled by the use of attachments or power ridges on the anterior teeth was evaluated in the second phase of our study. According to our FEM findings, Model 2.1, 2.2, and 2.3 can be used to minimise the side effects of posterior expansion on incisors. In phase 2 model 2.1, central incisors showed uncontrolled tipping as the crown moves buccally, the root moves palatally. However, it was shown that lateral incisors have uprighted in Model 2.1 as the buccal movement of the root is more than the buccal movement of the crown. If the aim is to increase the inclination of the incisors during posterior expansion, it can be advised to use Model 2.1 with power ridges. Although a study has indicated that the efficacy of power ridges is merely 35.2%,[140] we found that the use of power ridges on the both palatal and buccal surfaces were effective in torque control.

In Models 2.2 and 2.3, the central incisors and lateral incisors moved buccally with more pronounced movement at the crown level compared to the root level. Even though there were no attachments on the lateral incisors, they followed the central incisor’s movement. When the initial inclination of the upper incisors is normal, to prevent retroclination effects of posterior expansion with clear aligners, Model 2.2 and Model 2.3 can be used. Model 2.3 offers more parallel movement with less buccal displacement compared to Model 2.2. This may be due to the difference in the horizontal attachment design. With the gingival beveled horizontal attachment, the torque control is better. It is shown that in our study since Model 2.3 showed the closest positive value to the 0 point in magnitude values on incisors, this model seems to be the most suitable model for prevention of this undesirable effect on the anterior teeth where expansion showed a negative effect. In her thesis, Mehmedali P.[142] evaluated attachment selection for torque control in incisors. Apart from cortical bone values, the underlying structures were similar. She highlighted that among different attachment selections, the gingivally bevelled rectangular attachment was the most stressed in terms of torque movement, and she emphasised the effectiveness of GBHA in torque control, showing a similarity with our study. [142] Power ridges on both palatal and buccal surfaces can increase torque on anterior teeth, similar to Lozano et al's suggestions.

When evaluating the Z plane and magnitude, based on the previous studies during expansion we expected to observe relative extrusion on the molars and premolars. In all of the models, on the premolars, it was observed an intrusion on crowns and buccal roots and an extrusion on palatal roots. However, the effect of the movement on the anterior teeth is different. In Phase 1, the incisor’s crowns showed extrusion, as a result of retroclination whereas in Phase 2, all the models showed intrusion as a result of labial movements of the incisors crown.

In our study in all the models, although we attempted to achieve parallel buccal movements by adding attachments on the posterior teeth during expansion or controlling unwanted uprighting of the anterior teeth, the dominant movement was tipping and no pure bodily movement were obtained. Biomechanical tooth movement depends on various factors, including the point of force application, its magnitude, direction, and the tooth's centre of resistance. Achieving specific bodily tooth movement ideally requires the force vector to intersect the tooth's centre of resistance, which can be challenging in clinical practice, especially for bone-anchored teeth where the centre of resistance often resides within the root structure. [145] In fixed orthodontic treatment systems, biomechanical strategies indirectly facilitate bodily tooth movement. For example, wires with square sections can create a force couple opposing the moment of the force around the centre of resistance, enabling controlled movement. [146,147] Conversely, clear aligner systems pose challenges in employing similar biomechanical techniques. Forces exerted vary across the tooth's surface, and the aligner's mechanism relies on geometric discrepancies between the tooth and the aligner. Consequently, stresses are dispersed over a broader and less defined area of contact, limiting the predictability of achieving bodily movement. Recent systematic reviews have highlighted these challenges in clear aligner treatments for achieving desired bodily tooth movements. [148–150]

Our study has some limitations. FEM is a static analysis that exclusively shows the stress distribution and displacement trends of teeth in the periodontal region as a result of single activation force and it does not reflect the function of time and consequent displacement of the teeth. The results of the analyses may be influenced by the parameters set, the contact mode of each component, the cutting of the appliance edge, and the shape of the teeth. In addition, FEM studies do not totally reflect the clinical situation. Therefore, there might be some discrepancies between our findings and the real clinical outcomes. Furthermore, only a few attachment designs were evaluated in our study. Comparing different designs and dimensions of attachments in combination of different thicknesses and trim lines of aligners might be suggested for further studies.

6. CONCLUSION

- Gingival bevelled horizontal attachment model showed more parallel movement compared to the attachment free model during posterior expansion with clear aligner. However, the buccal expansion was lesser.
- Incisors showed retroclination during posterior expansion.
- Horizontal attachments on the central incisors prevented retroclination of the incisors during expansion with clear aligner.
- When power ridges were used on the central incisors to avoid retroclination of the incisors, an uncontrolled tipping was achieved.

7. REFERENCES

1. Rossini G, Parrini S, Castroflorio T, Deregibus A, Debernardi CL. Efficacy of clear aligners in controlling orthodontic tooth movement: a systematic review. *Angle Orthod*. 2015;85(5):881-889. doi:10.2319/061614-436.1
2. Russell JS. Aesthetic orthodontic brackets. *J Orthod*. 2005;32(2):146-163. doi:10.1179/146531205225021024
3. Wiechmann D. A New Bracket System for Lingual Orthodontic Treatment. *Journal of Orofacial Orthopedics/Fortschritte der Kieferorthopädie.* 2003;64(5):372-388. doi:10.1007/s00056-003-0325-4
4. Bouchant M, Saade A, El Helou M. Is maxillary arch expansion with Invisalign® efficient and predictable? A systematic review. *Int Orthod*. 2023;21(2):100750. doi:10.1016/j.ortho.2023.100750
5. Houle JP, Piedade L, Todescan R, Pinheiro FHSL. The predictability of transverse changes with Invisalign. *Angle Orthod*. 2017;87(1):19-24. doi:10.2319/122115-875.1
6. Nucera R, Dolci C, Bellocchio AM, et al. Effects of Composite Attachments on Orthodontic Clear Aligners Therapy: A Systematic Review. *Materials*. 2022;15(2):533. doi:10.3390/ma15020533
7. Weir T. Clear aligners in orthodontic treatment. *Aust Dent J*. 2017;62(S1):58-62. doi:10.1111/adj.12480
8. Tamer İ, Öztaş E, Marşan G. Orthodontic Treatment with Clear Aligners and The Scientific Reality Behind Their Marketing: A Literature Review. *Turk J Orthod*. 2019;32(4):241-246. doi:10.5152/TurkJOrthod.2019.18083
9. Cattaneo PM, Dalstra M, Melsen B. The Finite Element Method: a Tool to Study Orthodontic Tooth Movement. *J Dent Res*. 2005;84(5):428-433. doi:10.1177/154405910508400506
10. Tartaglia GM, Mapelli A, Maspero C, et al. Direct 3D Printing of Clear Orthodontic Aligners: Current State and Future Possibilities. *Materials (Basel)*. 2021;14(7). doi:10.3390/ma14071799
11. Kohda N, Iijima M, Muguruma T, Brantley WA, Ahluwalia KS, Mizoguchi I. Effects of mechanical properties of thermoplastic materials on the initial force of thermoplastic appliances. *Angle Orthod*. 2013;83(3):476-483. doi:10.2319/052512-432.1

12. Kwon JS, Lee YK, Lim BS, Lim YK. Force delivery properties of thermoplastic orthodontic materials. *Am J Orthod Dentofacial Orthop*. 2008;133(2):228-234; quiz 328.e1. doi:10.1016/j.ajodo.2006.03.034
13. Fink DF, Smith RJ. The duration of orthodontic treatment. *Am J Orthod Dentofacial Orthop*. 1992;102(1):45-51. doi:10.1016/0889-5406(92)70013-Z
14. Fisher MA, Wenger RM, Hans MG. Pretreatment characteristics associated with orthodontic treatment duration. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2010;137(2):178-186. doi:10.1016/j.ajodo.2008.09.028
15. Rosvall MD, Fields HW, Ziuchkovski J, Rosenstiel SF, Johnston WM. Attractiveness, acceptability, and value of orthodontic appliances. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2009;135(3):276-277. doi:10.1016/j.ajodo.2008.09.020
16. Johnson G, Walker MP, Kula K. Fracture strength of ceramic bracket tie wings subjected to tension. *Angle Orthod*. 2005;75(1):95-100. doi:10.1043/0003-3219(2005)075<0095:FSOCBT>2.0.CO;2
17. Jacobson A. The Essix appliance technology: applications, fabrication and rationale. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2003;124(6):749. doi:10.1016/j.ajodo.2003.10.012
18. Kesling HD. The philosophy of the tooth positioning appliance. *Am J Orthod Oral Surg*. 1945;31(6):297-304. doi:10.1016/0096-6347(45)90101-3
19. Karsli N, Yildirim F, Dingiloğlu A, Özsoy ÖP. Does the trimline extension and attachment size affect maxillary arch expansion in clear aligner therapy？A finite element study. *Australasian Orthodontic Journal*. 2024;40(1):121-133. doi:10.2478/aoj-2024-0014
20. Ghadirian H, Yazarloo S, Heidari S, Gholamrezayi E. Mechanical vibration as an adjunct to clear aligner treatment for accelerating tooth movement: A review. *Dent Res J (Isfahan)*. 2022;19:75.
21. Tosun Y. Sabit ortodontik apareylerin biyomekanik prensipleri. In: Tosun Y, ed. *Sabit Ortodontik Apareylerin Biyomekanik Prensipleri*. ; 1999.
22. Karamouzos A, Athanasiou AE, Papadopoulos MA. Clinical characteristics and properties of ceramic brackets: A comprehensive review. *American Journal of Orthodontics and Dentofacial Orthopedics*. 1997;112(1):34-40. doi:10.1016/S0889-5406(97)70271-3

23. Ghafari J. Problems associated with ceramic brackets suggest limiting use to selected teeth. *Angle Orthod*. 1992;62(2):145-152. doi:10.1043/0003-3219(1992)062<0145:PAWCBS>2.0.CO;2
24. Fauchard P. *Le Chirurgien Dentiste, Ou Traite' Des Dents Ou l'on Enseigne Les Moyens de Les Entretenir Propres & Saines, de Les Embellir, d'en Reparer La Perte & de Remedier a Leurs Maladies, a Celles Des Gencives & Aux Accidens Qui Peuvent Survenir Aux Autres Parties Voisines Des Dents*.; 1746.
25. Hoffmann-Axthelm W. *History Of Dentistry*. Quintessence Publishing Company, Incorporated. ; 1981.
26. Fujita K. Multilingual-bracket and mushroom arch wire technique. *Am J Orthod*. 1982;82(2):120-140. doi:10.1016/0002-9416(82)90491-2
27. Fujita K. New orthodontic treatment with lingual bracket mushroom arch wire appliance. *Am J Orthod*. 1979;76(6):657-675. doi:10.1016/0002-9416(79)90211-2
28. Fujita K. [Development of lingual-bracket technique. (Esthetic and hygienic approach to orthodontic treatment) (Part 2) Manufacture and treatment (author's transl)]. *Shika Rikogaku Zasshi*. 1978;19(46):87-94.
29. Djeu G, Shelton C, Maganzini A. Outcome assessment of Invisalign and traditional orthodontic treatment compared with the American Board of Orthodontics objective grading system. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2005;128(3):292-298. doi:10.1016/j.ajodo.2005.06.002
30. Alexander CM, Alexander RG, Gorman JC, et al. Lingual orthodontics: a status report. Part 5. Lingual mechanotherapy. *J Clin Orthod*. 1983;17(2):99-115.
31. Echarri P. Revisiting the History of Lingual Orthodontics: A Basis for the Future. *Semin Orthod*. 2006;12(3):153-159. doi:10.1053/j.sodo.2006.05.002
32. Creekmore T. Lingual orthodontics—Its renaissance. *American Journal of Orthodontics and Dentofacial Orthopedics*. 1989;96(2):120-137. doi:10.1016/0889-5406(89)90253-9
33. Wiechmann D. A New Bracket System for Lingual Orthodontic Treatment Part 1: Theoretical Background and Development. *Journal of Orofacial Orthopedics / Fortschritte der Kieferorthopädie*. 2002;63(3):234-245. doi:10.1007/s00056-002-0211-5
34. Romano R. *Lingual Orthodontics: B.C. Decker*. Quintessence Publishing Company, Incorporated; 1998.
35. Scuzzo G, TK. *Invisible Orthodontics: Current Concepts and Solutions in Lingual Orthodontics*. Quintessenz Verlag; 2003.

36. Fritz U, Diedrich P, Wiechmann D. Lingual Technique – Patients' Characteristics, Motivation and Accpetance Interpretation of a Retrospective Survey. *Journal of Orofacial Orthopedics / Fortschritte der Kieferorthopädie*. 2002;63(3):227-233. doi:10.1007/s00056-002-0124-3

37. Elkholy, F., Weber, S., Repky, S. *et al.* Are aligners capable of inducing palatal bodily translation or palatal root torque of upper central incisors? A biomechanical in vitro study. *Clin Oral Invest* 27, 4289–4300 (2023). https://doi.org/10.1007/s00784-023-05046-7

38. Pauls A, Nienkemper M, Schwestka-Polly R, Wiechmann D. Therapeutic accuracy of the completely customized lingual appliance WIN. *Journal of Orofacial Orthopedics / Fortschritte der Kieferorthopädie*. 2017;78(1):52-61. doi:10.1007/s00056-016-0058-9

39. https://orthopracticeus.com/technology/the-brius-system-independent-tooth-movement/.

40. Remensnyder O. A gum-massaging appliance in the treatment of pyorrhea. *Dent Cosmos*. Published online 1926:381-384.

41. Wells NE. Application of the positioner appliance in orthodontic treatment. *Am J Orthod*. 1970;58(4):351-366. doi:10.1016/0002-9416(70)90106-5

42. Nahoum HI. Forces and moments generated by removable thermoplastic aligners. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2014;146(5):545-546. doi:10.1016/j.ajodo.2014.08.006

43. Fiasconaro JE, Sherman H. Vacuum-formed prostheses. I. A temporary fixed bridge or splint. *The Journal of the American Dental Association*. 1968;76(1):74-78. doi:10.14219/jada.archive.1968.0021

44. Sheridan JJ, LeDoux W, McMinn R. Essix retainers: fabrication and supervision for permanent retention. *J Clin Orthod*. 1993;27(1):37-45.

45. Sheridan JJ, Armbruster P, Nguyen P, Pulitzer S. Tooth movement with Essix mounding. *J Clin Orthod*. 2004;38(8):435-441.

46. Chudasama D, Sheridan JJ. Guidelines for contemporary air-rotor stripping. *J Clin Orthod*. 2007;41(6):315-320.

47. Kravitz ND, Kusnoto B, BeGole E, Obrez A, Agran B. How well does Invisalign work? A prospective clinical study evaluating the efficacy of tooth movement with Invisalign. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2009;135(1):27-35. doi:10.1016/j.ajodo.2007.05.018

48. Wong BH. Invisalign A to Z. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2002;121(5):540-541. doi:10.1067/mod.2002.123036

49. Brezniak N. The clear plastic appliance: a biomechanical point of view. *Angle Orthod*. 2008;78(2):381-382. doi:10.2319/0003-3219(2008)078[0381:TCPA]2.0.CO;2

50. Graber LW, VRL, VKW, and HGJ. *Orthodontics-e-Book: Current Principles and Techniques*. Elsevier Health Sciences; 2016.

51. Kravitz ND, Kusnoto B, Agran B, Viana G. Influence of attachments and interproximal reduction on the accuracy of canine rotation with Invisalign. A prospective clinical study. *Angle Orthod*. 2008;78(4):682-687. doi:10.2319/0003-3219(2008)078[0682:IOAAIR]2.0.CO;2

52. Sandra Tai. *Clear Aligner Technique*. Quintessence Publishing; 2018.

53. Bowman SJ. Improving the predictability of clear aligners. *Semin Orthod*. 2017;23(1):65-75. doi:10.1053/j.sodo.2016.10.005

54. Eliades T, Papageorgiou SN, Ireland AJ. The use of attachments in aligner treatment: Analyzing the “innovation” of expanding the use of acid etching–mediated bonding of composites to enamel and its consequences. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2020;158(2):166-174. doi:10.1016/j.ajodo.2020.04.008

55. Simon M, Keilig L, Schwarze J, Jung BA, Bourauel C. Treatment outcome and efficacy of an aligner technique – regarding incisor torque, premolar derotation and molar distalization. *BMC Oral Health*. 2014;14(1):68. doi:10.1186/1472-6831-14-68

56. Bowman SJ, Celenza F, Sparaga J, Papadopoulos MA, Ojima K, Lin JCY. Creative adjuncts for clear aligners, part 2: Intrusion, rotation, and extrusion. *J Clin Orthod*. 2015;49(3):162-172.

57. El-Bialy T, GD, and DS. *El-Bialy, T., GaOrthodontic Biomechanics: Treatment of Complex Cases Using Clear Aligner*. Bentham Science Publishers; 2016.

58. Charalampakis O, Iliadi A, Ueno H, Oliver DR, Kim KB. Accuracy of clear aligners: A retrospective study of patients who needed refinement. *Am J Orthod Dentofacial Orthop*. 2018;154(1):47-54. doi:10.1016/j.ajodo.2017.11.028

59. Henick D, Dayan W, Dunford R, Warunek S, Al-Jewair T. Effects of Invisalign (G5) with virtual bite ramps for skeletal deep overbite malocclusion correction in adults. *Angle Orthod*. 2021;91(2):164-170. doi:10.2319/072220-646.1

60. Boyd RL. Esthetic orthodontic treatment using the invisalign appliance for moderate to complex malocclusions. *J Dent Educ*. 2008;72(8):948-967.

61. Castroflorio T, Garino F, Lazzaro A, Debernardi C. Upper-incisor root control with Invisalign appliances. *J Clin Orthod*. 2013;47(6):346-351; quiz 387.

62. Peretta R, Ghislanzoni LH. Torque and intrusion control of the upper incisors with a modified posted archwire. *J Clin Orthod*. 2015;49(3):201-203.
63. Kawamura J, Tamaya N. A finite element analysis of the effects of archwire size on orthodontic tooth movement in extraction space closure with miniscrew sliding mechanics. *Prog Orthod*. 2019;20(1):3. doi:10.1186/s40510-018-0255-8
64. Baldwin DK, King G, Ramsay DS, Huang G, Bollen AM. Activation time and material stiffness of sequential removable orthodontic appliances. Part 3: Premolar extraction patients. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2008;133(6):837-845. doi:10.1016/j.ajodo.2006.06.025
65. Dai FF, Xu TM, Shu G. Comparison of achieved and predicted tooth movement of maxillary first molars and central incisors: First premolar extraction treatment with Invisalign. *Angle Orthod*. 2019;89(5):679-687. doi:10.2319/090418-646.1
66. Yao S, Jiang W, Wang C, He Y, Wang C, Huang L. Improvements of tooth movement efficiency and torque control in expanding the arch with clear aligners: a finite element analysis. *Front Bioeng Biotechnol*. 2023;11. doi:10.3389/fbioe.2023.1120535
67. Fan D, Liu H, Yuan CY, Wang SY, Wang PL. Effectiveness of the attachment position in molar intrusion with clear aligners: a finite element study. *BMC Oral Health*. 2022;22(1):474. doi:10.1186/s12903-022-02472-z
68. Moya SP, Zafra JL. *Aligner Techniques in Orthodontics*. Wiley; 2021. doi:10.1002/9781119607267
69. Proffit WR FHLBSDM. *Contemporary Orthodontics-e- Book.* Elsevier Health Sciences; 2018.
70. Mcdonald RE, ve ADR. *Dentistry for the Child and Adolescent*. 7th ed. Mosby; 2000.
71. Larsson E. The effect of dummy-sucking on the occlusion: a review. *The European Journal of Orthodontics*. 1986;8(2):127-130. doi:10.1093/ejo/8.2.127
72. Marshall SD, Southard KA, Southard TE. Early Transverse Treatment. *Semin Orthod*. 2005;11(3):130-139. doi:10.1053/j.sodo.2005.04.006
73. Pinkham JR. *Pediatric Dentistry: Infancy through Adolescence*. 4th ed. Elsevier Saunders; 2005.
74. Pavoni C, Lione R, Laganà G, Cozza P. Self-ligating versus Invisalign: analysis of dento-alveolar effects. *Ann Stomatol (Roma)*. 2011;2(1-2):23-27.
75. Ferrario VF. Quantitative effects of a nickel-titanium palatal expander on skeletal and dental structures in the primary and mixed dentition: a preliminary study. *The European Journal of Orthodontics*. 2003;25(4):401-410. doi:10.1093/ejo/25.4.401

76. Santucci V, Rossouw PE, Michelogiannakis D, El-Baily T, Feng C. Assessment of Posterior Dentoalveolar Expansion with Invisalign in Adult Patients. *International Journal of Environmental Research and Public Health*. 2023; 20(5):4318. https://doi.org/10.3390/ijerph20054318

77. Van Keulen C. Unilateral posterior crossbite and chin deviation: is there a correlation? *The European Journal of Orthodontics*. 2004;26(3):283-288. doi:10.1093/ejo/26.3.283

78. Ülgen M. *Ortodontik Tedavi Prensipleri*. 7. Ankara Üniversitesi Basımevi; 2005.

79. McInaney JB, Adams RM, Freeman M. A Nonextraction Approach to Crowded Dentitions in Young Children: Early Recognition and Treatment. *The Journal of the American Dental Association*. 1980;101(2):251-257. doi:10.14219/jada.archive.1980.0185

80. Donohue VE. A clinical comparison of the quadhelix appliance and the nickel titanium (tandem loop) palatal expander: a preliminary, prospective investigation. *The European Journal of Orthodontics*. 2004;26(4):411-420. doi:10.1093/ejo/26.4.411

81. Toroglu MS, Uzel E, Kayalioglu M, Uzel İ. Asymmetric maxillary expansion (AMEX) appliance for treatment of true unilateral posterior crossbite. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2002;122(2):164-173. doi:10.1067/mod.2002.125563

82. Sandikçiolu M, Hazar S. Skeletal and dental changes after maxillary expansion in the mixed dentition. *American Journal of Orthodontics and Dentofacial Orthopedics*. 1997;111(3):321-327. doi:10.1016/S0889-5406(97)70191-4

83. LAGRAVÈRE MO, MAJOR PW, FLORES-MIR C. Skeletal and dental changes with fixed slow maxillary expansion treatment. *The Journal of the American Dental Association*. 2005;136(2):194-199. doi:10.14219/jada.archive.2005.0141

84. Cotton LA. Slow maxillary expansion: Skeletal versus dental response to low magnitude force in Macaca mulatta. *Am J Orthod*. 1978;73(1):1-23. doi:10.1016/0002-9416(78)90098-2

85. Hicks EP. Slow maxillary expansion. *Am J Orthod*. 1978;73(2):121-141. doi:10.1016/0002-9416(78)90183-5

86. Altug Atac AT, Karasu HA, Aytac D. Surgically assisted rapid maxillary expansion compared with orthopedic rapid maxillary expansion. *Angle Orthod*. 2006;76(3):353-359. doi:10.1043/0003-3219(2006)076[0353:SARMEC]2.0.CO;2

87. Podesser B, Williams S, Crismani AG, Bantleon HP. Evaluation of the effects of rapid maxillary expansion in growing children using computer tomography scanning: a pilot study. *The European Journal of Orthodontics*. 2007;29(1):37-44. doi:10.1093/ejo/cjl068

88. Mew J. Relapse following maxillary expansion. *Am J Orthod*. 1983;83(1):56-61. doi:10.1016/0002-9416(83)90272-5

89. Işeri H, Ozsoy S. Semirapid maxillary expansion--a study of long-term transverse effects in older adolescents and adults. *Angle Orthod*. 2004;74(1):71-78. doi:10.1043/0003-3219(2004)074<0071:SMESOL>2.0.CO;2

90. Bishara SE, Staley RN. Maxillary expansion: clinical implications. *Am J Orthod Dentofacial Orthop*. 1987;91(1):3-14. doi:10.1016/0889-5406(87)90202-2

91. Bell RA. A review of maxillary expansion in relation to rate of expansion and patient’s age. *Am J Orthod*. 1982;81(1):32-37. doi:10.1016/0002-9416(82)90285-8

92. Storey E. Tissue response to the movement of bones. *Am J Orthod*. 1973;64(3):229-247. doi:10.1016/0002-9416(73)90017-1

93. Mossaz-Joëlson K, Mossaz CF. Slow maxillary expansion: a comparison between banded and bonded appliances. *Eur J Orthod*. 1989;11(1):67-76. doi:10.1093/oxfordjournals.ejo.a035967

94. Huynh T, Kennedy DB, Joondeph DR, Bollen AM. Treatment response and stability of slow maxillary expansion using Haas, hyrax, and quad-helix appliances: A retrospective study. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2009;136(3):331-339. doi:10.1016/j.ajodo.2007.08.026

95. Lanteri V, Cossellu G, Gianolio A, et al. Comparison between RME, SME and Leaf Expander in growing patients: a retrospective postero-anterior cephalometric study. *Eur J Paediatr Dent*. 2018;19(3):199-204. doi:10.23804/ejpd.2018.19.03.6

96. Ekström C, Henrikson CO, Jensen R. Mineralization in the midpalatal suture after orthodontic expansion. *Am J Orthod*. 1977;71(4):449-455. doi:10.1016/0002-9416(77)90248-2

97. Galan-Lopez L, Barcia-Gonzalez J, Plasencia E. A systematic review of the accuracy and efficiency of dental movements with Invisalign®. *The Korean Journal of Orthodontics*. 2019;49(3):140. doi:10.4041/kjod.2019.49.3.140

98. Nemec M, Bartholomaeus HM, H. Bertl M, et al. Behaviour of Human Oral Epithelial Cells Grown on Invisalign® SmartTrack® Material. *Materials*. 2020;13(23):5311. doi:10.3390/ma13235311

99. Buschang PH, Shaw SG, Ross M, Crosby D, Campbell PM. Comparative time efficiency of aligner therapy and conventional edgewise braces. *Angle Orthod*. Published online November 18, 2013:131118094755008. doi:10.2319/062113-466.1

100. Putrino A, Barbato E, Galluccio G. Clear Aligners: Between Evolution and Efficiency—A Scoping Review. *Int J Environ Res Public Health*. 2021;18(6):2870. doi:10.3390/ijerph18062870

101. Levrini L, Carganico A, Abbate L. Maxillary expansion with clear aligners in the mixed dentition: A preliminary study with Invisalign® First system. *Eur J Paediatr Dent*. 2021;22(2):125-128. doi:10.23804/ejpd.2021.22.02.7

102. Robertson L, Kaur H, Fagundes NCF, Romanyk D, Major P, Flores Mir C. Effectiveness of clear aligner therapy for orthodontic treatment: A systematic review. *Orthod Craniofac Res*. 2020;23(2):133-142. doi:10.1111/ocr.12353

103. Kassam SK, Stoops FR. Are clear aligners as effective as conventional fixed appliances? *Evid Based Dent*. 2020;21(1):30-31. doi:10.1038/s41432-020-0079-5

104. Laganà G, Malara A, Lione R, Danesi C, Meuli S, Cozza P. Enamel interproximal reduction during treatment with clear aligners: digital planning versus OrthoCAD analysis. *BMC Oral Health*. 2021;21(1):199. doi:10.1186/s12903-021-01487-2

105. Taner T (Uğur), Ciğer S, El H, Germeç D, Es A. Evaluation of dental arch width and form changes after orthodontic treatment and retention with a new computerized method. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2004;126(4):463-474. doi:10.1016/j.ajodo.2003.08.033

106. Haouili N, Kravitz ND, Vaid NR, Ferguson DJ, Makki L. Has Invisalign improved? A prospective follow-up study on the efficacy of tooth movement with Invisalign. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2020;158(3):420-425. doi:10.1016/j.ajodo.2019.12.015

107. Duncan LO, Piedade L, Lekic M, Cunha RS, Wiltshire WA. Changes in mandibular incisor position and arch form resulting from Invisalign correction of the crowded dentition treated nonextraction. *Angle Orthod*. 2016;86(4):577-583. doi:10.2319/042415-280.1

108. Lione R, Paoloni V, De Razza FC, Pavoni C, Cozza P. Analysis of Maxillary First Molar Derotation with Invisalign Clear Aligners in Permanent Dentition. *Life (Basel)*. 2022;12(10). doi:10.3390/life12101495

109. Galluccio G, De Stefano AA, Horodynski M, et al. Efficacy and Accuracy of Maxillary Arch Expansion with Clear Aligner Treatment. *Int J Environ Res Public Health*. 2023;20(5). doi:10.3390/ijerph20054634

110. Houle JP, Piedade L, Todescan R, Pinheiro FHSL. The predictability of transverse changes with Invisalign. *Angle Orthod*. 2017;87(1):19-24. doi:10.2319/122115-875.1

111. Hariharan A, Arqub SA, Gandhi V, Da Cunha Godoy L, Kuo CL, Uribe F. Evaluation of interproximal reduction in individual teeth, and full arch assessment in clear aligner therapy: digital planning versus 3D model analysis after reduction. *Prog Orthod*. 2022;23(1):9. doi:10.1186/s40510-022-00403-w

112. Zhao X, Wang HH, Yang YM, Tang GH. [Maxillary expansion efficiency with clear aligner and its possible influencing factors]. *Zhonghua Kou Qiang Yi Xue Za Zhi*. 2017;52(9):543-548. doi:10.3760/cma.j.issn.1002-0098.2017.09.006

113. Grünheid T, Loh C, Larson BE. How accurate is Invisalign in nonextraction cases? Are predicted tooth positions achieved? *Angle Orthod*. 2017;87(6):809-815. doi:10.2319/022717-147.1

114. Vidal-Bernárdez M, Vilches-Arenas Á, Sonnemberg B, Solano-Reina E, Solano-Mendoza B. Efficacy and predictability of maxillary and mandibular expansion with the Invisalign® system. *J Clin Exp Dent*. Published online 2021:e669-e677. doi:10.4317/jced.58315

115. Deregibus A, Tallone L, Rossini G, Parrini S, Piancino M, Castroflorio T. Morphometric analysis of dental arch form changes in class II patients treated with clear aligners. *J Orofac Orthop*. 2020;81(4):229-238. doi:10.1007/s00056-020-00224-8

116. Morales-Burruezo I, Gandía-Franco JL, Cobo J, Vela-Hernández A, Bellot-Arcís C. Arch expansion with the Invisalign system: Efficacy and predictability. *PLoS One*. 2020;15(12):e0242979. doi:10.1371/journal.pone.0242979

117. Riede U, Wai S, Neururer S, et al. Maxillary expansion or contraction and occlusal contact adjustment: effectiveness of current aligner treatment. *Clin Oral Investig*. 2021;25(7):4671-4679. doi:10.1007/s00784-021-03780-4

118. Zhou N, Guo J. Efficiency of Upper Arch Expansion with the Invisalign System. *Angle Orthod*. 2020;90(1):23-30. doi:10.2319/022719-151.1

119. CAPUTO AA SJ. *Biomechanics in Clinical Dentistry*. Quintessence Publishing; 1987.

120. MCNEILL C. *Science and Practice of Occlusion*. Quintessence Publishing; 1997.

121. R.G. Craig. *Restorative Dental Materials* . 8th ed. Mosby; 1989.

122. VELİ İ. *Üst Kanin Distalizasyonunda Oluşan Değişikliklerin Sonlu Elemanlar Analizi Ile Incelenmesi. Doktora Tezi*. Dicle Üniversitesi; 2012.

123. AYALI A. *Mandibular Angulus Bölgesi Favorable ve Unfavorable Fraktürlerinde Uygulanan Farklı Fiksasyon Metotlarının Biyomekanik Etkilerinin Sonlu Elemanlar Analizi Yöntemi Ile İncelenmesi. Doktora Tezi.* Yakın Doğu Üniversitesi; 2012.

124. GÜMÜŞ H. Ö. *Üç Farklı Dental İmplant Yiv Tasarımının ve İki Farklı Dental İmplant Çapının Değişik Yoğunluktaki Kemik Üzerinde Oluşturdukları Gerilmelerin Üç Boyutlu Sonlu Elemanlar Gerilme Analiz Yöntemi İle Karşılaştırılması. Doktora Tezi*. Hacettepe Üniversitesi; 2007.

125. FRANKLİN F. E. *Stress Analysis. M. Kutz (Ed.). Mechanical Engineers' Handbook*. Wiley Publishing. ; 1998.

126. O'BRIEN WJ. *Dental Materials and Their Selection*. Quintessence Publishing; 1997.

127. ŞEKER E. *Greftlenmiş ve Greftlenmemiş Posterior Maksillada Uygulanan Implant Destekli Farklı Tasarımlı Sabit Protezlerin Destek Dokulardaki Etkilerinin Üç Boyutlu Sonlu Elemanlar Stres Analiz Yöntemi Ile Incelenmesi. Doktora Tezi.* Yakın Doğu Üniversitesi; 2011.

128. MOAVENI S. *Finite Element Analysis: Theory and Application with Ansys.* Prentice Hall; 2003.

129. HANCI M. BE, AA. Biyomekanik. In: Logos Yayıncılık; 2000:10-55.

130. HUGHES T. J. R. *The Finite Element Method.* Prentice-Hall.; 1987.

131. Geng JP, Tan KB, Liu GR. Application of finite element analysis in implant dentistry: a review of the literature. *J Prosthet Dent*. 2001;85(6):585-598. doi:10.1067/mpr.2001.115251

132. ADIGÜZEL O. Sonlu elemanlar analizi: derleme, bölüm 1: Dişhekimliğinde kullanım alanları, temel kavramlar ve eleman tanımları. *Dicle Dişhekimliği Dergisi*. 2010;11(1):18-23.

133. Chaconas SJ, de Alba y Levy JA. Orthopedic and orthodontic applications of the quad-helix appliance. *Am J Orthod*. 1977;72(4):422-428. doi:10.1016/0002-9416(77)90355-4

134. Birnie DJ, McNamara TG. The quadhelix appliance. *Br J Orthod*. 1980;7(3):115-120. doi:10.1179/bjo.7.3.115

135. Solano-Mendoza B, Sonnemberg B, Solano-Reina E, Iglesias-Linares A. How effective is the Invisalign® system in expansion movement with Ex30' aligners? *Clin Oral Investig*. 2017;21(5):1475-1484. doi:10.1007/s00784-016-1908-y

136. Tien R, Patel V, Chen T, et al. The predictability of expansion with Invisalign: A retrospective cohort study. *Am J Orthod Dentofacial Orthop*. 2023;163(1):47-53. doi:10.1016/j.ajodo.2021.07.032

137. Lione R, Paoloni V, Bartolommei L, et al. Maxillary arch development with Invisalign system: *Angle Orthod*. 2021;91(4):433-440. doi:10.2319/080520-687.1

138. Chisari JR, McGorray SP, Nair M, Wheeler TT. Variables affecting orthodontic tooth movement with clear aligners. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2014;145(4):S82-S91. doi:10.1016/j.ajodo.2013.10.022

139. Ercoli F, Tepedino M, Parziale V, Luzi C. A comparative study of two different clear aligner systems. *Prog Orthod*. 2014;15(1):31. doi:10.1186/s40510-014-0031-3

140. RÜVEYDA DOĞRUGÖREN. *Şeffaf Plak Mekaniklerinin Kök Torkuna Etkisi*. Sağlık Bilimleri Üniversitesi; 2023.

141. Zhang Y, Hui S, Gui L, Jin F. Effects of upper arch expansion using clear aligners on different stride and torque: a three-dimensional finite element analysis. *BMC Oral Health*. 2023;23(1):891. doi:10.1186/s12903-023-03655-y

142. PINAR HACIM MEHMEDALI. *Şeffaf Plak Tedavisinde Kullanılan Farklı Ataşman Tiplerinin Maksiller Keser Dişlerdeki Tork Hareketine Etkisinin Sonlu Elemanlar Analizi Ile Incelenmesi*. Ortodonti Ana Bilim Dalı. Sağlık Bilimleri Üniversitesi; 2021.

143. Elkenawy I, Fijany L, Colak O, et al. An assessment of the magnitude, parallelism, and asymmetry of micro-implant-assisted rapid maxillary expansion in non-growing patients. *Prog Orthod*. 2020;21(1):42. doi:10.1186/s40510-020-00342-4

144. Cozzani M, Nucci L, Lupini D, et al. Two different designs of mini-screw assisted maxillary expanders, using FEM to analyse stress distribution in craniofacial structures and anchor teeth. *Int Orthod*. 2022;20(1):100607. doi:10.1016/j.ortho.2022.100607

145. Elshazly TM, Keilig L, Salvatori D, Chavanne P, Aldesoki M, Bourauel C. Effect of trimming line design and edge extension of orthodontic aligners on force transmission: An in vitro study. *J Dent*. 2022;125:104276. doi:10.1016/j.jdent.2022.104276

146. R.S. Nanda YST. Biomechanics in Orthodontics: Principles and Practice. In: *Biomechanics in Orthodontics: Principles and Practice*. ; 2010:38-39.

147. Reimann S, Keilig L, Jager A, Bourauel C. Biomechanical finite-element investigation of the position of the centre of resistance of the upper incisors. *The European Journal of Orthodontics*. 2007;29(3):219-224. doi:10.1093/ejo/cjl086

148. Upadhyay M, Arqub SA. Biomechanics of clear aligners: hidden truths & first principles. *J World Fed Orthod*. 2022;11(1):12-21. doi:10.1016/j.ejwf.2021.11.002

149. Barone S, Paoli A, Razionale A V., Savignano R. Computer aided modelling to simulate the biomechanical behaviour of customised orthodontic removable appliances. *International Journal on Interactive Design and Manufacturing (IJIDeM)*. 2016;10(4):387-400. doi:10.1007/s12008-014-0246-z

150. Yassir YA, Nabbat SA, McIntyre GT, Bearn DR. Clinical effectiveness of clear aligner treatment compared to fixed appliance treatment: an overview of systematic reviews. *Clin Oral Investig*. 2022;26(3):2353-2370. doi:10.1007/s00784-021-04361-1

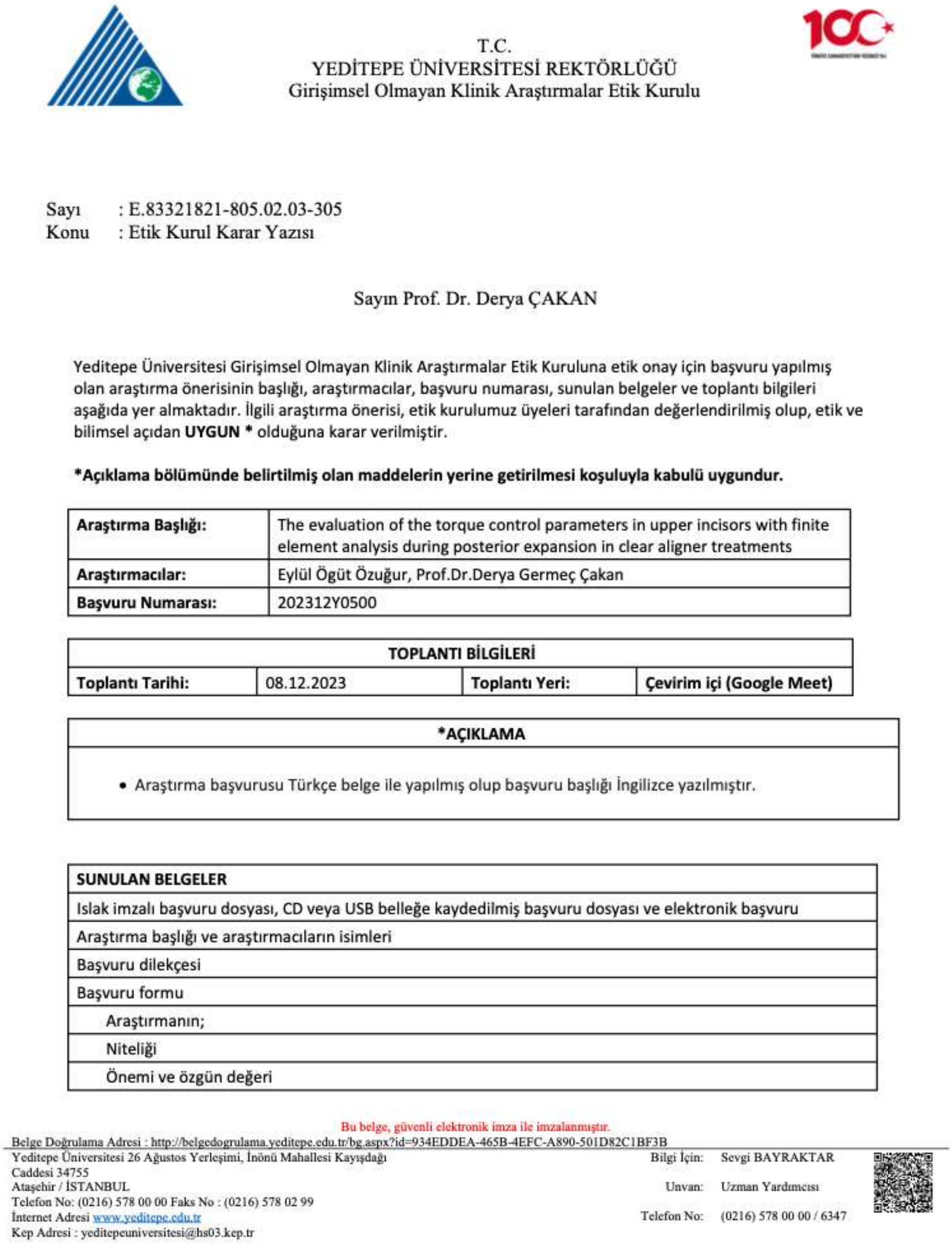
151. Cheng Y, Liu X, Chen X, et al. The three-dimensional displacement tendency of teeth depending on incisor torque compensation with clear aligners of different thicknesses in cases of extraction: a finite element study. *BMC Oral Health*. 2022;22(1):499. doi:10.1186/s12903-022-02521-7

152. Sandhya V, Arun A, Reddy VP, Mahendra S, Chandrashekar B, Aravind. Biomechanical Effects of Torquing on Upper Central Incisor with Thermoplastic Aligner: A Comparative Three-Dimensional Finite Element Study with and Without Auxillaries. *Journal of Indian Orthodontic Society*. 2022;56(1):49-56. doi:10.1177/0301574220974340

153. Jiang T, Jiang YN, Chu FT, Lu PJ, Tang GH. A cone-beam computed tomographic study evaluating the efficacy of incisor movement with clear aligners: Assessment of incisor pure tipping, controlled tipping, translation, and torque. Am J Orthod Dentofacial Orthop. 2021 May;159(5):635-643. doi: 10.1016/j.ajodo.2019.11.025. Epub 2021 Feb 12. PMID: 33583693.

8. APPENDICES

8.1. Ethical Committee Approval



T.C.
YEDİTEPE ÜNİVERSİTESİ REKTÖRLÜĞÜ
Girişimsel Olmayan Klinik Araştırmalar Etik Kurulu

Sayı : E.83321821-805.02.03-305
Konu : Etik Kurul Karar Yazısı

Sayın Prof. Dr. Derya ÇAKAN

Yeditepe Üniversitesi Girişimsel Olmayan Klinik Araştırmalar Etik Kuruluna etik onay için başvuru yapılmış olan araştırma önerisinin başlığı, araştırmacılar, başvuru numarası, sunulan belgeler ve toplantı bilgileri aşağıda yer almaktadır. İlgili araştırma önerisi, etik kurulumuz üyeleri tarafından değerlendirilmiş olup, etik ve bilimsel açıdan **UYGUN *** olduğuna karar verilmiştir.

***Açıklama bölümünde belirtilmiş olan maddelerin yerine getirilmesi koşuluyla kabulü uygundur.**

Araştırma Başlığı:	The evaluation of the torque control parameters in upper incisors with finite element analysis during posterior expansion in clear aligner treatments
Araştırmacılar:	Eylül Ögüt Özuğur, Prof.Dr.Derya Germeç Çakan
Başvuru Numarası:	202312Y0500

TOPLANTI BİLGİLERİ			
Toplantı Tarihi:	08.12.2023	**Toplantı Yeri:**	**Çevirim içi (Google Meet)**

***AÇIKLAMA**

- Araştırma başvurusu Türkçe belge ile yapılmış olup başvuru başlığı İngilizce yazılmıştır.

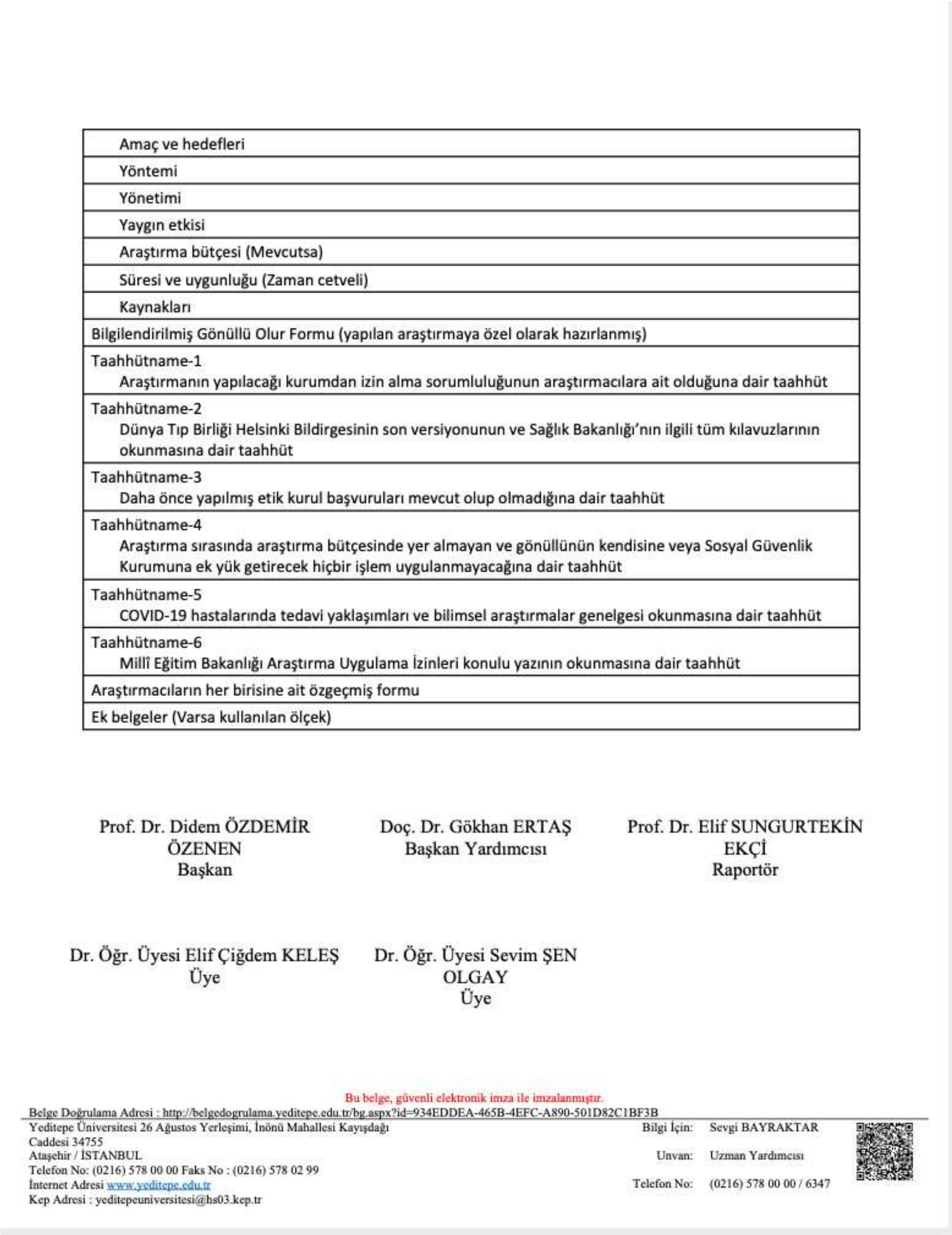
SUNULAN BELGELER
Islak imzalı başvuru dosyası, CD veya USB belleğe kaydedilmiş başvuru dosyası ve elektronik başvuru
Araştırma başlığı ve araştırmacıların isimleri
Başvuru dilekçesi
Başvuru formu
Araştırmanın;
Niteliği
Önemi ve özgün değeri

Bu belge, güvenli elektronik imza ile imzalanmıştır.

Belge Doğrulama Adresi : http://belgedogrulama.yeditepe.edu.tr/bg.aspx?id=934EDDEA-465B-4EFC-A890-501D82C1BF3B

Yeditepe Üniversitesi 26 Ağustos Yerleşimi, İnönü Mahallesi Kayışdağı
Caddesi 34755
Ataşehir / İSTANBUL
Telefon No: (0216) 578 00 00 Faks No : (0216) 578 02 99
İnternet Adresi www.yeditepe.edu.tr
Kep Adresi : yeditepeuniversitesi@hs03.kep.tr

Bilgi İçin: Sevgi BAYRAKTAR
Unvan: Uzman Yardımcısı
Telefon No: (0216) 578 00 00 / 6347



Amaç ve hedefleri
Yöntemi
Yönetimi
Yaygın etkisi
Araştırma bütçesi (Mevcutsa)
Süresi ve uygunluğu (Zaman cetveli)
Kaynakları
Bilgilendirilmiş Gönüllü Olur Formu (yapılan araştırmaya özel olarak hazırlanmış)
Taahhütname-1 Araştırmanın yapılacağı kurumdan izin alma sorumluluğunun araştırmacılara ait olduğuna dair taahhüt
Taahhütname-2 Dünya Tıp Birliği Helsinki Bildirgesinin son versiyonunun ve Sağlık Bakanlığı'nın ilgili tüm kılavuzlarının okunmasına dair taahhüt
Taahhütname-3 Daha önce yapılmış etik kurul başvuruları mevcut olup olmadığına dair taahhüt
Taahhütname-4 Araştırma sırasında araştırma bütçesinde yer almayan ve gönüllünün kendisine veya Sosyal Güvenlik Kurumuna ek yük getirecek hiçbir işlem uygulanmayacağına dair taahhüt
Taahhütname-5 COVID-19 hastalarında tedavi yaklaşımları ve bilimsel araştırmalar genelgesi okunmasına dair taahhüt
Taahhütname-6 Millî Eğitim Bakanlığı Araştırma Uygulama İzinleri konulu yazının okunmasına dair taahhüt
Araştırmacıların her birisine ait özgeçmiş formu
Ek belgeler (Varsa kullanılan ölçek)

Prof. Dr. Didem ÖZDEMİR ÖZENEN
Başkan

Doç. Dr. Gökhan ERTAŞ
Başkan Yardımcısı

Prof. Dr. Elif SUNGURTEKİN EKÇİ
Raportör

Dr. Öğr. Üyesi Elif Çiğdem KELEŞ
Üye

Dr. Öğr. Üyesi Sevim ŞEN OLGAY
Üye

Bu belge, güvenli elektronik imza ile imzalanmıştır.

Belge Doğrulama Adresi : http://belgedogrulama.yeditepe.edu.tr/bg.aspx?id=934EDDEA-465B-4EFC-A890-501D82C1BF3B

Yeditepe Üniversitesi 26 Ağustos Yerleşimi, İnönü Mahallesi Kayışdağı
Caddesi 34755
Ataşehir / İSTANBUL
Telefon No: (0216) 578 00 00 Faks No : (0216) 578 02 99
İnternet Adresi www.yeditepe.edu.tr
Kep Adresi : yeditepeuniversitesi@hs03.kep.tr

Bilgi İçin: Sevgi BAYRAKTAR
Unvan: Uzman Yardımcısı
Telefon No: (0216) 578 00 00 / 6347

8.2. Curriculum Vitae

Kişisel Bilgiler

Adı	Eylül	**Soyadı**	Ögüt Özuğur

Öğrenim Durumu

Derece	**Alan**	**Mezun Olduğu Kurumun Adı**	**Mezuniyet Yılı**
Doktora	Ortodonti	**T.C. Yeditepe Üniversitesi**	2024
Lisans	Diş Hekimliği	**T.C. Yeditepe Üniversitesi**	2019
Lise		**Özel Bilfen Üsküdar Fen Lisesi**	2013

Bildiği Yabancı Dilleri	**Yabancı Dil Sınav Notu**
İngilizce	Yökdil: 85

İş Deneyimi (Sondan geçmişe doğru sıralayın)

Görevi	**Kurum**	**Süre (Yıl - Yıl)**
Diş Hekimi	Öğüt İstanbul Ağız ve Diş Sağlığı Polikliniği	2019-2024

Görev Aldığı Projeler/Sertifikaları/Ödülleri

Türk Ortodonti Derneği GençTOD Komisyonu Başkanlığı
Invisalign Sertifikası
Türk Aligner Derneği Kongre Organizasyon Komitesi Üyesi