EGAS MONIZ SCHOOL of HEALTH & SCIENCE | INSTITUTO UNIVERSITÁRIO EGAS MONIZ

INSTITUTO UNIVERSITÁRIO EGAS MONIZ

MESTRADO INTEGRADO EM MEDICINA DENTÁRIA

COMPARISON OF DENTAL MOVEMENT EFFECTIVENESS BETWEEN FIXED MULTI-BRACKET ORTHODONTIC APPLIANCES AND ALIGNERS

Trabalho submetido por
Elise Juliette Marie Delfeld
para a obtenção do grau de Mestre em Medicina Dentária

outubro de 2024

EGAS MONIZ SCHOOL of HEALTH & SCIENCE | INSTITUTO UNIVERSITÁRIO EGAS MONIZ

INSTITUTO UNIVERSITÁRIO EGAS MONIZ

MESTRADO INTEGRADO EM MEDICINA DENTÁRIA

COMPARISON OF DENTAL MOVEMENT EFFECTIVENESS BETWEEN FIXED MULTI-BRACKET ORTHODONTIC APPLIANCES AND ALIGNERS

Trabalho submetido por
Elise Juliette Marie Delfeld
para a obtenção do grau de **Mestre** em Medicina Dentária

Trabalho orientado por
Mestre François Durand Pereira

outubro de 2024

ACKNOWLEDGMENTS

Ce travail représente l'aboutissement de plusieurs années d'efforts, de doutes mais également de persévérance. Il marque un tournant dans ma vie, professionnelle et personnelle, qui n'aurait probablement jamais vu le jour sans le soutien de nombreuses personnes qui ont marqué mon parcours.

Je souhaite tout d'abord dire un grand merci à mon directeur de thèse, Mestre François Durand Pereira. Sa disponibilité, ses précieux conseils et son accompagnement ont été essentiel dans la réalisation de ce travail. Pour toutes ces heures passées à me soutenir et m'aider, merci encore.

Je tiens ensuite à remercier ma famille, qui m'a entouré d'un amour et soutien inconditionnels tout au long de ces années (et depuis bien longtemps). À mes chers parents Isabelle et Christophe, mes grands-parents Mamé et Pierre, Moumoune et Jean-Jacques ainsi que Poupoune. À ma grande sœur Camille et son mari Vince, que je considère comme mon grand-frère (et Loula). Je ne pourrais suffisamment vous remercier pour tout ce que vous avez fait pour moi.

Sans oublier mes amies de longue date, ma famille élargie, Ivane, Marie, Iris et Astrid (ma future consœur) qui, depuis notre enfance ou adolescence, sont restées à mes côtés malgré la distance.

Je tiens aussi à remercier mes incroyables rencontres de Lisbonne. À Eloïse, ma super binôme de clinique avec qui j'ai partagé tant de moments intenses, à Charlotte, Alice, Priscille et Nour, mes piliers durant ces 5 années.

À Alexandra et Alice, deux amies qui m'ont été d'un immense soutien et qui ont rendu ces années plus lumineuses.

À Lola, une précieuse amitié découverte lors de notre dernière année de colocation.

À toutes les autres personnes qui ont joué un rôle important durant ces années : Clara, Axel, Marie, Ema, Charlotte, Kohann… et tous les autres qui ont, de près ou de loin, contribué à rendre ce parcours unique.

Un dernier merci à Pierre, mon meilleur ami, mon partenaire, mon bibi. Ton soutien et ta patience ont été essentiels dans cette aventure. J'ai hâte de cette nouvelle étape que nous allons entamer à deux. Merci pour tout ce que tu fais pour moi, je t'aime.

À tous ceux qui ont fait partie de ce voyage, je vous remercie du fond du cœur.

RESUMO

A ortodontia desempenha um papel essencial no alinhamento dos dentes e na correção das más oclusões. Os objetivos específicos de uma oclusão funcional ideal podem variar dependendo das necessidades individuais do paciente e dos objetivos específicos do tratamento ortodôntico. Tradicionalmente, os aparelhos fixos com múltiplos *brackets* têm sido amplamente utilizados, mas os alinhadores surgiram como uma alternativa estética, especialmente para indivíduos preocupados com sua aparência.

Para o desenvolvimento desta revisão de literatura, bases de dados como PubMed/Medline, Scielo, Google Scholar, The Cochrane Library e Elsevier Embase, foram usadas para reunir artigos que atendam aos critérios essenciais para a conclusão desta tese.

Tanto os alinhadores quanto os aparelhos fixos com múltiplos *brackets* induzem movimentos dentários, dependendo de parâmetros do sistema de forças, como sua intensidade, duração e ponto de aplicação. Diferentes variáveis estão envolvidas na criação de um sistema de movimento dentário eficaz, controlado e previsível. No entanto, tanto os alinhadores quanto os *brackets* apresentam certas limitações mecânicas no tratamento de más oclusões. O tratamento com alinhadores, como o Invisalign®, foi menos eficaz do que os aparelhos tradicionais no tratamento de más oclusões, com base no sistema de avaliação objetiva do American Board of Orthodontics (OGS).

Esta tese tem como objetivo comparar a eficiência dos movimentos dentários entre aparelhos ortodônticos fixos com *brackets* e os alinhadores. Para isso exploraremos a teoria dos movimentos dentários em ortodontia, examinaremos os aspetos biológicos, químicos e mecânicos envolvidos, bem como a biomecânica subjacente. A comparação entre os dois tipos de aparelhos destaca os seus componentes, o controle dos movimentos, as limitações e possibilidades associadas e as diferenças biomecânicas.

Palavras-chave: Orthodontics; Brackets; Aligners; Forces

ABSTRACT

Orthodontics plays an essential role in aligning teeth and correcting malocclusions. The specific goals of functional occlusion vary depending on the individual patient's needs and treatment objectives. Traditionally, fixed multi-bracket appliances have been widely used, but aligners emerged as an aesthetic alternative, especially for individuals concerned about their appearance.

For the development of this literature review, databases such as PubMed/Medline, Scielo, Google Scholar, The Cochrane Library, and Elsevier Embase were used with the aim of gathering articles that meet the essential criteria for the completion of this thesis.

Both aligners and fixed multi-bracket appliances induce dental movements depending on force system parameters such as intensity, duration, and point of application. Several variables are involved in creating an effective, controlled, and predictable dental movement system. However, both orthodontic aligners and fixed brackets have certain mechanical limitations in treating malocclusions. Treatment with aligners, such as Invisalign® were less effective than traditional braces in treating malocclusions, based on the American Board of Orthodontics objective grading system (OGS) scores.

This thesis aims to compare the efficiency of dental movements between fixed multi-bracket appliances and aligners. To achieve this goal, we will explore the theory of dental movements in orthodontics, examine the biological, chemical, and mechanical aspects involved, as well as the underlying biomechanics. The comparison between the two types of appliances highlights their components, their control over movements, associated limitations and possibilities, and biomechanical differences.

Keywords: Orthodontics; Brackets; Aligners; Forces

RESUME

L'orthodontie joue un rôle essentiel dans l'alignement des dents et la correction des malocclusions. Les objectifs spécifiques d'une occlusion fonctionnelle idéale peuvent varier en fonction des besoins individuels du patient et des objectifs spécifiques du traitement orthodontique. Traditionnellement, les appareils fixes multi-bagues ont été largement utilisés, mais les aligneurs ont émergé comme une alternative esthétique, en particulier pour les personnes soucieuses de leur apparence.

Pour le développement de cette revue de littérature, des bases de données telles que PubMed/Medline, Scielo, Google Scholar, The Cochrane Library et Elsevier Embase ont été utilisées afin de réunir des articles répondant aux critères essentiels pour la réalisation de cette thèse.

Les aligneurs et les appareils fixes multi-bagues induisent des mouvements dentaires en fonction de paramètres du système de force tels que leur intensité, leur durée et leur point d'application. Plusieurs variables sont impliquées dans la création d'un système de mouvement dentaire efficace, contrôlé et prévisible. Cependant, les aligneurs orthodontiques et les bagues fixes présentent certaines limites mécaniques dans le traitement des malocclusions. Les traitements avec aligneurs, tels que Invisalign, sont moins efficaces que les appareils traditionnels pour traiter les malocclusions, selon les scores du système de notation objectif du American Board of Orthodontics (OGS).

Cette thèse vise à comparer l'efficacité des mouvements dentaires entre les appareils orthodontiques fixes multi-bagues et les aligneurs. Pour atteindre cet objectif, nous explorerons la théorie des mouvements dentaires en orthodontie, examinerons les aspects biologiques, chimiques et mécaniques impliqués, ainsi que la biomécanique sous-jacente. La comparaison entre les deux types d'appareils met en lumière leurs composants, leur contrôle des mouvements dentaires, les limitations et possibilités associées, et les différences biomécaniques.

Mots-clés : Orthodontics; Brackets; Aligners; Forces

INDEX

FIGURES INDEX

TABLES INDEX

LIST OF ABBREVIATIONS

AI – Artificial Intelligence

BMP – Bone Morphogenetic Protein

CF – Circular Fibers

ERR – External Root Resorption

FDG – Dento-gingival Fibers

FDP – Dentoperiosteal Fibers

FGF23 – Fibroblast Growth Factor

M-CSF – Macrophage Colony Stimulating Factor

NiTi – Nickel-titanium

OPG - Osteoprotegerin

PDL – Periodontal Ligament

RANK – Receptor Activator of Nuclear Factor Kappa B

RANKL – Receptor Activator of Nuclear Factor Kappa B Ligand

SMD – Standardized Mean Difference

TADs – Temporary mini screws Anchors

TF – Transeptal Fibers

TGF-b1 – Transforming Growth Factor

TMA – Titanium Molybdenum Alloy or Beta-titanium

VEGF – Vascular Endothelial Growth Factor

3D – Three dimensional

I. INTRODUCTION

1.1. Background and justification

1.1.1. Introduction to Orthodontics and the Importance of Tooth Movement

Orthodontics is a specialty of dentistry that focuses on the diagnosis, prevention, interception, and correction of dental malocclusions and abnormalities of facial structures. It aims to align teeth and harmonize dentofacial relationships to improve chewing function, facial aesthetics, and overall oral health (Proffit et al., 2018). The practice of orthodontics relies on the application of controlled forces to move the teeth through the alveolar bone towards desired positions. This process is made possible by the remodeling of periodontal tissues, which allows the alveolar bone to adapt to the new dental positions (Krishnan & Davidovitch, 2009).

Orthodontic treatments can be performed using a variety of devices, including fixed multi-bracket appliances and clear aligners. Each of these devices applies mechanical forces specific to the teeth, influencing supporting structures such as the periodontal ligament and alveolar bone, to induce progressive and predictable tooth movements. These movements are essential not only for aesthetics, but also for the correction of functional abnormalities that could compromise oral health in the long term (Proffit et al., 2018).

1.1.2. Reasons for the interest in the comparison between conventional appliances and aligners

The introduction of clear aligners, such as the Invisalign system, has profoundly changed orthodontic practice by offering an aesthetically pleasing and removable alternative to traditional fixed appliances. This innovation has led to a growing interest in comparing the effectiveness of aligners versus fixed multi-bracket appliances, which have long been considered the standard in orthodontics (Proffit et al., 2018).

Fixed multi-bracket appliances, consisting of brackets bonded to the teeth and connected by metal wires, provide precise control of tooth movement through the

continuous and adjusted application of orthodontic forces. These devices are particularly effective in treating complex cases, such as severe malocclusions, marked tooth rotations, and complex vertical movements such as intrusion or extrusion of teeth. Their effectiveness is well documented in the literature (Proffit et al., 2018).

Conversely, clear aligners have distinct advantages, especially in terms of aesthetics and comfort for the patient. Made from transparent plastic materials, they make the treatment virtually invisible, which is especially appreciated by appearance-conscious adults and teenagers. In addition, their removable nature allows patients to maintain optimal oral hygiene, reducing the risk of cavities and periodontal disease during treatment (Tai, 2018).

However, despite these advantages, aligners show some limitations, especially in the management of complex tooth movements. Research has indicated that aligners perform less well for certain types of movement, such as tooth rotation or large vertical movements, due to a more diffuse and less constant application of forces than fixed appliances (Papadimitriou et al., 2018).

1.2. Objectives of the review

The main objective of this review is to evaluate and compare the effectiveness of dental movements performed using fixed multi-bracket appliances compared to transparent aligners. By reviewing the current scientific literature, this review aims to identify the advantages and limitations of each method, in order to provide practical recommendations for clinicians and perspectives for future research.
For this literature review, the databases PubMed/Medline, Scielo, Google Scholar, The Cochrane Library, and Elsevier Embase were explored to gather articles meeting the essential criteria for this thesis. The keywords used to guide the research include orthodontics, brackets, aligners, and forces.

1.3. Structure of the document

This document is structured in several chapters, each addressing a key aspect of the comparison between fixed multi-bracket appliances and clear aligners. Section 2.1

explores the theory of dental movements, focusing on the biological, chemical and mechanical aspects. Section 2.2 presents a detailed analysis of orthodontic appliances, while section 2.3 focuses on the comparative evaluation and clinical implications of the two approaches. Finally, the conclusion synthesizes the main findings, discusses the implications for clinical practice, and proposes directions for future research.

II. DEVELOPMENT

2.1. Theory of dental movements in orthodontics

2.1.1. Dental support tissues

Dental support tissues consist of several elements that contribute to the stability and proper functioning of the teeth. These tissues include the gingiva, periodontal ligament, cementum, and alveolar bone, each of which plays a distinct but complementary role in the overall health and movement of the teeth (Proffit et al., 2018).

Macroscopically, the gingiva is divided into free gingiva and adherent gingiva. For a fully erupted tooth, the edge of the free gingiva is normally between 1.5 and 2mm above the junction between the enamel and the cementum.

The adherent gingiva is separated from the mucosa by the mucogingival line and is strongly adhered to the cementum by collagen fibers, mainly the following four:

- Circular fibers (FC)
- Dento-gingival fibers (FDG): from free gingiva to cementum
- Dentoperiosteal fibers (FDP): from attached gingiva to cementum
- Transeptal fibers (FT): connect the cementum between adjacent teeth

(Lindhe & P. Lang, 2015)

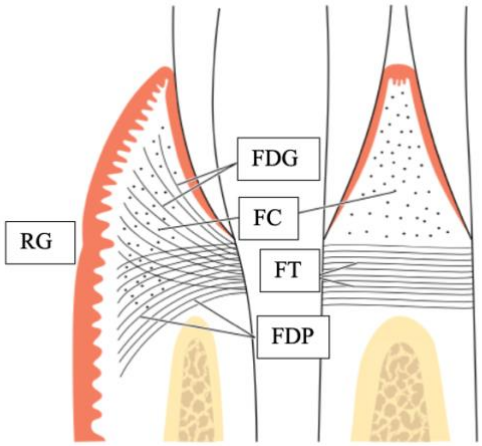


Figure 1: Organization of collagen fiber bundles in the gingiva in a buccolingual (left) and mesiodistal (right) section. FC, circular fibers; FDG, dentogingival fibers; FDP, dentoperiosteal fibers; RG, gingival sulcus; FT, transeptal fibers - Adapted from (Lindhe & P. Lang, 2015).

The periodontal ligament also contains fibers and is usually between 0.2 and 0.6mm thick. It provides the link between the tooth, specifically the cementum, and the alveolar bone. Under conditions of healthy periodontium, the periodontal ligament envelops the entire tooth root to a width of around 0.5mm (Li et al., 2018).
This bond is provided by collagen fibers:

- Fibers between the alveolus and the ridge
- Horizontal fibers
- Oblique fibers
- Apical fibers
- Inter-root fibers

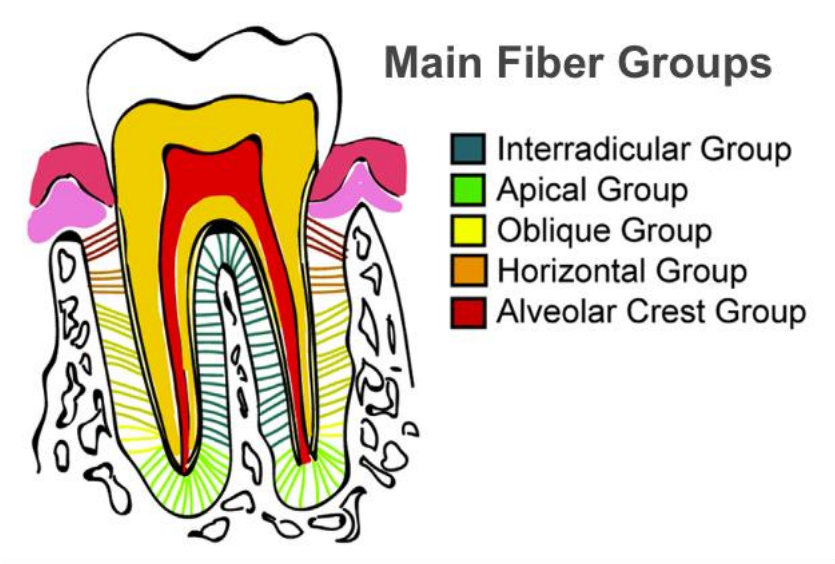


Figure 2: Components of the periodontium. The different types of main fiber groups are represented by different colors. Red for pulp, yellow for dentin, white crown for enamel, pink for gingiva, and black outline for alveolar bone - Adapted from (Li and al. 2018).

Although collagen fibers make up a large part of the periodontal ligament, forming its attachment system, it is important to consider two other essential elements. Firstly, the cellular components, which include a variety of mesenchymal cells as well as vascular and nervous components; and secondly, the interstitial fluids. These aspects are crucial to the normal function of the ligament and its ability to facilitate orthodontic tooth movement (Proffit et al., 2018).

Cementum is a mineralized tissue that covers the outside of tooth roots and sometimes even the crown or the inside of the root canal. Unlike bone, it has no nerves, blood vessels or lymphatic vessels. Despite this, cementum continually remodels itself throughout life. It is made up of collagen fibers and contains around 65% minerals, mainly hydroxyapatite (Lang et al., 2021).

During orthodontic treatment, cementum acts as a bridge. It transmits the pressure of the orthodontic appliance to the periodontal ligament and alveolar bone (Asiry, 2018).

Finally, the alveolar bone, a part of the jawbone (maxilla and mandible), plays an essential role in supporting the teeth. This bone structure develops in parallel with tooth eruption and is subject to continuous remodeling. When teeth are lost, the alveolar bone undergoes gradual resorption to adapt to the changing oral environment (Nanci & Bosshardt, 2006).

Anatomically, the alveolar bone is made up of two distinct types of bone:

- Cortical bone: this dense, compact bone forms the outer walls of the process and the alveoli themselves, also known as clean alveolar bone.
- Cancellous or trabecular bone: this type of bone fills the inner area of the process, providing support while remaining lighter (Nanci & Bosshardt, 2006).

The thickness of alveolar bone varies considerably from one individual to another and between different regions of the oral cavity. This variation influences the way the bone reacts to external forces, particularly during orthodontic treatment.

- Molar regions: generally thicker bone on the buccal side than on the lingual side.
- Incisor and premolar regions: often have a thinner bone plate on the lingual side than on the buccal side.
- Mandibular anterior teeth: the buccal surface may have very thin or no bone coverage (Li et al., 2018).

Thinner alveolar bone is more likely to be damaged by orthodontic forces, increasing the risk of complications such as fenestration or dehiscence. Understanding these variations is crucial to planning and implementing safe and effective orthodontic treatment (Lang et al., 2021).

2.1.2. Biology of dental movements

Orthodontic tooth movement is a complex inflammatory process involving a series of alterations and interactions between cells and tissues, as well as mechanical forces and their magnitude, direction and duration (Proffit et al., 2018). This section looks at the biological mechanisms that give rise to this phenomenon.

2.1.2.1. Bone turnover mechanism (bone remodeling)

Bone remodeling is an essential dynamic mechanism essential to orthodontic tooth movement. Bone remodeling is a joint process of resorption (osteoclastic activity) and apposition (osteoblastic activity) (Feller et al., 2015). It is essentially a replacement of resorbed bone with new bone (Ren et al., 2003).

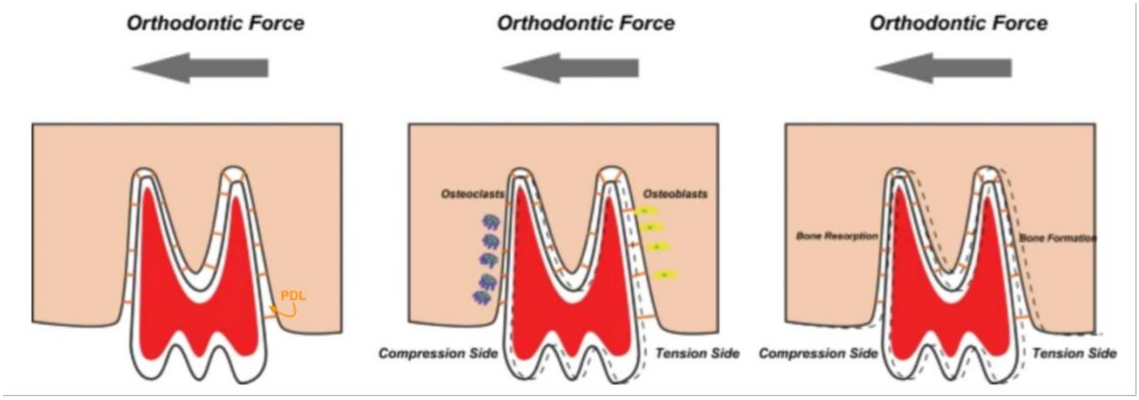


Figure 3: Applying orthodontic force to the tooth compresses the periodontal ligament (PDL). On the side where the tooth is compressed, which is in the direction of the orthodontic force, bone resorption occurs, mainly by osteoclasts. On the tension side, osteoblasts are responsible for the bone formation process – Adapted from (Disha et al., 2020).

2.1.2.2. Biological control of tooth movement

The pressure and tension forces generated by orthodontic appliances induce cellular and tissue changes, incorporating both mechanical and biological responses (Proffit et al., 2018). The previous section helps us to understand the basic process of tooth movement, but *how does orthodontic movement actually occur?*

Three theories apply: the pressure-tension theory, the bone flexion theory and the biological electricity theory.

a. Pressure-tension theory

The pressure-tension theory, one of the oldest hypotheses, has its origins in the fact that the force applied to the tooth causes compression of the periodontal ligament on the side facing the direction of movement and stretching on the opposite side. This explains the phenomenon of bone resorption due to pressure and bone apposition caused by tension (Cattaneo et al., 2009).

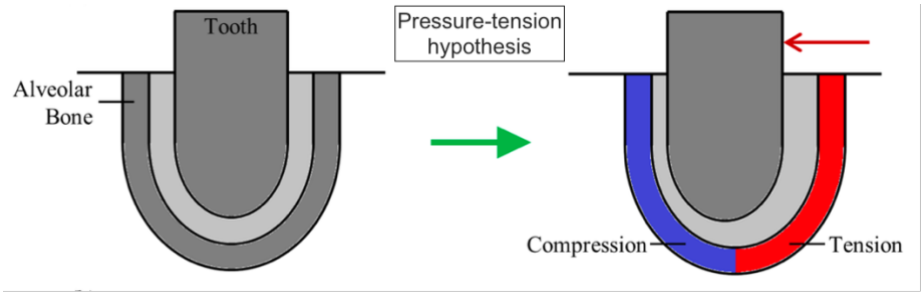


Figure 4: Simplified two-dimensional representation of a tooth-PDL-bone complex illustrating "pressure-tension hypothesis" showing tooth displacement leading to compression and tension in the surrounding bone – Adapted from (McCormack et al., 2014)

The mechanical impact on the cells of the periodontal ligament induces the release of cytokines, prostaglandins and other chemical messengers. In addition, the periodontal ligament undergoes a reduction in blood flow in compressed areas, while blood flow remains stable or increases in areas under tension (McCormack et al., 2014).

This perspective on dental relocation is broken down into three main phases:

1. The initial compression of the tissues is accompanied by changes in blood flow due to the pressure exerted on the periodontal ligament.
2. The development and/or emission of communicating chemical substances.
3. Stimulation of osteoclasts and osteoblasts, leading to restructuring of the alveolar bone.

(Proffit et al., 2018)

b. Bone flexion theory

Bone flexion theory proposes an understanding of orthodontic tooth movement that goes beyond the traditional pressure-tension hypothesis. According to Baumrind (1969), this theory suggests that the application of orthodontic forces not only deforms the periodontal ligament, but also causes the alveolar bone itself to flex. According to this hypothesis, the walls of the tooth socket behave like cantilevered beams: fixed at one end towards the apex of the tooth and free at the other towards the crown. When an orthodontic force is applied, it displaces the free end, causing the walls of the socket to bend slightly. This deformation means that the bone on the side towards which the tooth is pushed curves outwards, while the bone on the opposite side is pulled closer (McCormack et al., 2014).

Building on the seminal ideas proposed by Frost (1964) and further developed by Currey (1968), the alveolar bending hypothesis is supported by stress gradients within the bone. These gradients dictate the nature of bone adaptation: bone is added where stresses become more tense with depth from the surface, and conversely, bone is removed where stresses become less tense. This principle is crucial in explaining how bone remodeling around the tooth facilitates orthodontic tooth movement (McCormack et al., 2014).

In addition, Meikle (2006) discusses the role of bone flexion in orthodontic tooth movement, pointing out that bone deformation accompanies tooth movement. Early observations noted that the crown of a tooth could be moved significantly more than the average reduction in width of the PDL on the pressure side, suggesting that the bone deforms more readily than the PDL itself. This observation was crucial in revisiting the importance of bone flexion in tooth movement, a concept that had been neglected for decades.

c. The theory of biological electricity

The first to mention this theory were Bassett and Backer in 1962. The theory of biological electricity proposes an explanation of dental movement through changes in

bone metabolism, guided by electrical signals resulting from the flexion and compression of the alveolar bone.

Initially, the electrical signals considered to be responsible for dental movement were piezoelectric. They refer specifically to the immediate production of electrical charges in certain materials, including bone, when they are subjected to pressure or deformation. These signals are characterized by a rapid decrease and generate a signal of opposite polarity when the stress stops, emphasizing that maintaining the pressure does not generate additional currents (Proffit et al., 2018).

In contrast, biological electrical theory encompasses a broader spectrum of bone electrical responses to stress, including 'streaming' potentials generated by fluid movement in bone under stress, and is more concerned with the long-term effects of these electrical signals on bone remodeling and tooth movement (Proffit et al., 2018):

When the bone bends under the effect of a force, this provokes an ionic interaction generating electrical signals and a variation in temperature, identifiable by a small voltage called the "streaming potential". These signals, which are different from piezoelectricity, can be triggered by external electric fields that modify cellular activity. In addition, active bone emits a "bioelectric potential" that reflects negative variations proportional to its metabolic activity. The response of alveolar bone to orthodontic forces influences the periodontal ligament, with increased osteoclastic activity in negatively charged areas and enhanced osteoblastic activity in positively charged areas. (Asiry, 2018)

Figure 5: Schematic adaptation of biological electricity theory of dental movement – Adapted from (Asiry, 2018)

2.1.3. Biochemistry of dental movements

2.1.3.1. Signaling and chemical mediation

The orthodontic forces applied cause alterations to the extracellular matrix and cytoskeleton of the cells in the periodontal ligament and alveolar bone, mediating the bone remodeling that ultimately allows orthodontic movement of the teeth (Feller et al., 2015).

In the periodontal ligament and alveolar bone, mechanically induced tensile stresses upregulate the expression of osteogenic genes (which promote bone formation), while compressive stresses primarily mediate catabolic tissue changes (which promote bone resorption) (Feller et al., 2015).

2.1.3.2. Osteoclasts in bone resorption: RANKL, osteoprotegerin (OPG), M-CSF

Bone resorption is essential for orthodontic movement, with osteoclasts playing a key role. There are very few, if any, osteoclasts, so they need to be recruited and activated (Proffit et al., 2018).

The differentiation and activation of osteoclasts is regulated by signaling molecules, released mainly by osteoblasts, which are already present, and by stromal cells of the periodontal ligament such as fibroblasts. These signaling molecules include three key factors: Receptor Activator of Nuclear Factor Kappa B ligand (RANKL), Osteoprotegerin (OPG) and Macrophage Colony Stimulating Factor (M-CSF) (Proffit et al., 2018).

RANKL binds to its receptor RANK on osteoclast precursors in the ligament, promoting the differentiation of pre-osteoclasts into osteoclasts.

To counterbalance this, OPG acts as a 'decoy' receptor for RANKL, preventing osteoclast activation. In fact, it inhibits the binding of RANKL to RANK: by binding to and occupying RANKL, OPG prevents RANKL from binding to the osteoclast receptor, so differentiation no longer occurs (Roberts-Harry and Sandy, 2004).

M-CSF also acts under the receptor of pre-osteoclasts and induces differentiation.

The balance between RANKL and OPG is crucial for the control of bone resorption during tooth movement (Proffit et al., 2018).

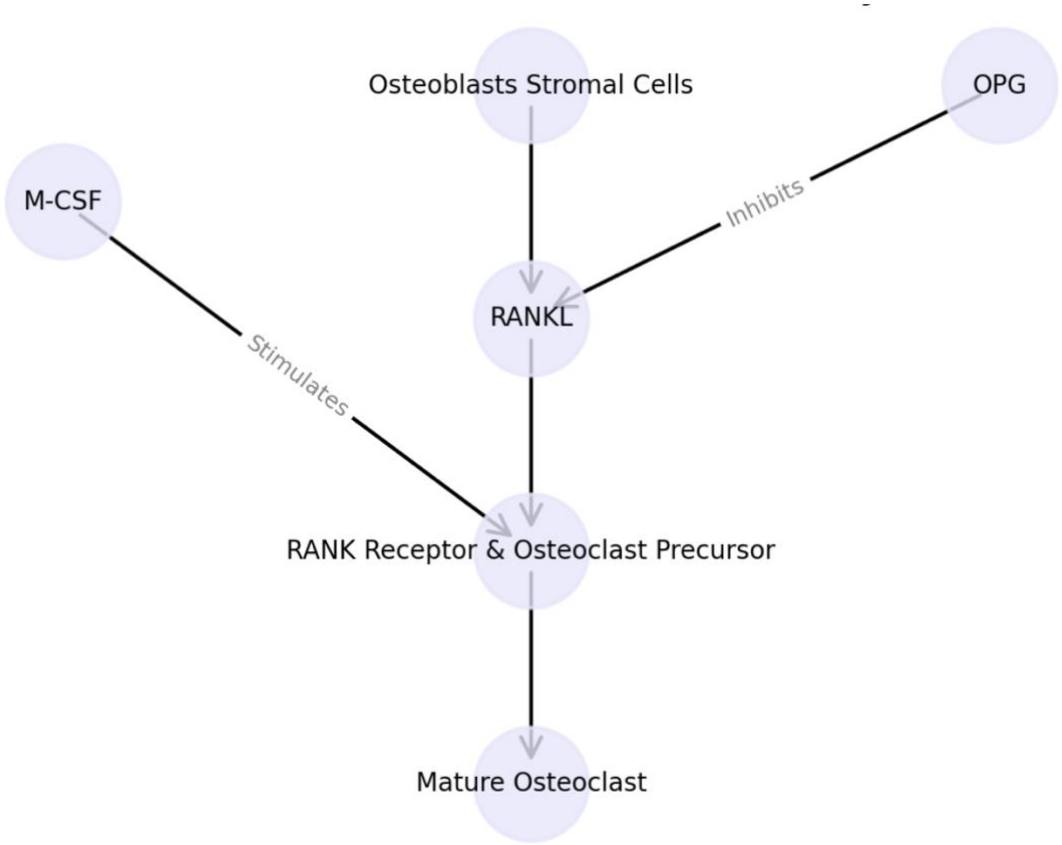


Figure 6: Interactions between the mediating factors RANKL, OPG and M-CSF during osteoclastic differentiation and activation.

2.1.3.3. Osteoblasts and bone apposition

Osteoblasts are responsible for the formation of new bone tissue, a vital process after bone resorption during tooth movement.

Osteoblast activity is stimulated by growth factors and cytokines released in response to mechanical stress, including Bone Morphogenetic Protein (BMP), Vascular Endothelial Growth Factor (VEGF), and Transforming Growth Factor (TGF-b1), promoting proliferation and differentiation of progenitor cells into osteoblasts (Krishnan and

Davidovitch, 2009). Subsequently, osteoblasts synthesize bone matrix and regulate its mineralization (Proffit et al., 2018).

2.1.3.4. Role of osteocytes

Osteocytes also play an important role: they are derived from osteoblasts in the final phase of differentiation, which lodge in the bone matrix during the processes of bone formation and mineralization.

Their distinctive feature is the presence of particularly well-developed dendrites. As they are encapsulated within the bone, these cells require a means of communication with the outside world, so they extend through the interstitial spaces of the bone matrix (Feller et al., 2015).

Under the effect of force, the bone deforms, and the interstitial fluid moves inside the bone. This stimulates the osteocytes, which can react in one of two ways:

- Osteocytes themselves stimulate the formation of RANKL and M-CSF
- Bone deformation can lead to apoptosis of osteocytes, which promotes the release of fibroblast growth factor (FGF23) and the SOST gene (which provides instructions for making the protein sclerostin).

Sclerostin is produced in osteocytes and its main function is to inhibit the function of osteoblasts, thereby inhibiting bone formation (Proffit et al., 2018).

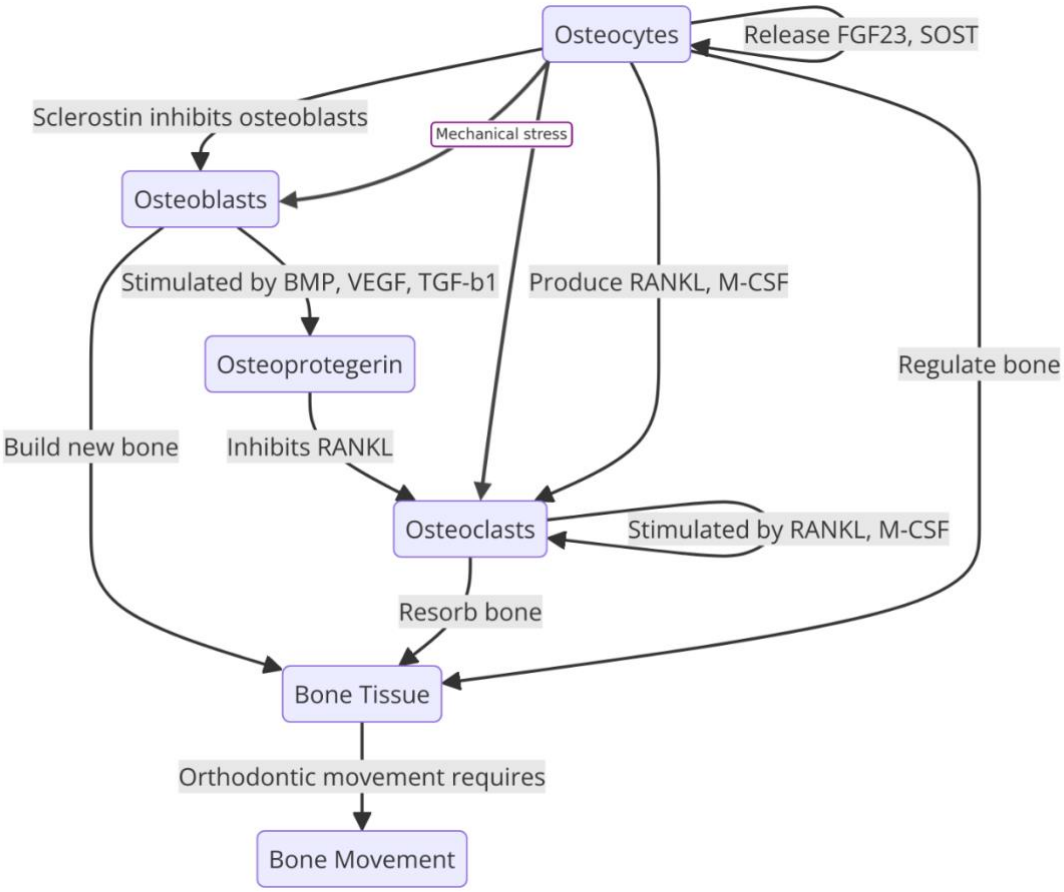


Figure 7: Summary diagram of cellular mechanisms of action

2.1.4. Biomechanics of dental movements

2.1.4.1. The force

A load exerted on an object that causes it to move to a new position is commonly referred to as a force. In physical terms, this force is measured in newtons, based on the formula *Force = Mass x Acceleration*, where mass is expressed in kilograms (kg) and acceleration in meters per second squared (m/s^2). This means that the unit of force is the newton, defined as a kilogram meter per second squared ($kg \cdot m/s^2$) (Proffit et al., 2018).

However, in orthodontic practice, it is common to express force in gram-force ($g \cdot f$), although this unit is not used in a strictly scientific context. This is due to the consideration that the impact of acceleration due to gravity (approximately 9.8 m/s^2 at sea level) on the magnitude of the force applied to the teeth is negligible in clinical practice. For example, for an object weighing 100 g, the force due to gravity would be

F = 0.1 kg x 9.8 m/s² = 0.98 N, or 98 centinewtons (cN). Thus, it is approximately considered that 1 g·f corresponds to 0.98 cN, and that 1.02 g·f equals 1 cN, a difference deemed clinically insignificant in orthodontics (Proffit et al., 2018).

According to Newton's Third Law of Motion, for every action, there is an equal and opposite reaction. This principle is fundamental in understanding how forces interact with objects, including teeth during orthodontic treatment. When a force is applied to a tooth, the periodontal ligament and surrounding bone exert a reactionary force in the opposite direction (Proffit et al., 2018).

A force is characterized by its vector, which includes:

1. Intensity, reflected by the length of the vector: a longer vector indicates greater force.
2. The direction, defined by its line of action, the orientation and the initial point of application of the force.

For a complete analysis of its potential impact in various planes, it is crucial to decompose the force. This decomposition makes it possible to dissociate a vector according to pre-established reference axes, but also to add two or more vectors, resulting in the resultant force which combines the horizontal and vertical components (Proffit et al., 2018).

Orthodontic force is the primary stimulus for tooth movement in orthodontic treatment, inducing complex biological responses in the periodontal ligament and alveolar bone. The required force to move a tooth is not uniform across all types of teeth; it depends significantly on the root surface area of the tooth being moved. For instance, a larger root surface area, such as that of molars, requires a greater force compared to teeth with smaller root surface areas, like incisors. This correlation between root surface area (measured in square millimeters, mm²) and the applied orthodontic force is crucial for effective treatment planning (Ren et al., 2003).

The minimal force necessary to initiate tooth movement is typically around 20 to 30 gram-force (g·f) per square millimeter of root surface area. For example, incisors, which have a smaller root surface area, require forces ranging from 20 to 60 g·f for movement,

while molars, with their larger root surface areas, need higher forces often between 100 and 200 g·f (Proffit et al., 2018). These forces must be carefully controlled to avoid adverse effects like root resorption, which is more likely to occur with excessive force. Additionally, lighter forces are generally preferred as they tend to result in more stable and biologically favorable tooth movements (Roscoe et al., 2015).

2.1.4.2. Center of mass and center of resistance

The center of mass is the point through which a force applied to a free body, i.e. without constraint, must pass for it to move linearly without rotation (translational movement). It is a body's point of equilibrium (Proffit et al., 2018).

Teeth are not free bodies: they are limited by the surrounding tissues and the periodontal ligament. The equivalent of a center of mass in a limited body, such as a tooth, is therefore the center of resistance (Proffit et al., 2018).

While the center of resistance is a critical point for understanding how forces affect tooth movement, its location is not fixed and can vary depending on several anatomical factors. The position of the center of resistance is influenced by the length and shape of the tooth root as well as the level of surrounding alveolar bone. For instance, a tooth with a longer or more complex root anatomy will typically have a center of resistance positioned further apically (Nanda, 2005).

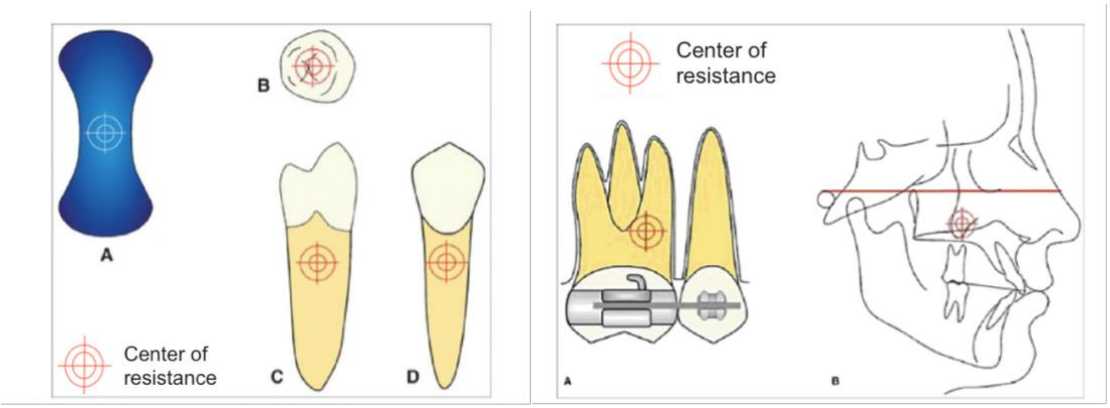


Figure 8 (left): Center of resistance. **A** Center of mass of a free body. **B** Frontal. **C** Occlusal. **D** Mesial views of the center of resistance of a single tooth – Adapted from (Nanda, 2005).

Figure 9 (right): Center of resistance for **A** two-tooth segment and **B** a maxilla – Adapted from (Nanda, 2005).

Similarly, changes in alveolar bone support, whether due to bone loss or other factors, can alter this position, necessitating adjustments in the application of orthodontic forces. This understanding is essential for precise treatment planning and effective force application in orthodontics (Nanda, 2005).

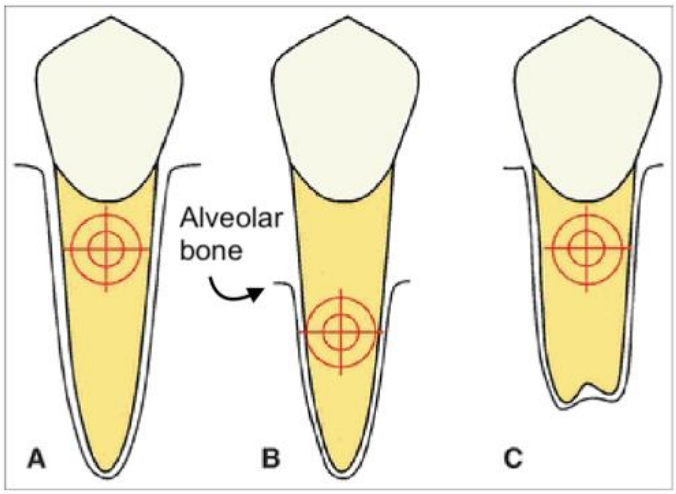


Figure 10: Location of the center of resistance depends on the alveolar bone height and root length. **A** Location of the center of resistance with alveolar bone loss and **B** with a shortened root – Adapted from (Nanda, 2005).

2.1.4.3. Center of rotation

The center of rotation describes the point around which the tooth rotates when it is subjected to a moment of force. It is the point around which the tooth moves when we apply the force away from the center of resistance (Proffit et al., 2018). This concept is fundamental to understanding tooth rotation mechanisms and planning orthodontic forces to minimize unwanted movement (Krishnan, 2024).

2.1.4.4. Force systems (moments, force torque)

The force can never be applied directly to the tooth's center of resistance, so it is applied to the crown, creating a moment of force.

This can be explained by the tendency of a force to produce a rotation of a body, when it is not applied through the center of resistance. This happens whenever a force outside the center of resistance is applied and, in this case, instead of pure translation, rotation also occurs (Proffit et al., 2018).

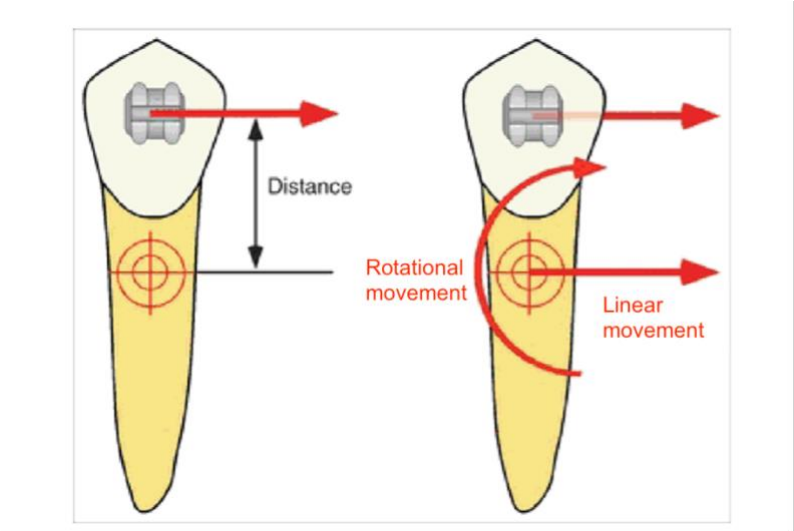


Figure 11: Moment of a force. A force that does not pass through the center of resistance produces a rotational movement as well as linear movement – Adapted from (Nanda, 2005).

The moment of force is determined by multiplying the intensity of the force by the distance between the perpendicular of the line of action (on the crown) and the center of resistance, in grams/millimeters. For example, if we have a force of 50 grams and the distance to the center of resistance is 10mm, this will give a moment of 500g per mm (Proffit et al., 2018).

A binary moment, or couple is when two parallel forces of equal intensity are applied, acting in opposite directions and separated by a certain distance. So, wherever the forces are applied, the tooth will rotate through the center of resistance regardless of the morphology of the tooth because it is constrained by the periodontal ligament and the point of application of the binary moment (Nanda, 2005).

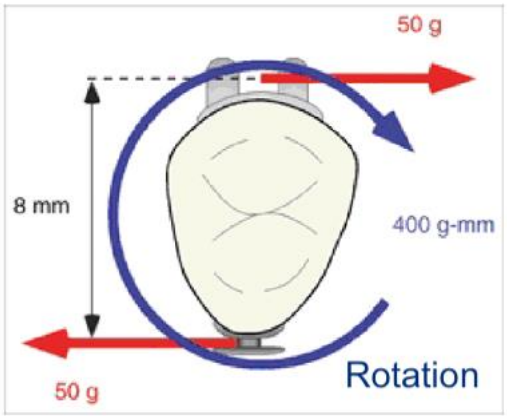


Figure 12: Moment of a couple. A couple produces pure rotation about the center of resistance – Adapted from (Nanda, 2005).

Force systems encompass force moments and torques, which are essential to control dental movement accurately. Simon et al (2014) demonstrated that transparent aligners generate force systems capable of inducing specific dental movements, including torsion, derotation and distalization, with significant variations influenced by the presence of attachments (see **2.2.2. Structural description of aligners**).

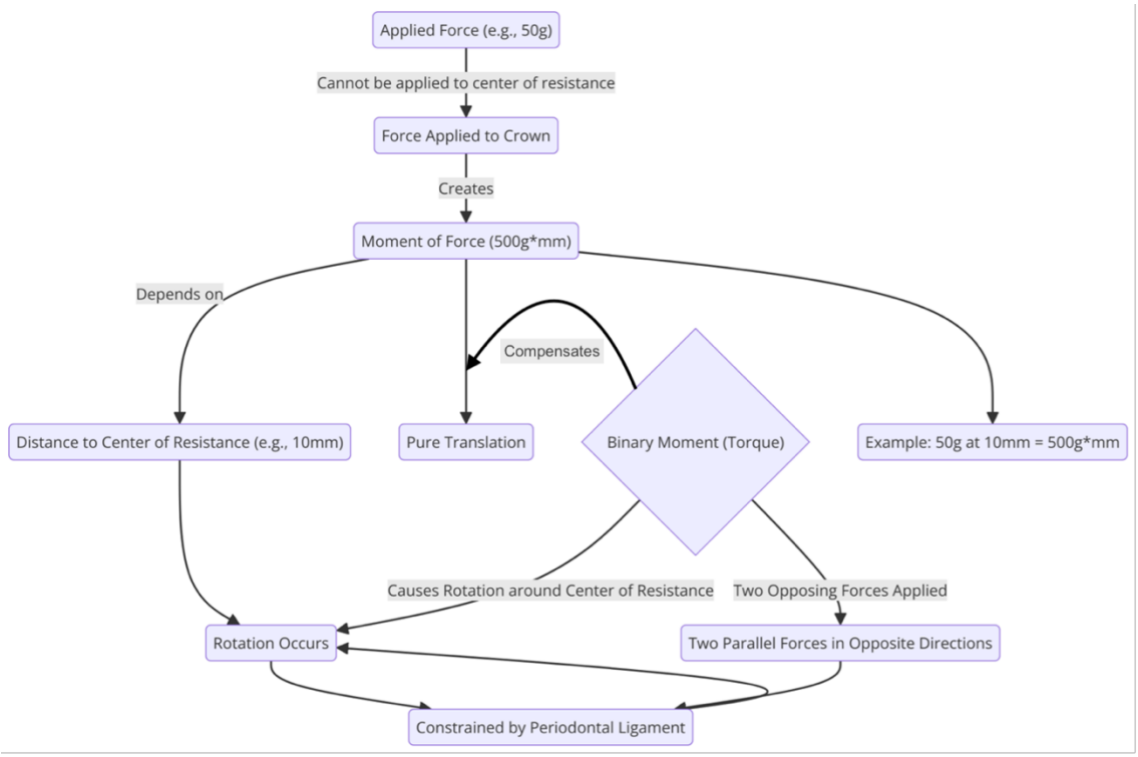


Figure 13: Summary diagram of interaction of forces and moments in orthodontics

2.1.4.5. Notion of anchoring *(and anchoring control)*

In the field of biomechanics, the notion of anchoring refers to the resistance offered by an element to movement. This concept is directly related to Newton's Third Law of Motion, which states that for every action, there is an equal and opposite reaction, as introduced earlier in section **2.1.4.1 The force**. So, when an element moves, it means that the driving forces have surpassed the forces of resistance (Langlade, 1978).

Orthodontic anchorage is a technique used to control teeth movement during orthodontic treatment. Effective management of anchorage is critical to the success of orthodontic treatment, particularly in cases involving large tooth movements or correction of skeletal imbalances.

Technological advances, such as temporary anchorage mini screws, have greatly improved the ability of orthodontists to control anchorage (Krishnan, 2024).

2.1.5. Orthodontic forces and movements

The type and magnitude of force to be used for different dental movements are not the same, making it essential to find the ideal force for each type of movement. There are six basic types of dental movement in orthodontics. A clear understanding of these movements in relation to the center of rotation is crucial for the precise application of forces (Proffit et al., 2018).

2.1.5.1. Tipping movement

The tipping movement, often performed by removable appliances, occurs when a single force is applied to a tooth, causing it to rotate around its center of resistance.
This movement results in two zones of compression, one near the apex and the other opposite, near the alveolar crest. To be optimal, the average ideal force is 35-60g (Proffit et al., 2018). Considering the center of rotation, this movement typically places the rotation point often near the apex, depending on the magnitude and direction of the applied force (Smith & Burstone, 1984).

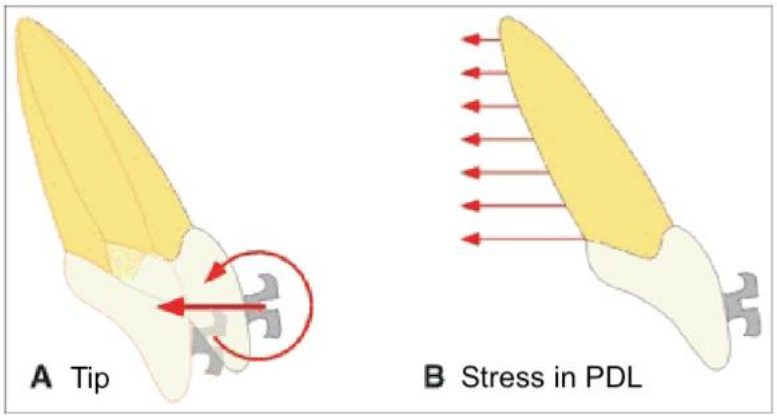


Figure 14: Schematic representation of the tipping movement. **A** Controlled tipping with the center of rotation at the root apex. **B** Stress pattern in the periodontal ligament with controlled tipping. The stresses are greatest at the cervical margin – Adapted from (Nanda, 2005)

In clinical practice, it is observed that when excessive force is applied during tipping movements, especially in teeth with complex root anatomy, there is a heightened risk of adverse outcomes. For instance, a higher-than-optimal force can lead to localized periodontal ligament damage, increasing the likelihood of root resorption, particularly near the apex where compression is most concentrated (Proffit et al., 2018).

2.1.5.2. Translational movement

Translational movement is characterized by the movement of the tooth as a whole unit, requiring the application of two simultaneous forces on the crown.
This movement uniformly engages the compression zone along the entire length of the root, with an ideal force of between 70 and 120g (Proffit et al., 2018). In this movement, the center of rotation is effectively at infinity, meaning all parts of the tooth move in parallel making it a purely translational movement (Yoshida et al., 2001).

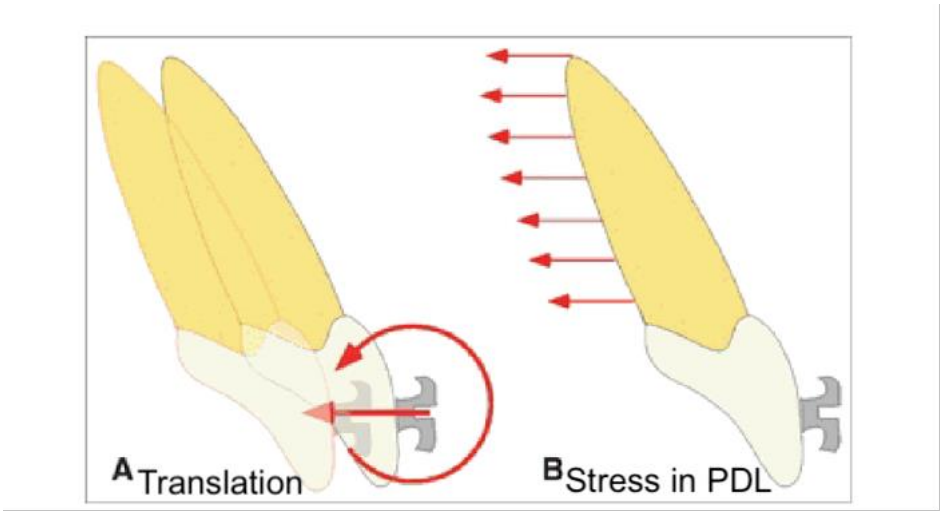


Figure 15: Schematic representation of translational movement. **A** Translational or bodily tooth movement. **B** Stress pattern in the periodontal ligament with translation. Uniform stresses occur throughout the periodontal ligament – Adapted from (Nanda, 2005)

Achieving pure translational movement requires a delicate balance of forces to ensure that the tooth moves as a single unit without unintended tipping or rotation. Inadequate control over the applied forces can result in a partial translation accompanied by unwanted rotational forces, leading to misalignment and potentially requiring corrective adjustments (Nanda, 2005).

2.1.5.3. Torque movement

Torque involves rotation of the root of the tooth with the axis (or center of rotation) located in the crown. This specific movement requires an optimal force of 50 to 100g and mainly affects the apex of the tooth (Proffit et al., 2018). In this context, the center of rotation is generally near the crown, and precise control of the applied force is crucial to prevent unwanted root movement (Naini & Gill, 2023).

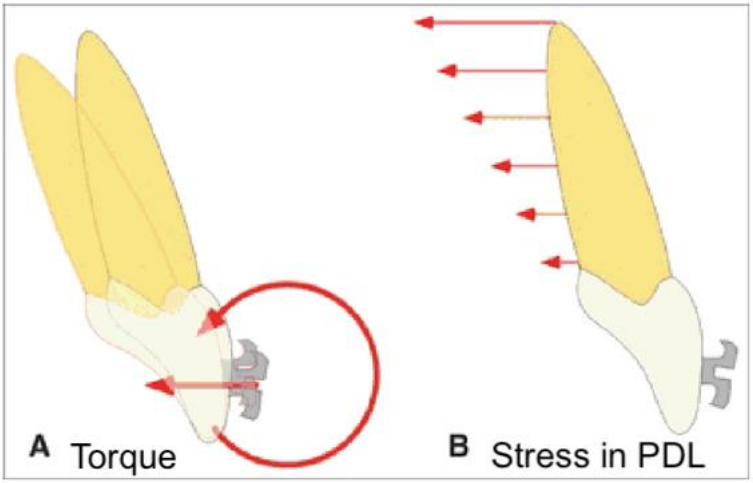


Figure 16: Schematic representation of torque movement. **A** Torque movement with the center of rotation at the incisal edge. **B** Stress pattern in the periodontal ligament with root movement. The stresses are greatest at the apex – Adapted from (Nanda, 2005)

Torque movements, which primarily affect the tooth's root, are particularly sensitive to the magnitude and direction of applied forces. If the force is too great or improperly directed, it can lead to root displacement or destabilization of the tooth's position post-treatment, compromising the longevity of the orthodontic results (Retrouvey, 2017).

2.1.5.4. Rotational movement

The rotation of a tooth around its major axis is theoretically uniformly distributed over the periodontal ligament, without creating specific areas of compression.
An ideal rotational force is between 35 and 60g (Proffit et al., 2018). Here, the center of rotation aligns with the tooth's long axis ensuring balanced forces on both sides of the tooth (Seidel et al., 2023).

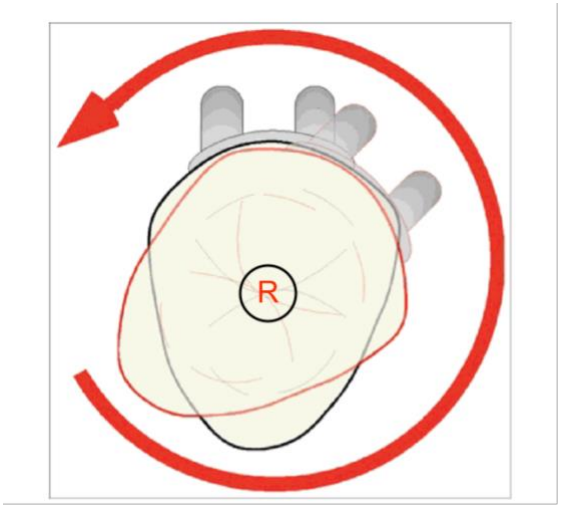


Figure 17: Schematic representation of rotational movement. Pure rotation occurs around a tooth's center of resistance. Center of rotation (R) – Adapted from (Nanda, 2005).

In rotational movements, accurately determining the center of rotation is crucial for ensuring that the tooth rotates around its intended axis without causing undue stress on the periodontal ligament. Customized orthodontic devices, such as brackets and wires, are often adjusted to apply forces that are finely tuned to achieve this precise movement while preserving periodontal health (Smith & Burstone, 1984).

2.1.5.5. Extrusion movement

Extrusion involves vertical movement of the tooth along its long axis in the coronal direction. Although theoretically this does not create compression zones, an ideal extrusion force is estimated to be between 35 and 60g (Proffit et al., 2018). Extrusion forces primarily affect the apex of the tooth and precise force management is essential to avoid creating excessive stress in the apical region, which could lead to undesired root movement or damage to the periodontal ligament.

The distribution of forces during extrusion must be balanced to ensure an efficient and controlled vertical displacement (Rudolph et al., 2001).

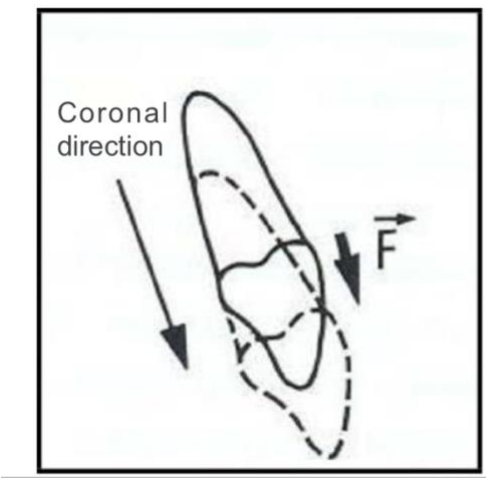


Figure 18: Schematic representation of extrusion movement – Adapted from (Langlade, 1978)

Extrusion is often employed in clinical scenarios such as the correction of infra-erupted teeth, particularly in cases of anterior open bite. However, care must be taken to apply controlled forces to avoid undesirable outcomes, such as the elongation of the clinical crown or the exposure of root surfaces, which can lead to aesthetic and functional issues (Proffit et al., 2018).

2.1.5.6. Intrusion movement

The intrusion movement, in an apical direction along the long axis of the tooth, is delicate because of the compression zone concentrated at the apex, the most sensitive area of the tooth. A light force of 10 to 20g is recommended to minimize the risks (Proffit et al., 2018). During intrusion, the center of rotation tends to be near the middle of the root, which requires careful application of forces to ensure that the tooth moves vertically without tipping or causing damage to the surrounding periodontal structures. This delicate movement requires constant monitoring of the force applied to avoid overloading the apical area (Geron et al., 2004).

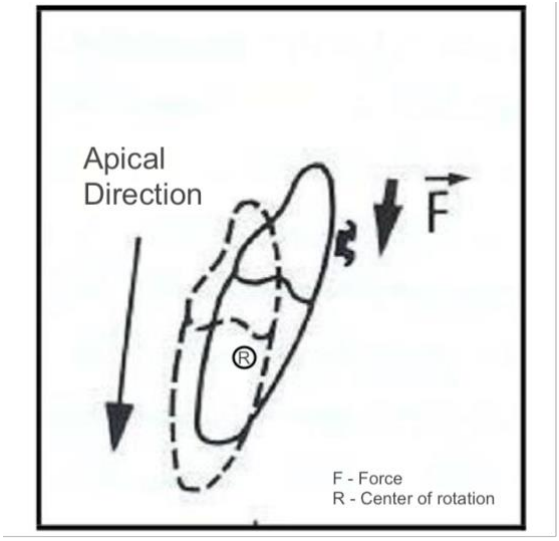


Figure 19: Schematic representation of the intrusion movement - Adapted from (Langlade, 1978)

Intrusion movements pose a significant challenge due to the concentrated force at the apex, the most vulnerable part of the tooth. Clinically, over-intrusion or application of excessive force can lead to apex damage or even loss of vitality of the tooth. Therefore, it is imperative to apply minimal forces that are precisely controlled to achieve the desired intrusion without compromising the tooth's health (Proffit et al., 2018).

In deep bite cases, intrusion is used to correct anterior tooth over-eruption. This movement requires caution, as excessive force can lead to root resorption or periodontal damage (Nanda, 2005). Light, continuous forces are recommended to balance effective intrusion and periodontal preservation. Intermittent forces from aligners may reduce risks, particularly in patients with periodontal issues (Simon et al., 2014). Regular radiographic monitoring is essential to ensure root health and proper force distribution during treatment (Geron et al., 2004).

Orthodontic movements require a thorough understanding of the forces applied and their biological effects on the teeth and surrounding tissues. Precision in the application of forces is crucial to minimize iatrogenic effects such as pulpal reaction, reaction under periodontal tissues, pain, tooth mobility, and especially orthodontic-related root resorption (Proffit et al., 2018).

2.1.6. Supporting Tissues Responses and Influence on Dental Movement Limits

a. Forces Applied to Teeth and Periodontal Tissue

The forces applied to the teeth and periodontal tissues during orthodontic treatment can be classified according to its intensity and duration: light, moderate, heavy and continuous or intermittent. Light forces are generally recommended because they minimize the risk of root resorption and damage to periodontal tissue (Cattaneo et al., 2009). Continuous forces, while more effective at moving teeth, can lead to chronic inflammation of periodontal tissue and bone resorption if left unchecked. Intermittent forces, applied periodically, allow tissues to recover between force applications, reducing stress on the periodontal ligament and alveolar bone (Bollen et al., 2008).

Orthodontic movement is an inflammatory response of the periodontal tissues. This response results in compression of the periodontal ligament on the side of the application of force and tension on the opposite side, which induces bone remodeling. However, this inflammation should not exceed a certain threshold to avoid the risk of root resorption and loss of bone support if orthodontic forces are not properly controlled (Cattaneo et al., 2009).

b. Responses and Influence of the Support Tissues to Stresses imposed by Orthodontic movement

Periodontal tissues have an intrinsic elasticity that enables them to adapt to the stresses imposed by orthodontic forces. This adaptive capacity is crucial to prevent irreversible damage such as the loss of periodontal support, external apical root resorption, and gingival recession. For instance, movements of the lower incisors, especially their proclination, are often associated with increased gingival recession, as evidenced by studies such as Boke et al. (2014). Despite this adaptability, complications can still arise when forces exceed physiological limits or oral hygiene is insufficient. These complications include loss of periodontal support and gingival recession, particularly when excessive forces are applied, or the patient exhibits inadequate oral hygiene. External apical resorption is another potential consequence, often seen when orthodontic forces are applied over an extended period (Crego-Ruiz & Jorba-García, 2023).

Orthodontic movements are fundamentally driven by an inflammatory response of the periodontal tissues. This response results in compression of the periodontal ligament on the side where the force is applied and tension on the opposite side, triggering bone remodeling. However, inflammation must be carefully controlled to avoid surpassing a critical threshold, as excessive inflammation increases the risk of root resorption and bone loss (Cattaneo et al., 2009).

The forces applied to periodontal tissues during orthodontic treatment place natural limits on dental movement to prevent permanent damage. The magnitude and duration of the force, along with the tissue's ability to adapt, set the boundaries for safe tooth movement. Optimal orthodontic planning must consider the tissue's capacity to reshape and remodel under controlled forces (Rekhi et al., 2020).

Furthermore, retainers play an essential role in preserving the position of teeth following orthodontic treatment. Littlewood et al. (2016) emphasize that retention is critical to prevent relapse. Fixed retention devices, such as bonded wires, offer continuous retention and help reduce tooth displacement but may introduce oral hygiene challenges. Conversely, removable retention aligners promote better oral hygiene but

require patient compliance for effectiveness. The choice of retention method should be tailored to the patient's needs and the specific characteristics of the previous orthodontic treatment.

While clear aligners tend to distribute forces more diffusely and reduce inflammation compared to fixed appliances, they are less effective for complex movements such as large rotations or vertical displacements. Fixed appliances allow for more concentrated and controlled force applications, making them more suitable for such movements (Jiang et al., 2018). Clear aligners also struggle with root movements that require precise force applications, further limiting their capability for certain tooth movements (Rossini et al., 2015).

On the other hand, fixed appliances, due to their constant contact with teeth and tissues, may induce more significant inflammation in the periodontal tissues. Managing this inflammation is essential to avoid complications like root resorption. Even though aligners are potentially less invasive, they must be carefully monitored to ensure that the forces they exert do not overload the periodontal tissues (Proffit et al., 2018).

2.2. Orthodontic Appliance analysis: Multi-Attachment Fixed Appliances vs Aligners

2.2.1. Structural description of multi-attachment fixed appliances

Fixed multi-bracket appliances are widely used in orthodontics to correct malocclusions. They consist of several elements that work together to move the teeth in a controlled manner. These components include brackets, archwires, ligatures, and adhesives, each of which plays a specific role in the movement of teeth (Proffit et al., 2018).

The movement of teeth during orthodontic treatment can be classified into three orders, each corresponding to a specific plane of movement (Proffit et al., 2018):

1. First order: This plane corresponds to the horizontal movement of the teeth in the vestibular or lingual direction. First-order wire bends or adjustments in this plane are intended to control movements in the horizontal plane, mainly influencing the vestibular or lingual positioning of the teeth (Proffit et al., 2018).
2. Second order: This plane controls the angulation of the tooth in the mesial-distal direction, i.e. the front-to-back tip of the crown or root of the tooth. The forces applied allow the teeth to be straightened or tipped along this vertical axis, which is crucial for adjusting the correct angulation of each tooth (Proffit et al., 2018). Second-order wire bends are often necessary to influence the angulation of the crown and ensure a good fit in the arch (Kapila & Sachdeva, 1989).
3. Third order: This plane is responsible for the control of the dental torque, i.e. the root angulation in the vestibulo-lingual or palatal direction. This movement is particularly important for the incisors, where precise control of the root axis is required for optimal alignment (Kapila & Sachdeva, 1989). Third-order wire bends aim to precisely adjust the torque of the teeth, thus ensuring a correct orientation of the root (Proffit et al., 2018).

In fixed orthodontics, wire bends are specific adjustments made to the wires to influence these three orders of movement. They help control tooth movements in all three dimensions of space, ensuring that each tooth reaches its ideal position (Proffit et

al., 2018). These adjustments are crucial to ensure complete correction of malocclusions while ensuring long-term stability of treatment (Kapila & Sachdeva, 1989).

For these movements to be achieved with precision, the choice of archwires is crucial. Depending on the type of movement to be generated (first, second, or third order), specific materials and calibers are selected. Each material has its own mechanical properties that influence the amount and nature of the forces applied to the teeth (Proffit et al., 2018).

Orthodontic wires, also known as archwires, are inserted into the brackets and exert the forces needed to move the teeth into the desired position. The materials, calibers and shapes of archwires vary depending on the treatment stage and the desired tooth movements (Proffit et al., 2018).

The following table summarizes the different types of orthodontic wires, highlighting their key properties and clinical applications at various stages of treatment:

Table 1: Different types of orthodontic wires used at various stages of treatment (Kapila & Sachdeva, 1989; Proffit et al., 2018)

Type of wire	**Main properties**	**Clinical use**
Nickel-titanium (NiTi)	- High elasticity - Shape-memory properties	- Initial phase of treatment - Provides light and continuous forces - Gentle tooth alignment without excessive stress on periodontal tissues
Stainless steel	- Very rigid - Applies stable and strong forces	- Later stages of treatment - Moves teeth with more precision - Torque control and final stability
Beta-titanium (TMA)	- Balance between flexibility and strength - Easy to bend manually	- Intermediate phase of treatment - Precise control of tooth movements without breaking the wire

The diameter of the archwire, or its caliber, also plays a significant role in how forces are transmitted to the teeth. In the early stages, round wires with smaller diameters, such as 0,016", are often used to apply light forces, which is necessary to avoid traumatizing the teeth and their supporting structures. These round wires are less effective in

controlling rotations or more complex movements but are well-suited for initial tooth alignment (Proffit et al., 2018).

As treatment progresses, rectangular or square wires with larger calibers, such as 0,019" x 0,025", are introduced. These wires are inserted into the brackets to transmit stronger forces and provide better control over root movements, especially for torque. By filling more of the bracket slot, rectangular wires allow for more precise control of tooth movement, which is crucial for achieving the desired final tooth positions (Kapila & Sachdeva, 1989).

Brackets are designed with standardized slots to hold the archwires, and two common slot sizes are 0,018" and 0,022". Brackets with 0,018" slots are typically used with smaller diameter wires during the early stages of treatment. The extra space between the wire and the slot allows for lighter forces, which are helpful during the early phases when gentle, progressive movement is required (Vieira et al., 2018). Brackets with 0,022" slots, on the other hand, accommodate larger wires, such as the 0,019" x 0,025" rectangular wires used in the later stages. These larger wires fill most of the slot, allowing for the transmission of greater forces and more precise control, particularly for torque movements, where the wire needs to engage closely with the bracket slot to guide the root of the tooth (Vieira et al., 2018).

This progression from flexible to stiffer wires, and from smaller to larger calibers, ensures that each stage of treatment applies the appropriate amount of force with the necessary level of control. This allows for smooth and effective tooth movement, from initial alignment to more complex adjustments in the later stages (Proffit et al., 2018).

Once the appropriate archwires are selected and adjusted, the brackets play a crucial role in transmitting the forces from the wires to the teeth. Brackets are attached directly to the teeth and act as anchor points for orthodontic wires, allowing the necessary forces to be transmitted. Each bracket is designed with a precisely cut slot, referred to as the 'prescription,' which is specifically angulated and inclined. This slot incorporates precise values for inclination, angulation, and rotation, allowing the brackets to transmit the forces exerted by the orthodontic wire, which deforms within the slot to gradually move the tooth toward the desired final position within the dental arch.

The "prescriptions" of these brackets can vary depending on the treatment philosophies of certain orthodontic systems. For instance, Andrews developed the Straight-Wire Appliance, which standardized angulation and torque built into the brackets, aiming to minimize the need for wire bending during treatment (Andrews, 1972). Roth later modified Andrews' system by incorporating more emphasis on functional occlusion and stability, adjusting angulation and torque values for better post-treatment outcomes (Roth, 1981). Alexander's system, meanwhile, is known for its customized approach, which tailors treatment based on patient-specific needs, utilizing growth guidance principles and low-force mechanics for efficient treatment (Alexander, 1986).

They can be made from different materials, each with its own characteristics (Proffit et al., 2018):

Metal brackets, typically made of stainless steel, are the most used because of their durability (good corrosion resistance) and ability to withstand high forces. However, their highly visible appearance has led to the development of more discreet alternatives. (Proffit et al., 2018).

Ceramic brackets are popular for aesthetic reasons because they are less visible than metal brackets. They are made from translucent or tinted ceramic materials to blend in with the natural color of the teeth, making them much less visible than metal brackets (Proffit et al., 2018). Although aesthetically advantageous, ceramic brackets have historically exhibited higher friction than metal brackets, which could slow down orthodontic treatment. Recent advances in design, such as low-friction coatings, have reduced this friction making these brackets more effective in orthodontic treatment without compromising aesthetics, but ceramic brackets remain more fragile than metal ones (Tageldin et al., 2016).

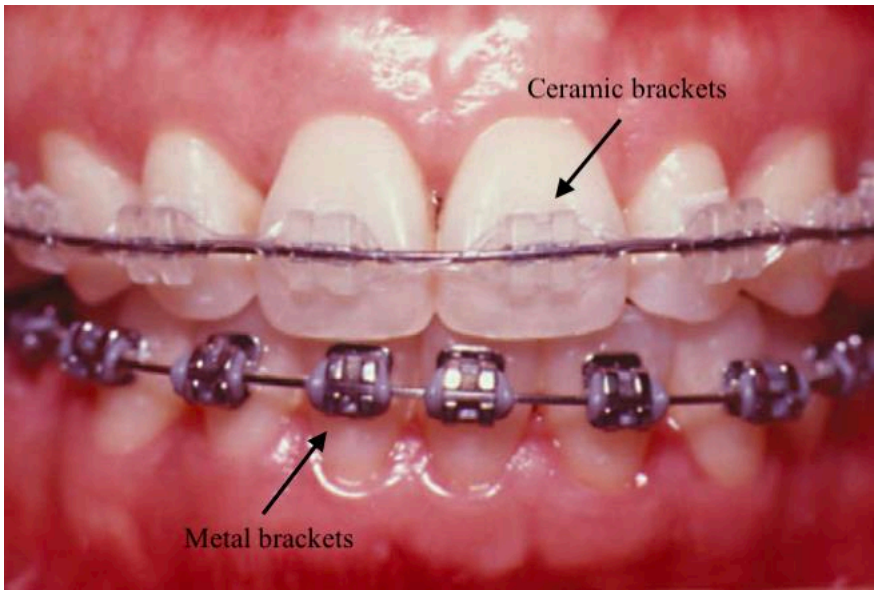


Figure 20: Photographic adaptation of ceramic and metal brackets (Proffit et al., 2018).

In addition to ceramic brackets, some patients opt for plastic brackets, mainly for aesthetic reasons. However, these brackets are less popular due to their lower strength and tendency to discolor over time (Proffit et al., 2018).

Patients looking for an even more discreet orthodontic option can opt for the lingual technique, where the brackets are placed on the inside of the teeth, making them invisible from the outside. However, while this approach perfectly addresses aesthetic concerns, it has several drawbacks. The lingual technique is more technically complex to perform, due to limited access and the need for greater precision in the placement of brackets. In addition, it is often more expensive than traditional treatments with vestibular brackets, due to the customization and specific adjustments required. Finally, some patients may experience initial discomfort, particularly in the tongue, due to the internal position of the brackets (Wiechmann, 2003).

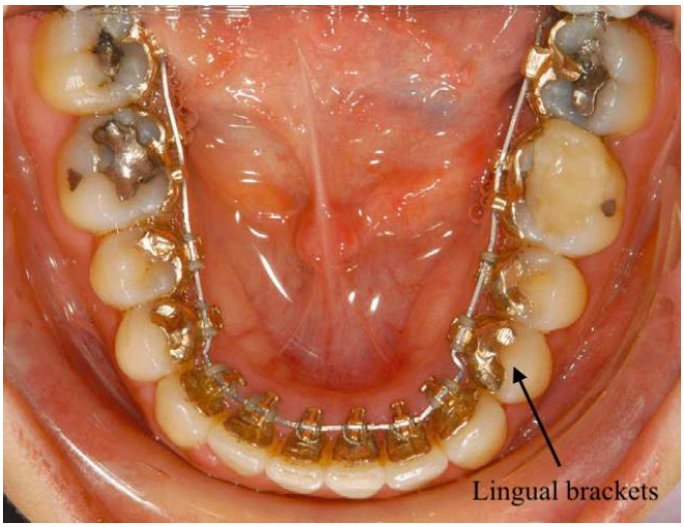


Figure 21: Photographic adaptation of lingual brackets (Proffit et al., 2018).

There are two types of brackets: conventional and self-ligating. Conventional ones use ligatures to attach the wires to the brackets while the self-ligators use a built-in mechanism to secure the wires without ligatures and potentially decreasing the processing time (Proffit et al., 2018).

In the case of conventional brackets, the use of ligatures (elastic or metallic) is essential to hold the wires in place and allow the transmission of orthodontic forces to the teeth. Elastic ligatures, made of rubber, are easy to apply and adjust, while metal ligatures, made from thin metal wires, provide a stiffer attachment and are less likely to warp (Proffit et al., 2018).

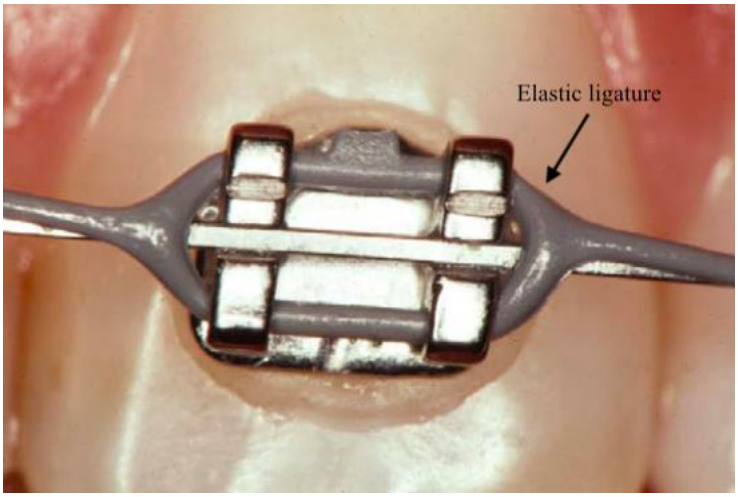


Figure 22: Photographic adaptation of elastic ligature around the bracket (Proffit et al., 2018).

As well as holding the wires in place using ligatures, the use of orthodontic adhesives is crucial to securely attach the brackets to the teeth throughout the treatment. Composite resin-based adhesives are widely used for their strength and ability to adhere firmly to tooth surfaces (Proffit et al., 2018). These adhesives are often light-cured, which allows for more precise placement of the brackets and ensures good adhesion throughout processing. Although glass ionomer adhesives can release fluoride to prevent cavities, they are less used due to their slightly lower adhesion compared to composite resins (Proffit et al., 2018).

Finally, auxillary devices such as intermaxillary elastics and orthodontic springs are often needed to correct more complex misalignments, such as Class II or Class III malocclusions. Intermaxillary elastics apply a constant force between the maxilla and the mandible, promoting movements such as the retraction of the anterior teeth or the protraction of the posterior teeth, depending on the occlusion to be corrected (Proffit et al., 2018).

Intermaxillary elastics are available in different sizes, thicknesses, and strengths, allowing orthodontists to customize the treatment to each patient's specific needs. They are usually attached to the hooks of brackets or brackets attached to the teeth (Proffit et al., 2018). These devices are effective but require good patient cooperation to be fully functional (Papageorgiou et al., 2020).

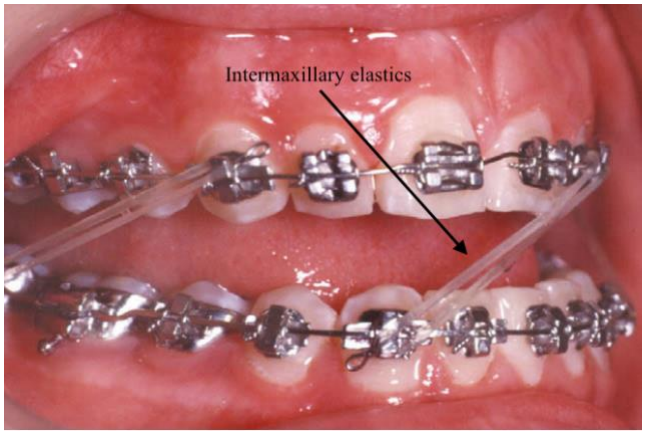


Figure 23: Photographic adaptation of intermaxillary elastics (Proffit et al., 2018).

In addition to intermaxillary elastics, orthodontic springs (such as compression springs and expansion springs) also play a crucial role in applying specific forces to align teeth. They are commonly used to close interdental spaces after extractions or to create space needed for the alignment of misaligned teeth.

- Compression springs: These springs are designed to exert a continuous force that gradually brings the teeth together. They are particularly useful in cases where it is necessary to close off spaces left by extractions. Their use must be carefully planned to avoid complications, such as root resorption, which can occur if the applied forces are excessive or misdirected.
- Expansion springs: Used to create space between teeth, these springs are essential in situations where teeth are blocked or congested. They are effective at aligning teeth smoothly, by applying force that gradually pulls adjacent teeth apart, allowing for proper alignment (Proffit et al., 2018).

However, although advances in orthodontics have led to the development of brackets made of more discreet materials and techniques such as lingual orthodontics, the growing demand for aesthetic and removable solutions has led to the rise of clear aligners, such as Invisalign aligners. These aligners, although aesthetic and comfortable, raise questions about their effectiveness compared to that of fixed multi-attachment appliances, especially for more complex cases (Papageorgiou et al., 2018).

2.2.2. Structural description of aligners

Aligners, also known as clear aligners, are an aesthetic alternative to fixed multi-bracket appliances to correct malocclusions. They are designed to be both discreet and comfortable while gradually aligning the teeth (Tai, 2018). The idea of using aligners to align teeth dates to Kesling in the 1940s, who proposed the first version of a transparent rubber "positioner" to adjust teeth. However, it was not until 1997, with the launch of Invisalign by Align Technology, that aligners became widespread worldwide (Papadimitriou et al., 2018).

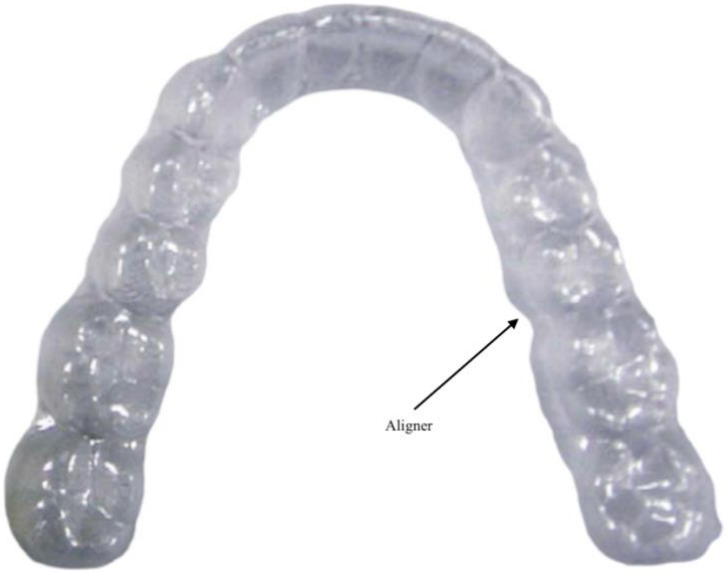


Figure 24: Photographic adaptation of an aligner (Proffit et al., 2018)

The Invisalign® system has introduced a major innovation with the development of ClinCheck, a 3D virtual planning software. With the ClinCheck, the orthodontist can visualize each step of the tooth movement even before starting treatment, allowing for extremely accurate planning (Tai, 2018). This software simulates the movement of each tooth from the beginning to the end of the treatment and allows adjustments to be customized to the patient's specific needs. Patients can thus see a preview of their treatment, which improves communication with the orthodontist and allows for better monitoring throughout the treatment (Papadimitriou et al., 2018).

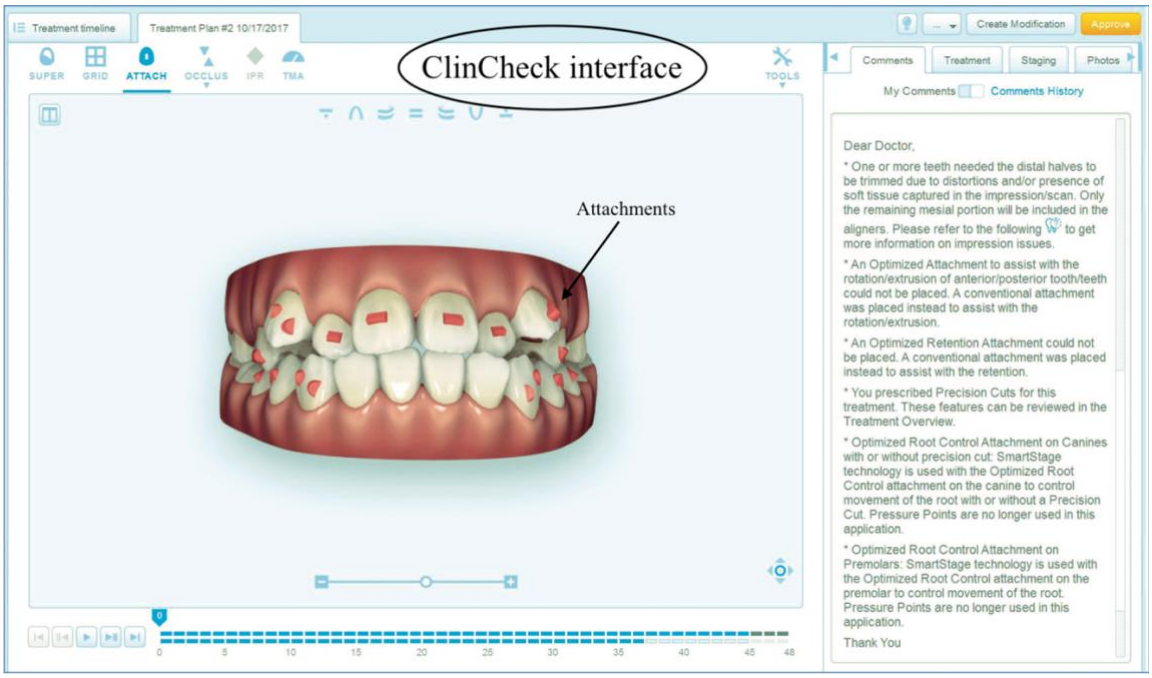


Figure 25: Communication interface in ClinCheck between the technician and clinician (Adapted from Tai, 2018)

While the use of software such as ClinCheck has greatly improved treatment planning and predictability, there are still some criticisms regarding the accuracy of complex movements, such as extrusion and torque. Some authors question the ability of aligners to compete with fixed appliances in these cases, suggesting that automating treatment plans may not always consider all the intricacies of complex tooth movements (Papageorgiou et al., 2018).

Aligners are primarily made from thermoformed plastics, such as polyurethane and polyethylene terephthalate glycol (PETG), materials known for their transparency, flexibility, and durability (AlMogbel, 2023). They must be rigid enough to exert the forces necessary to move the teeth, while also being flexible enough to provide comfort and be resistant to stains and wear (Bichu et al., 2023).

Historically, the first aligners were produced via thermoforming, a technique still widely used today by systems such as Invisalign, Spark or Smilers. This process begins with taking dental impressions or using digital scanners to create a virtual model of the patient's teeth. A plastic sheet is then heated and molded around a 3D printed model of the patient's teeth (Tai, 2018). While this process is effective, the quality of the aligner

depends on the accuracy of the heating and molding process, which can sometimes result in minor imperfections or variations in thickness (Jindal et al., 2020).

However, recent advances have introduced the use of 3D printed materials, which have superior mechanical properties compared to traditional thermoformed materials. These 3D printed materials stand out for their better homogeneity in the distribution of forces applied to the teeth. This is because, during 3D printing, aligners are manufactured with very high accuracy from detailed digital models, which reduces the thickness variations and surface imperfections often seen in thermoformed materials (Jindal et al., 2020). This reduces the adjustments and corrections needed during processing (Jindal et al., 2020). Moreover, 3D printing's ability to faithfully reproduce the anatomical details of teeth improves the accuracy of tooth movements, increasing the effectiveness of orthodontic treatment (Bichu et al., 2023).

The future of aligners could thus move towards direct-to-office printing, reducing production costs and eliminating delays related to shipping factory-produced aligners. With the advancement of 3D printing technologies, dental practices will potentially have the ability to produce aligners on-site, making the process more accessible and less expensive for patients (Jindal et al., 2020).

For aligners to be effective, patients must follow strict wearing protocols. It is recommended that aligners be worn for 20 to 22 hours a day, removing them only for eating, drinking (except water), brushing and flossing (Weir, 2017). Aligners are usually changed every one to two weeks, depending on the treatment plan defined by the orthodontist, with each aligner providing a gradual movement of the teeth (Tai, 2018).

In addition to the manufacture of the aligners, the use of auxiliary devices such as composite attachments and intermaxillary elastics plays a vital role in the correction of complex malocclusions. Composite attachments, which are small resin prominences, are often used to improve retention and facilitate complex tooth movements, such as rotations or vertical movements. However, one study has shown that the effectiveness of the attachments is highly dependent on the type of material and the thickness of the gutters used.

For example, ellipsoid attachments did not show a significant effect on retention for some aligners, while beveled attachments increased retention in other cases (Dasy et al., 2015).

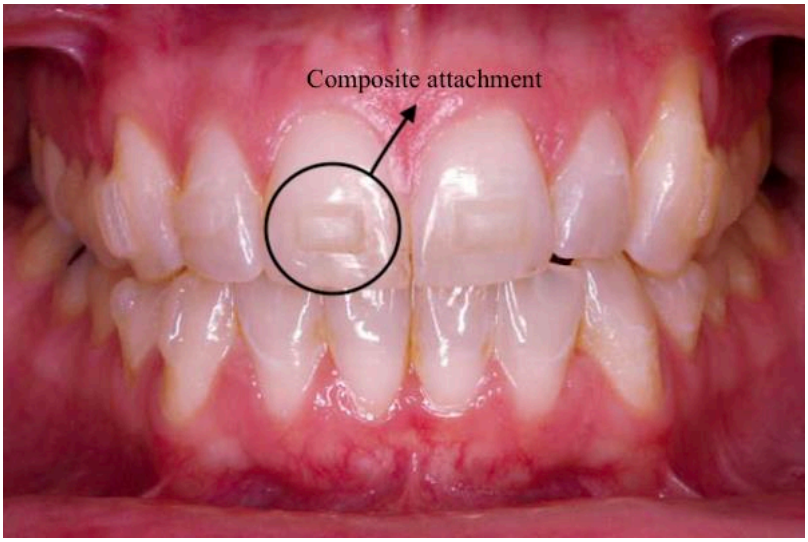
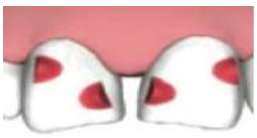
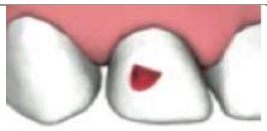
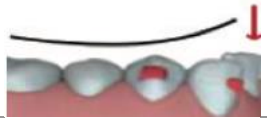
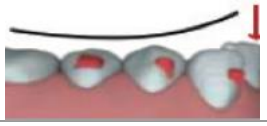


Figure 26: Photographic adaptation of composite attachment bonded to the buccal surface of the teeth (Proffit et al., 2018)

Moreover, the study points out that aligners retention also depends on the composition of the materials. In some cases, aligners made from more rigid materials, such as CA-hard, can provide sufficient retention even without attachments, especially for simple tooth movements. For example, the Essix ACE aligner showed less retention when associated with ellipsoid attachments, suggesting that adding attachments does not consistently improve retention in all situations (Dasy et al., 2015).

However, for more complex movements, such as rotations or vertical translations, attachments may be necessary to ensure predictability and optimal control of the forces applied (Weir, 2017). The use of Optimized Attachments, such as those of Invisalign®, allows the attachments to be strategically placed according to the required tooth movements, thus maximizing the effectiveness of the aligners in complex cases (Weir, 2017). The following table outlines the range of conventional and optimized attachments that are commonly used to assist in specific tooth movements:

Table 2: Range of Conventional and Optimized Attachments for Aligners (Adapted from Tai, 2018)

Situation	Default size/Placement	Examples
Root control of maxillary central and lateral incisors	Optimized root control attachments: one buccal attachment on the lateral incisor and up to two additional pressure points of necessary	
Root control of canines and premolars	Two buccal attachments on premolars (if space allows) or one attachment with one pressure point	
Multiplane movement of maxillary lateral incisors	Optimized multiplane attachment: one buccal attachment and a pressure point on the lingual side, if necessary	
Rotation of canines and premolars	Optimized rotation attachments for controlling the rotation of canines and premolars	
Extrusion of individual or multiple teeth	Optimized attachments for extrusion movements	
Premolar extraction space closure	Vertical root control attachments on the canine and two 1-mm rectangular attachments on the distal teeth	
Mandibular incisor extraction space closure	1-mm vertical rectangular attachments placed on two adjacent teeth	
Anterior intrusion without premolar rotation	1-mm horizontal beveled attachment placed bilaterally on the first premolar in each quadrant	
Anterior intrusion with premolar rotation	1-mm horizontal beveled attachment on rotation premolars. If both are rotating, no retention attachment is placed	

Finally, intermaxillary elastics are often used in addition to aligners to correct more severe malocclusions, such as mismatches between the jaws. These elastics, attached to the aligners with hooks or buttons, apply crucial intermaxillary forces for the correction of such malocclusions. Although these devices improve the effectiveness of aligner treatments, their use requires rigorous cooperation from patients to be fully effective (Papadimitriou et al., 2018).

Aligners have been praised for their comfort and aesthetics, with studies showing that patients generally prefer aligners over multi-brackets systems due to their discretion and ease of use (Weir, 2017). However, questions about their effectiveness remain, especially for some more complex movements such as extrusion or torque, which are sometimes better performed with fixed multi-brackets devices. It is therefore crucial to analyze the results of comparative studies and systematic reviews to better assess the effectiveness of aligners in different types of malocclusions (Papageorgiou et al., 2018).

2.2.3. Biomechanics of aligners

The biomechanics of clear aligners play a vital role in the success of orthodontic treatments. These devices use strategically applied forces to move teeth to predetermined positions, created from digital models of the patient's teeth. Each aligner exerts specific pressure on certain teeth, gradually moving them (Tai, 2018).
Recent advances in materials, including the introduction of new polymers with optimized mechanical properties, have significantly improved the distribution of forces applied by aligners. These new materials allow for a more even distribution of forces, reducing adverse effects such as loss of alignment between successive aligners and increasing the accuracy of tooth movements throughout the treatment (Jindal et al., 2020).

In addition, regular re-evaluations and adjustments in digital processing plans are often necessary to correct deviations from expected results during processing. While these adjustments are less common with fixed appliances, they are crucial for clear aligners to maintain treatment effectiveness. Aligners require continuous monitoring to ensure that the applied forces remain appropriate to the patient's needs and that treatment goals are met without compromising periodontal health (Papadimitriou et al., 2018).

Auxiliary devices, such as temporary anchored devices (TADs), are often used in addition to aligners to improve the efficacy of complex movements. TADs are small titanium screws that are inserted into the alveolar bone to provide a stable and temporary anchor. They allow the application of controlled orthodontic forces to specific teeth without relying on other teeth for anchoring, which improves the control

of vertical and rotational movements, often difficult to achieve with aligners alone (Tai, 2018).

2.2.4. Comparative Evaluation of Multi-Attachment Fixed Appliances and Clear Aligners

a. Comfort, Aesthetics, and Oral Hygiene

Clear aligners offer significant benefits in terms of comfort and aesthetics. Patients often prefer aligners because of their invisibility and superior comfort compared to fixed braces. A systematic review conducted by Cardoso et al. (2020) confirms that patients treated with clear aligners report less pain than those with fixed appliances, especially at the beginning of treatment. This conclusion is reinforced by the systematic review by Pithon et al. (2017), which highlights that aligners also improve patient satisfaction during treatment.

In terms of aesthetics, aligners are a preferred option for adults and teens looking for a discreet solution. In contrast, multi-attachment fixed appliances are more visible and can affect patients' self-esteem, especially in adults (ElShehaby et al., 2020).

Clear aligners offer an oral hygiene advantage because they are removable, allowing patients to clean their teeth more effectively. This reduces the risk of plaque buildup and gum inflammation. However, this benefit largely depends on the patient's compliance, as not wearing the aligners for the recommended 20 to 22 hours per day can compromise treatment outcomes. For a more detailed comparison of hygiene benefits and disadvantages, see section 2.3.4. (Pithon et al., 2017).

b. Treatment Efficiency and Efficacy

Clear aligners have proven to be effective for certain types of dental movements, such as anterior tooth intrusion, with an average of 0.72 mm of intrusion according to Rossini et al. (2015)’s systematic review. However, for more complex movements, such as extrusion, aligners face greater challenges, with a success rate of only 30%. Fixed appliances, on the other hand, have a higher success rate for movements like extrusion

and rotation, thanks to the continuous forces they apply (Tsichlaki et al., 2016). While aligners may be more comfortable, they often require attachments to improve the precision of rotations and other difficult movements (Rossini et al., 2015). For a more detailed comparison of these movements, please refer to section 2.3.1, where a deeper analysis is conducted.

c. Root Resorption and Tissue Health

Root resorption is a concern for both types of appliances, but studies show that aligners may have a lower risk of external root resorption (ERR). Meta-analysis by Fang et al. (2019) found that the incidence and severity of root resorption were significantly lower with aligners compared to fixed appliances (SMD = -0.65). This is mainly due to the intermittent forces exerted by the aligners, which are less likely to cause continuous stress on the periodontal ligament, but also because the movements achieved by aligners are generally less complex and less effective compared to those obtained with fixed appliances.

In contrast, stationary appliances have a higher risk of causing root resorption due to the continuous forces applied over long periods of time. The systematic review by Papageorgiou et al. (2016) showed that root resorption is more common with fixed appliances, especially when forces are not well controlled. Regular monitoring is therefore essential for patients using fixed appliances to detect and manage root resorption before it compromises tooth longevity.

d. Treatment Duration

Aligners are often touted as an option to speed up treatment, but the results are mixed. The systematic review by Tsichlaki et al. (2016) found that the average duration of treatment with fixed appliances is approximately 19.9 months. Although aligners can shorten the duration of treatment in simple cases, they often require multiple phases of refinement, which can extend the total duration of treatment. Fixed appliances, on the other hand, offer more consistent results across a wide range of cases, although they may require a longer duration for complex movements.

e. Critical Appraisal of Literature and Conflicts of Interest

A critical review of the aligner literature reveals potential biases, particularly in studies funded by aligner manufacturers. Rossini et al. (2015) noted that, although aligners are effective for some movements, the methodological quality of many studies on the effectiveness of aligners is limited, with significant biases and potential conflicts of interest. Studies such as those by Papageorgiou et al. (2020) also highlight the need for caution when interpreting positive results for aligners, as these studies often lack methodological rigor and may be influenced by commercial interests.

Table 3: Recapitulative of comparisons between fixed appliances and clear aligners (Cardoso et al., 2020; Fang et al., 2019; Papageorgiou et al., 2020; Pithon et al., 2017; Rossini et al., 2015; Tsichlaki et al., 2016)

Aspect	**Fixed Appliances**	**Clear Aligners**
Comfort and Aesthetics	Visible, less comfortable, can cause irritation	Discreet, comfortable, less pain
Oral Hygiene	Difficult to clean, higher plaque risk	Easy to clean, removable, compliance required
Root Resorption Risk	Higher risk, continuous forces	Lower risk, intermittent forces
Treatment Duration	Consistent for complex cases, may take longer	Shorter for simple cases, may need refinement
Literature and Bias	More reliable, independent studies	Potential conflicts of interest

2.3. Comparative analysis and Clinical Implications

2.3.1. Comparative Analysis of the Effectiveness of Dental Movements between Conventional Appliances and Aligners

In the framework of this thesis, the objective is to compare the efficiency of dental movements between two main orthodontic techniques: transparent aligners and fixed multi-bracket appliances. This section draws on several recent studies and systematic reviews to examine the extent to which aligners, despite their advantages, are less effective for certain complex movements compared to fixed appliances.

Buschang et al. (2013) conducted a comparative retrospective study to assess the time efficiency and precision of aligner therapy compared to fixed multi-bracket appliances. Their study concluded that fixed appliances offer superior control over complex movements such as rotations and vertical adjustments, primarily because the brackets are bonded directly to the teeth, forming a unified structure that allows the force to be transmitted efficiently and continuously. The authors noted that aligners, relying on friction between the aligner and the tooth, show greater variability in force application, leading to less predictable outcomes. This observation is consistent with the findings of Tsichlaki et al. (2016), who emphasized that the continuous forces provided by fixed appliances are essential for complex tooth movements. Both studies agree that aligners struggle with maintaining stable forces over time, making them less reliable for such movements.

Rossini et al. (2015) conducted a systematic review with the goal of evaluating the efficacy of clear aligners in controlling orthodontic tooth movements. Their primary focus was on movements like extrusion, rotation, and intrusion. Rossini et al. found that while aligners could achieve an average intrusion of 0.72 mm, their efficiency dropped significantly when it came to more complex movements such as extrusion (with a success rate of only 30%) and canine/premolar rotations (with a success rate of just 36%). This result supports Buschang et al. (2013) and Tsichlaki et al. (2016) in highlighting the limitations of aligners for complex movements. Rossini et al. explain that the primary limitation lies in the frictional mechanism by which aligners exert force, which contrasts with the direct force application by fixed appliances.

However, Gu et al. (2017) provided an interesting counterpoint by focusing on overall treatment time and patient outcomes. Their study found that Invisalign reduced treatment time by an average of 5.7 months compared to fixed appliances. Yet, Gu et al. also acknowledged that fixed braces were more effective for complex movements such as torque adjustments and posterior occlusal contacts. This study highlights a key advantage of aligners, reduced treatment duration for simple cases, while still supporting the broader consensus that fixed appliances are superior for more complex cases.

Papageorgiou et al. (2020) conducted a systematic review with meta-analyses to compare the overall occlusal outcomes and efficiency of treatments using aligners and fixed appliances. The authors found that while aligners were associated with a slightly lower risk of external root resorption due to their less aggressive force application, they were less effective for achieving complex tooth movements, such as buccolingual inclinations and occlusal contacts. This supports the findings of Rossini et al. (2015) and Buschang et al. (2013), further underscoring the limitations of aligners for complex movements. However, Papageorgiou et al. focused more on occlusal outcomes, providing additional insight into the broader effects of aligners on the entire dental arch.

Lombardo et al. (2020) provided a long-term perspective, focusing on the stability of corrections achieved with fixed appliances versus aligners. Their prospective study confirmed that patients treated with fixed appliances had fewer recurrences, particularly for complex corrections like torque adjustments and rotations. This aligns with the findings of Buschang et al. and Tsichlaki et al., reinforcing the idea that the continuous forces provided by fixed appliances ensure better long-term stability. However, Lombardo's study goes further by emphasizing that the intermittent forces of aligners may contribute to higher recurrence rates.

Sachdev et al. (2021) focused their study on the accuracy of mesiodistal movements, reporting a 72.33% success rate with aligners, which they deemed acceptable for simple cases. However, like the earlier studies, they noted that fixed appliances provide superior control over translational movements due to their ability to apply continuous forces. Sachdev et al. thus confirm the broader consensus that aligners are more suited for simple movements, while fixed appliances excel in more complex cases.

In a recent study, Rocha et al. (2024) examined the predictability of arch expansion with the Invisalign® system, comparing predicted outcomes from the ClinCheck® software with actual clinical results. They found significant discrepancies between the predicted and actual outcomes, particularly for more complex movements. Rocha et al.'s findings are critical because they highlight a major limitation of ClinCheck®: the software does not fully account for the loss of force transmission due to the frictional mechanism of aligners. This contrasts sharply with the predictable force application of fixed appliances, where the force is directly transmitted from the bracket to the tooth.

Finally, Caruso et al. (2024) conducted a systematic review on the forces generated by aligners and their predictability. Their review found that while ClinCheck® provides reasonably accurate predictions for simple movements, it significantly overestimates the efficacy of aligners for complex movements such as torque adjustments and rotations. Caruso et al. emphasized that ClinCheck® does not consider the limitations inherent to the frictional force mechanism of aligners, which leads to less predictable clinical outcomes. This supports the earlier conclusions of Rocha et al. (2024), reinforcing the need for more accurate software management to better predict complex movements.

Based on these systematic reviews and studies, it is clear that fixed braces are significantly more effective for managing complex tooth movements such as rotations, torque adjustments, and vertical movements. This superiority is largely due to the direct transmission of forces via the brackets, which are bonded to the teeth and form a unified structure that allows for continuous and stable force application. In contrast, aligners operate via a friction mechanism that introduces variability and reduces the precision of force application, making them less effective for complex movements. This limitation is further compounded by the fact that the ClinCheck® software, which is used to predict treatment outcomes for aligners, does not fully account for this loss of force transmission. Although Invisalign® aligners offer advantages in terms of comfort, aesthetics, and shorter treatment times for simpler cases, their limitations in handling complex movements highlight the need for rigorous software management and improvements in clinical mechanics.

2.3.2. Factors Influencing the Effectiveness of Tooth Movement

The effectiveness of tooth movement depends largely on how force is applied. Fixed braces allow precise control of forces through brackets and metal wires, making them more reliable for performing complex dental movements. Buschang et al. (2013) showed that fixed devices can apply continuous and predictable forces, which are essential for complex movements, such as rotations and torque adjustments. On the other hand, aligners, which rely on plastic aligners to exert forces, can cause variations in the force applied depending on the fit and wearing of the aligners. Chisari et al. (2014) noted that this variation can make outcomes less predictable, especially in cases requiring complex root rotations and adjustments.

Movement	Fixed Appliances	Clear Aligners
Inclination	Precise and continuous control via brackets and wires	Less efficient, limited application of continuous forces
Translation	Predictable with light and continuous forces	Less predictable, often requires attachments
Torque	Well controlled thanks to precise wire adjustments	Limited control, less precision
Rotation	Highly effective for complex rotations	More difficult, often requires attachments for precision
Extrusion	Better control, continuous forces ensure vertical movements	Limited control, less predictable extrusion
Intrusion	Continuous forces ensure accurate intrusions	Less efficient, difficulty maintaining continuous pressure

Table 4: Summary comparing the efficiency of dental movements between fixed multi-brackets appliances and aligners for different types of dental movements (Buschang et al., 2013; Papadimitriou et al., 2018; Rossini et al., 2015; Sachdev et al., 2021; Tsichlaki et al., 2016)

2.3.3. Comparison of the Long-Term Effectiveness of the Two Approaches

Long-term effectiveness is a crucial aspect of orthodontic treatments. Fixed appliances have shown superior effectiveness in terms of long-term outcome stability compared to aligners. A study conducted by Lombardo et al. (2020) found that patients treated with fixed appliances had fewer recurrences compared to those treated with aligners. The continuous forces applied by fixed appliances help to keep corrections to complex tooth movements, including rotations and torque adjustments, more stable.

In contrast, Zheng et al. (2017) observed that patients treated with aligners had a higher tendency to recurrence, especially in cases of complex corrections, often requiring additional post-treatment adjustments.

2.3.4. Analysis of the Advantages and Disadvantages of Each Approach

Both clear aligners and fixed appliances have distinct advantages and disadvantages that can influence their effectiveness and patient experience during orthodontic treatment.

One of the most significant advantages of clear aligners is their superior comfort and aesthetic appeal. Aligners are nearly invisible, making them a popular choice for patients who are concerned about the appearance of their orthodontic appliances. In contrast, fixed appliances are much more noticeable, which can lead to feelings of self-consciousness, particularly among adults and older teens. Thanks to their absence of brackets and metal wires, aligners are generally better tolerated by patients in terms of comfort, with less irritation to the oral tissues. Cardoso et al. (2020) showed that patients experience less pain when wearing aligners compared to fixed braces, and Pithon et al. (2017) confirmed higher overall satisfaction, largely due to their discreet and comfortable appearance.

In addition to the aesthetic and comfort-related benefits, aligners also offer the possibility of performing teeth whitening simultaneously during the orthodontic treatment, which is a highly appealing option for patients concerned about the appearance of their teeth (Cardoso et al., 2020). This additional benefit enhances the overall aesthetic result of the treatment. However, this advantage is accompanied by potential side effects such as transient pulpitis or tooth sensitivity, which can occur during the whitening process (Ata-Ali et al., 2016). Nonetheless, these are typically mild and temporary, and patients are generally willing to accept them in exchange for the dual benefit of orthodontic correction and teeth whitening.

Patient cooperation is a determining factor in the effectiveness of aligners, as they must be worn consistently to ensure good results. Kravitz et al. (2023) noted that insufficient adherence to instructions may prolong or decrease the effectiveness of treatment. On the

other hand, fixed appliances, being permanent, apply the required forces without depending on the cooperation of patients, thus ensuring better consistency of treatment. This consistency makes fixed appliances a more reliable option for treating complex cases, as noted by Lombardo et al. (2017).

One of the most significant advantages of aligners is their removability, allowing patients to take them out during meals and when brushing or flossing their teeth. This feature greatly reduces the risk of plaque buildup, gingivitis, and cavities, as confirmed by Miethke and Vogt (2005). However, patient compliance plays a crucial role; without adherence to the 20–22 hours per day recommendation, the advantages in terms of hygiene may be nullified.

Pithon et al. (2017), in their systematic review concerning the different plaque removal methods with orthodontic appliances, emphasized that maintaining good oral hygiene with fixed appliances is more challenging due to the presence of brackets and wires, which create areas where food can become trapped. This can increase the risk of plaque accumulation and gum disease, even in patients who are diligent about oral hygiene. Nonetheless, these observations have been reiterated throughout the literature, as patient compliance remains a critical factor for both treatment modalities.

However, fixed appliances provide superior long-term stability and effectiveness in cases involving complex movements. Although aligners offer convenience and comfort, they are more prone to recurrences or incomplete movements, especially in cases involving significant malocclusions. Studies have shown (Lombardo et al., 2017; Tsichlaki et al., 2016) that fixed appliances deliver more consistent and predictable results across a wide range of cases. For example, Tsichlaki et al. (2016) noted that the forces applied by fixed appliances are more controlled and predictable, allowing for better outcomes in difficult cases.

On the downside, fixed appliances are associated with greater discomfort, especially during the initial phase of treatment when brackets and wires are first applied. Ata-Ali et al. (2016) found that many patients experience discomfort, irritation, and even pain in the first few weeks of wearing fixed appliances, although these symptoms tend to subside as the treatment progresses.

In contrast, patients wearing aligners experience fewer issues with discomfort throughout the duration of their treatment, as aligners are generally gentler on the mouth's soft tissues.

2.3.5. Implications for Orthodontic Practice

2.3.5.1. Implications for the Choice of Orthodontic Appliances according Treatment Objectives

The choice between fixed braces and aligners should be guided by the specific goals of the treatment and the individual needs of the patients. For complex corrections involving significant dental movements such as rotations and torque adjustments, fixed appliances are often preferred due to their ability to apply continuous and controlled forces, which is essential for these movements. Buschang et al. (2013) showed that fixed devices provide better control for these challenging movements. On the other hand, for simpler or moderate cases, where aesthetics and comfort are priorities, aligners may be an adequate option. Flores-Mir et al. (2018) note that patients often prefer aligners for their discretion and comfort, while remaining effective for less complex tooth movements.

2.3.5.2. Recommendations for the Effective Use of Orthodontic Appliances in Clinical Practice

To maximize the effectiveness of fixed devices, it is essential to define clear treatment protocols and make regular adjustments in order to maintain optimal forces. Ke et al. (2019) emphasize the importance of these adjustments and rigorous follow-up to prevent complications and ensure optimal progression of tooth movement.

Aligners, on the other hand, require strict cooperation from patients, with daily wear from 20 to 22 hours. Regular follow-up is also necessary to check the fit of the aligners and the progress of the treatment (Chisari et al., 2014). Their success depends directly on patients' adherence to daily recommendations.

2.3.5.3. Prospects for Orthodontic Research and Development

Technological advancements play a vital role in improving orthodontic treatments, especially when it comes to the effectiveness of aligners for complex tooth movements like rotations and extrusions. Zheng et al. (2017) showed that the integration of new materials and improved protocols can increase the accuracy and overall efficiency of aligners.

In addition, the integration of artificial intelligence (AI) into orthodontic treatment planning is a promising new direction for improving the accuracy of tooth movements. Chen et al. (2020) showed that AI can automate treatment planning and increase clinical efficiency, while reducing human error.

III. CONCLUSION

3.1. Summary of Main Conclusions

This review compared the effectiveness of tooth movements achieved with fixed multi-attachment appliances and clear aligners, highlighting the advantages and disadvantages of each method. Fixed appliances, consisting of brackets and metal wires, have been shown to be particularly effective in the treatment of complex malocclusions, including large rotations and vertical movements, such as intrusion and extrusion of teeth. Their ability to apply continuous and well-controlled forces makes them a prime option for complex orthodontic treatments.

On the other hand, clear aligners, have significant advantages in terms of aesthetics and comfort, especially thanks to their removable nature and relative invisibility, which makes them popular with both adult and adolescent patients. In addition, aligners allow for better oral hygiene as they can be removed during meals and brushing, reducing the risk of cavities and periodontal disease. However, these devices show limitations, especially in the management of complex dental movements, such as large rotations and vertical movements, due to their more diffuse and less constant mode of force application compared to fixed appliances.

Although aligners can be effective for some types of tooth movements, their predictability remains lower than that of fixed appliances, especially in cases requiring complex corrections. This underlines the importance of choosing the therapeutic tool according to the specific goals of the treatment and the individual characteristics of each patient.

In addition, actual clinical results obtained with aligners, especially those predicted by the ClinCheck software, often show deviations, especially for complex movements like rotations and torque adjustments. This highlights the importance of rigorous management of the ClinCheck software to improve aligner predictability.

Ultimately, the decision to choose between aligners and fixed appliances should be guided by the nature of the dental movements required and the patient's priorities, such as aesthetics, comfort, or the need for complex corrections.

3.2. Importance of Results for Orthodontics

The results of this review are essential to guide future orthodontic practices, as they highlight the benefits and limitations of the two main treatment methods currently available. By highlighting the effectiveness of fixed multi-bracket appliances for complex cases, this revision confirms their central role as a reference method in orthodontics. At the same time, the evaluation of clear aligners highlights their potential for aesthetic treatments in simple to moderate cases, while highlighting the need for further research to improve their effectiveness in complex movements.

3.3. Limitations of Narrative Review and Studies Included

This narrative review has several limitations inherent in its methodology. Unlike systematic reviews or meta-analyses, which use a rigorous methodology to identify, select, and analyze relevant studies, narrative reviews often rely on a more subjective selection of sources, which can introduce bias into conclusions. This is because narrative reviews do not always follow a structured protocol for research and inclusion of studies, which can limit the reproducibility and scientific rigor of the results.

In addition, variability in study protocols, patient samples, and end-of-treatment criteria may influence the results and their comparability. For example, differences between the included studies, in terms of treatment duration, types of movements assessed, and methodologies employed, may affect the generalizability of findings. The rapid evolution of orthodontic technologies, with new versions and continuous improvements to aligners, could make some results quickly obsolete. For example, advances in the accuracy of ClinCheck algorithms and mechanical adjustments of aligners could change current conclusions regarding their effectiveness for complex movements.

Finally, another limitation of this narrative revision lies in the lack of quantitative synthesis of the data. Unlike meta-analyses, which integrate and quantify the results of studies to give an accurate estimate of effects, this narrative review is limited to a

qualitative description of the studies. This can make conclusions less robust and more open to interpretation, especially in areas where study results are heterogeneous.

3.4. Suggestions for Future Research

To deepen the understanding and improve the effectiveness of orthodontic treatments, future research should explore several aspects. First, longitudinal studies following patients over the long term are needed to assess the stability of the results obtained with clear aligners, especially in complex cases requiring significant tooth movements. Second, it is crucial to optimize treatment protocols for fixed devices, exploring technological innovations such as the integration of temporary anchored devices (TADs) to improve the control of complex movements. Finally, advances in aligner materials and design must continue to increase their accuracy and reduce the risk of recurrence after treatment, especially for vertical movements and complex rotations.

Future research should also focus on improving ClinCheck's prediction algorithms to minimize discrepancies between predictions and clinical outcomes, especially for complex movements such as torque adjustments and rotations. Optimizing aligner mechanics by continuously and uniformly improving applied forces remains a priority.

In addition, it is essential to prioritize systematic reviews and meta-analyses, as they offer a higher level of evidence by synthesizing the results of multiple studies, thus providing a more comprehensive understanding of the relative effectiveness of different orthodontic treatments. In addition, future research should focus on how new technologies, such as artificial intelligence (AI), can optimize treatment planning and improve the accuracy of fixed and removable appliances.

BIBLIOGRAPHY

Alexander, R. G. (1986). The alexander discipline. *Contemporary concepts and philosophies*, *17*, 307.

AlMogbel, A. (2023). Clear Aligner Therapy: Up to date review article. *Journal of Orthodontic Science*, *12*, 37. https://doi.org/10.4103/jos.jos_30_23

Andrews, L. F. (1979). The straight-wire appliance. *British journal of orthodontics*, *6*(3), 125-143.

Asiry, M. A. (2018). Biological aspects of orthodontic tooth movement: A review of literature. *Saudi Journal of Biological Sciences*, *25*(6), 1027–1032. https://doi.org/10.1016/j.sjbs.2018.03.008

Ata-Ali, F., Ata-Ali, J., Ferrer-Molina, M., Cobo, T., De Carlos, F., & Cobo, J. (2016). Adverse effects of lingual and buccal orthodontic techniques: A systematic review and meta-analysis. *American Journal of Orthodontics and Dentofacial Orthopedics*, *149*(6), 820–829. https://doi.org/10.1016/j.ajodo.2015.11.031

Bassett, C. A., & Becker, R. O. (1962). Generation of electric potentials by bone in response to mechanical stress. *Science (New York, N.Y.)*, *137*(3535), 1063–1064. https://doi.org/10.1126/science.137.3535.1063

Baumrind, S. (1969). A reconsideration of the propriety of the “pressure-tension” hypothesis. *American Journal of Orthodontics*, *55*(1), 12–22. https://doi.org/10.1016/S0002-9416(69)90170-5

Berglundh et al. (n.d.). *Lindhe’s Clinical Periodontology and Implant Dentistry, 2 Volume Set, 7th Edition | Wiley*. Wiley.Com. Retrieved March 7, 2024, from https://www.wiley.com/en-it/Lindhe%27s+Clinical+Periodontology+and+Implant+Dentistry%2C+2+Volume+Set%2C+7th+Edition-p-9781119438885

Bichu, Y. M., Alwafi, A., Liu, X., Andrews, J., Ludwig, B., Bichu, A. Y., & Zou, B. (2023). Advances in orthodontic clear aligner materials. *Bioactive Materials*, *22*, 384–403. https://doi.org/10.1016/j.bioactmat.2022.10.006

Boke, F., Gazioglu, C., Akkaya, S., & Akkaya, M. (2014). Relationship between orthodontic treatment and gingival health: A retrospective study. *European Journal of Dentistry*, *8*(3), 373–380. https://doi.org/10.4103/1305-7456.137651

Bollen, A.-M., Cunha-Cruz, J., Bakko, D. W., Huang, G. J., & Hujoel, P. P. (2008). The Effects of Orthodontic Therapy on Periodontal Health. *The Journal of the American Dental Association*, *139*(4), 413–422. https://doi.org/10.14219/jada.archive.2008.0184

Buschang, P. H., Shaw, S. G., Ross, M., Crosby, D., & Campbell, P. M. (2013). Comparative time efficiency of aligner therapy and conventional edgewise braces. *The Angle Orthodontist*, *84*(3), 391–396. https://doi.org/10.2319/062113-466

Cardoso, P. C., Espinosa, D. G., Mecenas, P., Flores-Mir, C., & Normando, D. (2020). Pain level between clear aligners and fixed appliances: A systematic review. *Progress in Orthodontics*, *21*(1), 3. https://doi.org/10.1186/s40510-019-0303-z

Caruso, S., De Felice, M.E., Valenti, C. *et al.* An evaluation of the Invisalign® Aligner Technique and consideration of the force system: a systematic review. *Syst Rev* 13, 43 (2024). https://doi.org/10.1186/s13643-023-02437-5

Cattaneo, P., Dalstra, M., & Melsen, B. (2009). Strains in periodontal ligament and alveolar bone associated with orthodontic tooth movement analyzed by finite element. *Orthodontics & Craniofacial Research*, *12*(2), 120–128. https://doi.org/10.1111/j.1601-6343.2009.01445.x

Chen, Y.-W., Stanley, K., & Att, W. (2020a). Artificial intelligence in dentistry: Current applications and future perspectives. *Quintessence International, 51*(3), 248–257. https://doi.org/10.3290/j.qi.a43952

Chen, Y.-W., Stanley, K., & Att, W. (2020b). Corrigendum: Artificial intelligence in dentistry: current applications and future perspectives. *Quintessence International*, *51*(5), 430. https://doi.org/10.3290/j.qi.a44465

Chisari, J. R., McGorray, S. P., Nair, M., & Wheeler, T. T. (2014). Variables affecting orthodontic tooth movement with clear aligners. *American Journal of Orthodontics and Dentofacial Orthopedics*, *145*(4 Suppl), S82-91. https://doi.org/10.1016/j.ajodo.2013.10.022

Crego-Ruiz, M., & Jorba-García, A. (2023). Assessment of the periodontal health status and gingival recession during orthodontic treatment with clear aligners and fixed appliances: A systematic review and meta-analysis. *Medicina Oral, Patologia Oral Y Cirugia Bucal*, *28*(4), e330–e340. https://doi.org/10.4317/medoral.25760

Currey, J. D. (1968). The adaptation of bones to stress. *Journal of Theoretical Biology*, *20*(1), 91–106. https://doi.org/10.1016/0022-5193(68)90094-5

Dasy, H., Dasy, A., Asatrian, G., Rózsa, N., Lee, H.-F., & Kwak, J. H. (2015). Effects of variable attachment shapes and aligner material on aligner retention. *The Angle Orthodontist*, *85*(6), 934–940. https://doi.org/10.2319/091014-637.1

ElShehaby, M., Mofti, B., Montasser, M. A., & Bearn, D. (2020). Powered vs manual tooth brushing in patients with fixed orthodontic appliances: A systematic review and meta-analysis. *American Journal of Orthodontics and Dentofacial Orthopedics*, *158*(5), 639–649. https://doi.org/10.1016/j.ajodo.2020.04.018

Fang, X., Qi, R., & Liu, C. (2019). Root resorption in orthodontic treatment with clear aligners: A systematic review and meta-analysis. *Orthodontics & Craniofacial Research*, *22*(4), 259–269. https://doi.org/10.1111/ocr.12337

Feller, L., Khammissa, R. a. G., Schechter, I., Thomadakis, G., Fourie, J., & Lemmer, J. (2015). Biological Events in Periodontal Ligament and Alveolar Bone Associated with

Application of Orthodontic Forces. *The Scientific World Journal*, *2015*, 876509. https://doi.org/10.1155/2015/876509

Flores-Mir, C., Brandelli, J., & Pacheco-Pereira, C. (2018). Patient satisfaction and quality of life status after 2 treatment modalities: Invisalign and conventional fixed appliances. *American Journal of Orthodontics and Dentofacial Orthopedics*, *154*(5), 639–644. https://doi.org/10.1016/j.ajodo.2018.01.013

Frost, H. M. (1964). *The Laws of Bone Structure*. C.C. Thomas.

Geron, S., Romano, R., & Brosh, T. (2004). Vertical Forces in Labial and Lingual Orthodontics Applied on Maxillary Incisors—A Theoretical Approach. *The Angle Orthodontist*, *74*(2), 195–201. https://doi.org/10.1043/0003-3219(2004)074<0195:VFILAL>2.0.CO;2

Grant, M. J., & Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Information and Libraries Journal*, *26*(2), 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x

Higgins, J. P. T., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M. J., & Welch, V. A. (Eds.). (2022). Cochrane Handbook for Systematic Reviews of Interventions (Version 6.3). Cochrane. https://doi.org/10.1002/9781119536604

Jiang, T., Jiang, Y.-N., Chu, F.-T., Lu, P.-J., & Tang, G.-H. (2021). 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. *American Journal of Orthodontics and Dentofacial Orthopedics*, *159*(5), 635–643. https://doi.org/10.1016/j.ajodo.2019.11.025

Jindal, P., Worcester, F., Siena, F. L., Forbes, C., Juneja, M., & Breedon, P. (2020). Mechanical behaviour of 3D printed vs thermoformed clear dental aligner materials

under non-linear compressive loading using FEM. *Journal of the Mechanical Behavior of Biomedical Materials*, *112*, 104045. https://doi.org/10.1016/j.jmbbm.2020.104045

Kapila, S., & Sachdeva, R. (1989). Mechanical properties and clinical applications of orthodontic wires. *American Journal of Orthodontics and Dentofacial Orthopedics*, *96*(2), 100–109. https://doi.org/10.1016/0889-5406(89)90251-5

Ke, Y., Zhu, Y., & Zhu, M. (2019). A comparison of treatment effectiveness between clear aligner and fixed appliance therapies. *BMC Oral Health*, *19*(1), 24. https://doi.org/10.1186/s12903-018-0695-z

Kravitz, N. D., Dalloul, B., Zaid, Y. A., Shah, C., & Vaid, N. R. (2023). What percentage of patients switch from Invisalign to braces? A retrospective study evaluating the conversion rate, number of refinement scans, and length of treatment. *American Journal of Orthodontics and Dentofacial Orthopedics*, *163*(4), 526–530. https://doi.org/10.1016/j.ajodo.2022.03.016

Krishnan, V. (2024). Changing orthodontic mechanics with Temporary Anchorage Devices. *Journal of the World Federation of Orthodontists*, *13*(1), 1. https://doi.org/10.1016/j.ejwf.2024.01.003

Krishnan, V., & Davidovitch, Z. (2009). On a Path to Unfolding the Biological Mechanisms of Orthodontic Tooth Movement. *Journal of Dental Research*, *88*(7), 597–608. https://doi.org/10.1177/0022034509338914

Lang, N. P., & Lindhe, J. (2015). *Clinical Periodontology and Implant Dentistry, 2 Volume Set*. John Wiley & Sons.

Langlade, M. (1978). *Thérapeutique orthodontique*. Maloine.

Li, Y., Jacox, L. A., Little, S. H., & Ko, C.-C. (2018). Orthodontic tooth movement: The biology and clinical implications. *The Kaohsiung Journal of Medical Sciences*, *34*(4), 207–214. https://doi.org/10.1016/j.kjms.2018.01.007

Li, Y., Zhan, Q., Bao, M., Yi, J., & Li, Y. (2021). Biomechanical and biological responses of periodontium in orthodontic tooth movement: Up-date in a new decade. *International Journal of Oral Science*, *13*(1), 20. https://doi.org/10.1038/s41368-021-00125-5

Littlewood, S. J., Millett, D. T., Doubleday, B., Bearn, D. R., & Worthington, H. V. (2016). Retention procedures for stabilising tooth position after treatment with orthodontic braces. *Cochrane Database of Systematic Reviews*, *1*. https://doi.org/10.1002/14651858.CD002283.pub4

Lombardo, L., Arreghini, A., Ramina, F., Ghislanzoni, L. T. H., & Siciliani, G. (2017). Predictability of orthodontic movement with orthodontic aligners: a retrospective study. Progress In Orthodontics, 18(1). https://doi.org/10.1186/s40510-017-0190-0

Lombardo, L., Martines, E., Mazzanti, V., Arreghini, A., Mollica, F., & Siciliani, G. (2017b). Stress relaxation properties of four orthodontic aligner materials: A 24-hour in vitro study. *The Angle Orthodontist*, *87*(1), 11–18. https://doi.org/10.2319/113015-813.1

McCormack, S. W., Witzel, U., Watson, P. J., Fagan, M. J., & Gröning, F. (2014). The Biomechanical Function of Periodontal Ligament Fibres in Orthodontic Tooth Movement. *PLOS ONE*, *9*(7), e102387. https://doi.org/10.1371/journal.pone.0102387

Meikle, M. C. (2006). The tissue, cellular, and molecular regulation of orthodontic tooth movement: 100 years after Carl Sandstedt. *European Journal of Orthodontics*, *28*(3), 221–240. https://doi.org/10.1093/ejo/cjl001

Miethke, R.-R., & Vogt, S. (2005). A comparison of the periodontal health of patients during treatment with the Invisalign system and with fixed orthodontic appliances. *Journal of Orofacial Orthopedics = Fortschritte Der Kieferorthopadie: Organ/Official Journal Deutsche Gesellschaft Fur Kieferorthopadie*, *66*(3), 219–229. https://doi.org/10.1007/s00056-005-0436-1

Naini, F. B., & Gill, D. S. (2023). Principles of Orthodontic Biomechanics. In *Preadjusted Edgewise Fixed Orthodontic Appliances* (pp. 29–56). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118817551.ch2

Nanci, A., & Bosshardt, D. D. (2006). Structure of periodontal tissues in health and disease. *Periodontology 2000*, *40*(1), 11–28. https://doi.org/10.1111/j.1600-0757.2005.00141.x

Nanda, R. (2005). *Biomechanics and Esthetic Strategies in Clinical Orthodontics*. Elsevier Health Sciences.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *PLOS Medicine*, *18*(3), e1003583. https://doi.org/10.1371/journal.pmed.1003583

Papadimitriou, A., Mousoulea, S., Gkantidis, N., & Kloukos, D. (2018). Clinical effectiveness of Invisalign® orthodontic treatment: A systematic review. *Progress in Orthodontics*, *19*(1), 37. https://doi.org/10.1186/s40510-018-0235-z

Papageorgiou, S. N., Gölz, L., Jäger, A., Eliades, T., & Bourauel, C. (2016). Lingual vs. labial fixed orthodontic appliances: Systematic review and meta-analysis of treatment effects. *European Journal of Oral Sciences*, *124*(2), 105–118. https://doi.org/10.1111/eos.12250

Papageorgiou, S. N., Höchli, D., & Eliades, T. (2017). Outcomes of comprehensive fixed appliance orthodontic treatment: A systematic review with meta-analysis and methodological overview. *The Korean Journal of Orthodontics*, *47*(6), 401. https://doi.org/10.4041/kjod.2017.47.6.401

Papageorgiou, S. N., Koletsi, D., Iliadi, A., Peltomaki, T., & Eliades, T. (2020). Treatment outcome with orthodontic aligners and fixed appliances: A systematic review with meta-analyses. *European Journal of Orthodontics*, *42*(3), 331–343. https://doi.org/10.1093/ejo/cjz094

Pithon, M., Sant'Anna, L., Baião, F., Coqueiro, R., Maia, L., & Paranhos, L. (2017). Effectiveness of different mechanical bacterial plaque removal methods in patients with fixed orthodontic appliance: A systematic review/meta-analysis. *Bioscience Journal*, *33*, 537–554. https://doi.org/10.14393/BJ-v33n2-35755

Proffit, W. R. (2018). *Contemporary orthodontics* (6th edition). Elsevier.

Rekhi, U., Catunda, R. Q., & Gibson, M. P. (2020). Surgically accelerated orthodontic techniques and periodontal response: A systematic review. *European Journal of Orthodontics*, *42*(6), 635–642. https://doi.org/10.1093/ejo/cjz103

Ren, Y., Maltha, J. C., & Kuijpers-Jagtman, A. M. (2003). Optimum Force Magnitude for Orthodontic Tooth Movement: A Systematic Literature Review. *The Angle Orthodontist*, *73*(1), 86–92. https://doi.org/10.1043/0003-3219(2003)073<0086:OFMFOT>2.0.CO;2

Retrouvey, J.-M. (2017). Biomechanics in orthodontics. *American Journal of Orthodontics and Dentofacial Orthopedics*, *152*(1), 134–135. https://doi.org/10.1016/j.ajodo.2017.04.010

Roberts-Harry, D., & Sandy, J. (2004a). Orthodontics. Part 5: Appliance choices. *British Dental Journal*, *196*(1), 9–18. https://doi.org/10.1038/sj.bdj.4810872

Roberts-Harry, D., & Sandy, J. (2004b). Orthodontics. Part 11: Orthodontic tooth movement. *British Dental Journal*, *196*(7), 395-400. https://doi.org/10.1038/sj.bdj.4811129

Rocha, A. S., Gonçalves, M., Oliveira, A. C., & Pinho, T. (2024). Efficiency and predictability of maxillary expansion with Invisalign® system. *Scientific Letters*, *1*(1), 4. https://doi.org/10.48797/sl.2024.119

Roscoe, M. G., Meira, J. B. C., & Cattaneo, P. M. (2015). Association of orthodontic force system and root resorption: A systematic review. *American Journal of Orthodontics and Dentofacial Orthopedics*, *147*(5), 610–626. https://doi.org/10.1016/j.ajodo.2014.12.026

Rossini, G., Parrini, S., Castroflorio, T., Deregibus, A., & Debernardi, C. L. (2015). Efficacy of clear aligners in controlling orthodontic tooth movement: A systematic review. *The Angle Orthodontist*, *85*(5), 881–889. https://doi.org/10.2319/061614-436.1

Roth, R. H. (1981). Functional occlusion for the orthodontist. *Journal of Clinical Orthodontics, 15*(1), 32–39.

Rudolph, D. J., Willes, M. G., & Sameshima, G. T. (2001). A Finite Element Model of Apical Force Distribution From Orthodontic Tooth Movement. *The Angle Orthodontist*, *71*(2), 127–131. https://doi.org/10.1043/0003-3219(2001)071<0127:AFEMOA>2.0.CO;2

Sachdev, S., Tantidhnazet, S., & Saengfai, N. N. (2021). Accuracy of Tooth Movement with In-House Clear Aligners. *Journal of the World Federation of Orthodontists*, *10*(4), 177–182. https://doi.org/10.1016/j.ejwf.2021.08.003

Seidel, C. L., Lipp, J., Dotzer, B., Rankovic, M. J., Mertmann, M., Wichelhaus, A., & Sabbagh, H. (2023). Investigation of Forces and Moments during Orthodontic Tooth Intrusion Using Robot Orthodontic Measurement and Simulation System (ROSS). Bioengineering, 10(12), 1356. https://doi.org/10.3390/bioengineering10121356

Simon, M., Keilig, L., Schwarze, J., Jung, B. A., & Bourauel, C. (2014). Forces and moments generated by removable thermoplastic aligners: Incisor torque, premolar

derotation, and molar distalization. *American Journal of Orthodontics and Dentofacial Orthopedics*, *145*(6), 728–736. https://doi.org/10.1016/j.ajodo.2014.03.015

Smith, R. J., & Burstone, C. J. (1984). Mechanics of tooth movement. *American Journal of Orthodontics*, *85*(4), 294–307. https://doi.org/10.1016/0002-9416(84)90187-8

Tageldin, H., Llano-Pérula, M., Thevissen, P., Celis, J.-P., & Willems, G. (2016). Quantifying Resistance to Sliding in Orthodontics: A Systematic Review. *British Journal of Medicine and Medical Research*, *17*(2), 1–30. https://doi.org/10.9734/BJMMR/2016/27208

Tai, S. (2018b). *Clear Aligner Technique*. Quintessence Publishing (IL)

Tsichlaki, A., Chin, S. Y., Pandis, N., & Fleming, P. S. (2016). How long does treatment with fixed orthodontic appliances last? A systematic review. *American Journal of Orthodontics and Dentofacial Orthopedics*, *149*(3), 308–318. https://doi.org/10.1016/j.ajodo.2015.09.020

Vieira, E. P., Watanabe, B. S. D., Pontes, L. F., Mattos, J. N. F., Maia, L. C., & Normando, D. (2017). The effect of bracket slot size on the effectiveness of orthodontic treatment: A systematic review. *The Angle Orthodontist*, *88*(1), 100–106. https://doi.org/10.2319/031217-185.1

Weir, T. (2017). Clear aligners in orthodontic treatment. *Australian Dental Journal*, *62*(S1), 58–62. https://doi.org/10.1111/adj.12480

Wiechmann, D., Rummel, V., Thalheim, A., Simon, J.-S., & Wiechmann, L. (2003). Customized brackets and archwires for lingual orthodontic treatment. *American Journal of Orthodontics and Dentofacial Orthopedics*, *124*(5), 593–599. https://doi.org/10.1016/j.ajodo.2003.08.008

Yoshida, N., Jost-Brinkmann, P.-G., Koga, Y., Mimaki, N., & Kobayashi, K. (2001). Experimental evaluation of initial tooth displacement, center of resistance, and center of

rotation under the influence of an orthodontic force. *American Journal of Orthodontics and Dentofacial Orthopedics*, *120*(2), 190–197. https://doi.org/10.1067/mod.2001.115036

Zheng, M., Liu, R., Ni, Z., & Yu, Z. (2017). Efficiency, effectiveness and treatment stability of clear aligners: A systematic review and meta-analysis. *Orthodontics & Craniofacial Research*, *20*(3), 127–133. https://doi.org/10.1111/ocr.12177