INSTITUTO UNIVERSITÁRIO EGAS MONIZ

MESTRADO INTEGRADO EM MEDICINA DENTÁRIA

REVISÃO NARRATIVA DE MODELOS FINITOS EM ALINHADORES

Trabalho submetido por

Joan Carlos Eusebio Jiménez

para obtenção do grau de Mestre em Medicina Dentária

Outubro de 2023

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Prof. Doutora Teresa Sobral Costa

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RESUMO

A ortodontia é uma área da medicina dentária que teve uma grande expansão nos últimos anos. Os alinhadores transparentes tornaram-se uma opção muito solicitada no tratamento ortodonticos devido à sua estética e conforto, no entanto, a previsibilidade dos movimentos dentários em ortodontia invisível sempre foi e é uma preocupação.

Nas últimas décadas, novos avanços na tecnologia, introduziram a análise de elementos finitos. A análise de elementos finitos é descrita como uma ferramenta que permite aos clínicos reconhecer de antemão as mudanças que surgem durante o tratamento ortodôntico e que podem potencialmente afetar o dente, o osso alveolar e o periodonto. O sucesso do tratamento com alinhadores transparentes depende muito do design do alinhador e da previsibilidade do movimento dentário. A literatura sugere que a análise de elementos finitos é uma ferramenta poderosa para simular e analisar o comportamento mecânico de materiais e estruturas, permitindo tentativa e erro virtual, ao mesmo tempo que minimiza a necessidade de ajustes clínicos extensos. À medida que esta tecnologia continua a evoluir, é importante que os profissionais se mantenham informados e educados sobre os avanços mais recentes. Ao abraçar esses avanços, podemos aumentar ainda mais os benefícios dos tratamentos com alinhadores transparentes e continuar a fornecer aos nossos pacientes o mais alto nível de eficácia.

O objetivo desta revisão narrativa é avaliar o papel do modelo de elementos finitos em ortodontia e como a previsibilidade desse método computadorizado contribuiu para um maior sucesso nas tecnologias de alinhadores transparentes.

Foi realizada uma pesquisa bibliográfica nos motores de busca, Google Scholar, PubMed, Web of Science, Science Direct, SciELO, NCBI e Springer Nature, de artigos científicos publicados nos últimos 10 anos em Inglês, Português e Espanhol com as palavras-chave: “finite elements in invisalign”, “orthodontics”, “finite elements orthodontics”, “finite elements in clear aligners”.

ABSTRACT

Orthodontics is an area of dentistry that has expanded greatly in recent years. Clear aligners have become a highly requested option in orthodontic treatment due to their aesthetics and comfort, however, the predictability of tooth movement in invisible orthodontics has always been a concern.

Over the last decades new advances in modern technology have introduced finite element analysis. Finite element analysis is described as a tool that allows clinicians to recognize beforehand the changes that surface during orthodontic treatment and that may potentially furthermore affect the tooth, alveolar bone, and the periodontium.

The aim of this narrative review is to evaluate the role of the finite element model in orthodontics, and how the predictability of this computerized method has contributed to a higher success in clear aligner technologies. A bibliographic collection will be carried out in the search engines Google Scholar, PubMed, Web of Science, Science Direct, SciELO, NCBI, and Springer Nature, of scientific articles published in the last 10 years in English, Portuguese, and Spanish with the keywords: "finite elements in invisalign", "orthodontics", "finite elements orthodontics", "finite elements in clear aligners".

The clear aligner market has experienced significant growth in recent years, with more patients opting for an aesthetic alternative to traditional braces. However, the success of clear aligner treatment relies heavily on aligner design and dental tooth movement predictability. Literature suggests finite element analysis is a powerful tool for simulating and analyzing the mechanical behavior of materials and structures, allowing for virtual trial and error, while minimizing the need for extensive clinical adjustments. As this technology continues to evolve, it is important for professionals to stay informed and educated on the latest advancements. By embracing these advancements, we can further enhance the benefits of clear aligner treatments and continue to provide our patients with the highest level of care.

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Abbreviation list

ABO=The American Board of Orthodontics

CAD = Computer Aided Design

CAD-CAM= Computer-aided design and Computer-aided manufacturing

CAT= Clear Aligner Therapy

CBCT= Cone beam Computerized Tomography

CRES= Center of Resistance

CROT= Center of Rotation

CR-Eval= Cast-Radiograph Evaluation

CT= Computerized Tomography

FEA = Finite Element Analysis

FD= Fibrous dysplasia

FEHM= Finite Element Head Model

FE= Finite Element

FEM = Finite Element Method

MSM= Mass-spring-models

MTM= Mass-tensor-models

NiTi= Nickel-titanium

OHRQoL= Oral health-related quality of life

OTM= Orthodontic tooth movement

PAR=Peer Assessment Rating

PDL= Periodontal Ligament

PMHS= Postmortem human subject tests

PMMA= Polymethylmethacrylate

WHO= World Health Organization

3D= Three Dimensional

WSL= White spot lesions

ANSYS= Analysis system

1 Introduction

Clear aligner technology (CAT) has become the most popular orthodontic treatment option for adult patients seeking corrections for dental malocclusions. Clear aligner technology is well recognized for its comfort and aesthetically pleasing appearance. However, limitations with aligner technology has become a matter of concern when adjustments that involve arduous forces are addressed.

Finite element analysis (FEA) is a modern computerized method, where a mathematical model of dentition is obtained from Computer Aided Design (CAD). Finite element analysis has proven to calculate initial tooth movement instantaneously after force is applied. The FEA has been used to interpret stress-distortion responses and has demonstrated to be an effective tool for simulating tooth migration patterns in orthodontics.

Authors consider there are still concerns regarding clinical outcomes and unanticipated orthodontic tooth movements in clear aligner therapy. Studies suggest this may be attributed to lack of clarification of force and transmission mechanism in aligners therapy.

Findings indicate the finite element model for transparent thermoplastic tooth aligners has been successfully developed and verified, therefore, the model can be employed with confidence to predict the forces and movements applied to the teeth by the clear aligner systems.

The variability of results suggest more research is required to address the role of finite element method (FEM) in aligner therapy, and how the predictability of this computerized method is contributing to higher success in aligner technologies.

2 LITERATURE REVIEW

2.1 Dental Malocclusion

The Glossary of Orthodontic Terms defines malocclusion as the state of any deviation from the normal or ideal occlusion (Daskalogiannakis, 2000).

Dental malocclusion is one of the most common dental problems, being referred to as abnormal occlusion or disturbed craniofacial relationship. Dental malocclusions have proven to affect esthetic appearance, function, facial harmony, and psychosocial well-being (Zou et al., 2018). Malocclusions have been found to be generally associated with oral health related quality of life (OHRQoL) (Närhi et al., 2021).

The classification of malocclusions is complex due to its impact on dental, facial, and skeletal abnormalities, as well as the functions of the stomatognathic system. Studies indicate that malocclusions are highly prevalent, ranging from 62% to 96% during early stages of life. Moreover, most of these dental abnormalities persist without resolution (Moimaz et al., 2021).

2.2 Orthodontics

Orthodontics is a branch of dentistry dedicated to the investigation and practice of moving teeth through the bone (Li et al., 2018). Orthodontic treatment, commonly used in children, is now being increasingly used in adults due to innovative technology and techniques. Orthodontics strives to achieve an enhanced bite and improved aesthetics, emphasizing functionality and stability (Marincak et al., 2022).

Noyes first defined orthodontics in 1911 as “the study of the relation of the teeth to the development of the face and the correction of arrested and perverted development”. (Basavaraj Subhashchandra Phulari, 2013)

Later on The American Board of Orthodontics (ABO) defines Orthodontics as “the specific area of the dental profession that has the responsibility, study and supervision of the growth and development of dentition and its related anatomical structures from birth to dental maturity, including all preventive and corrective procedures of dental irregularities requiring the repositioning of teeth by functional and mechanical means to establish normal occlusion and pleasing facial contours.”

The average orthodontic treatment ranges from 18-24 months, accordingly requiring patient cooperation and commitment (Li et al., 2018). Poorly aligned teeth can lead to various negative effects, including oral hygiene issues, periodontal disease, dental caries, esthetic problems, increased risk of trauma, and function abnormalities (Basavaraj Subhashchandra Phulari, 2013).

2.3 Orthodontic tooth movement

Orthodontic tooth movement is achieved through physical stimulation and tissue remodeling, adhering to Newton's laws of motion. Applied force induces bone remodeling and tooth displacement, facilitated by the periodontal ligament (PDL). This procedure involves a combination of bone adaptation and reversible lesions to the periodontium. The tooth's biological system responds to changes in force and direction through receptor cells and signaling pathways, leading to bone remodeling and orthodontic tooth movement. According to the pressure theory, chemical signals stimulate cellular differentiation and tooth movement within the periodontal ligament. This theory suggests that after force is applied, the tooth moves from its original position within the periodontal ligament space, resulting in compression in some areas and tension in others. Compression and tension zones are associated with specific mediators regulating resorption and deposition, respectively. Blood flow is affected differently on the compression and tension sides, with a decrease on the compression side and maintenance or increase on the tension side (Figure 1) (Li et al., 2018).

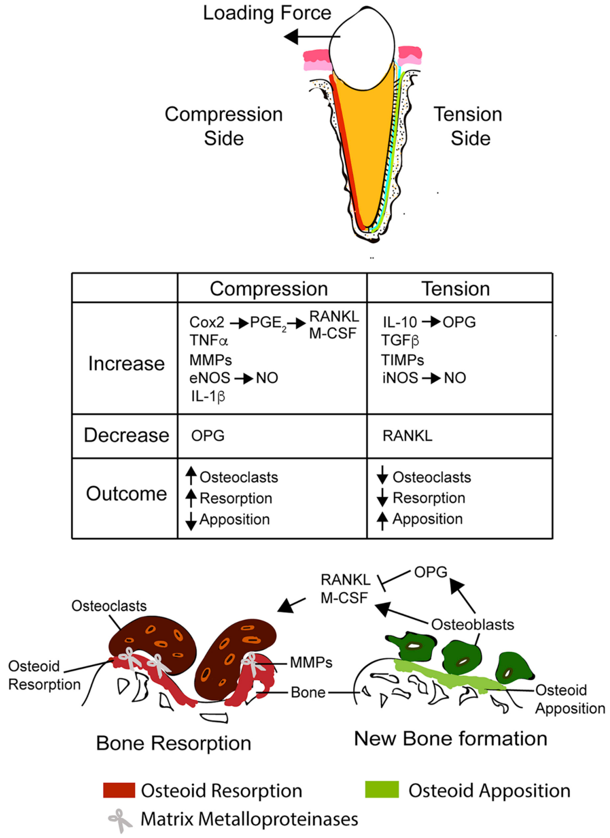

Figure 1- *Signaling associated with compression and tension as a consequence of orthodontic loading*

Source: (Li et al., 2018) Orthodontic tooth movement: The biology and clinical implications. *The Kaohsiung Journal of Medical Sciences*, *34*(4), 207–214.

2.4 Fixed orthodontic appliance

Orthodontic treatment has become increasingly widespread due to advancements in technology and continuous development of new techniques (Marincak et al., 2022).

Orthodontic treatment with fixed orthodontic appliances typically lasts less than 2 years but can vary greatly (Tsichlaki et al., 2016). The success of fixed orthodontic appliances depends on the secure attachment of brackets and bands to the teeth, which is achieved through bonding with adhesive systems (Millett et al., 2016).

The presence of fixed orthodontic appliances can compromise oral hygiene by creating additional surfaces for plaque retention, increasing the risk of gingivitis and gum inflammation. Proper oral hygiene practices are crucial in maintaining oral health while undergoing orthodontic treatment (Marincak et al., 2022). The incidence and prevalence of White Spot Lesions (WSLs) in orthodontic patients is significant due to difficulties in maintaining oral hygiene and plaque accumulation. These subsurface enamel porosities result from demineralization and can lead to cavity formation and caries if left untreated (Venkatachalapathy et al., 2015).

2.5 Clear Aligner Technology (CAT)

Increasing demand for aesthetically pleasing orthodontic devices, especially among adults, led to the development of clear aligner therapy (CAT), providing a comfortable and visually appealing alternative to conventional fixed appliances (Nucera et al., 2022).

The use of aligners to straighten teeth was first introduced in 1946 by Harold D. Kesling. However, back then thermoformed appliances were utilized for limited tooth movement, primarily involving the tipping of crowns and minor rotations (Morton et al., 2017).

Align Technology introduced Invisalign® in 1999, a revolutionary orthodontic treatment that utilizes clear aligners made from removable thermoplastic materials. This innovative approach incorporates Computer-aided design (CAD) and Computer-aided manufacturing (CAM) technologies, as well as tooth movement simulation softwares, to improve the effectiveness and efficiency of orthodontic procedures (Weinstein et al., 2021). Invisalign® is a professional orthodontic treatment option that uses clear aligners made of transparent thermoplastic materials to gradually and effectively move teeth into the desired position (Upadhyay & Arqub, 2021).

Following the introduction of invisalign, clear aligner therapy experienced significant advancements, including the use of intraoral digital scans which substituted physical impressions. These advancements include digital image acquisition, treatment planning, model production, and 3D (three-dimensional) printing, resulting in more precise and predictable tooth movements. Three-dimensional printing has currently become the leading technology for fabricating orthodontic models (Figure 2) (Hartshorne & Wertheimer, 2022).

Figure 2- *A fully assembled dental model 3D printed in Model Resin.*

Source: (Sertoglu, 2021) *Formlabs advances dental 3D printing with new hardware, software, and materials updates*. 3D Printing Industry.

According to Tartaglia et al. (2021), benefits of using clear aligner therapy as orthodontic treatment incorporate, the ability to remove the appliance for eating and oral hygiene, increased comfort, shorter treatment time, outstanding clear appearance and simplicity of use.

2.5.1 Materials

Currently, a variety of materials are used to manufacture aligners systems such as polyethylene terephthalate glycol, polypropylene, polycarbonate, thermoplastic polyurethanes, and ethylene-vinyl acetate (Lombardo et al., 2015). Moreover, materials such as copolyester, and polyvinyl chloride, can also be employed for clear aligner manufacturing (Hartshorne & Wertheimer, 2022).

Combining multiple polymers like polyester, polyurethane, and polypropylene improves aligner effectiveness. Research indicates enhanced mechanical and chemical qualities leading to superior clinical outcomes (Bichu et al., 2023). Biomechanical properties of these materials, including elasticity, hardness, and transparency, play a significant role in their selection and effectiveness (Hartshorne & Wertheimer, 2022). Aligner material selection for orthodontic treatment depends on the manufacturing method, which can involve molding on physical models, 3D printing from virtual planning software, or direct 3D printing without physical models (Tartaglia et al., 2021).

Thermoplastic polymers used for clear aligner therapy can be categorized as amorphous or semicrystalline, depending on their molecular structure. Amorphous polymers have irregular molecular arrangements, resulting in materials that are softer and more transparent. On the other hand, semicrystalline polymers have both tightly packed chains and irregular areas, making them harder and more opaque (Bichu et al., 2023). Nonetheless, the presence of microplastics in oceans calls attention to the negative consequences of aligner plastic waste on the environment and human well-being. To address this issue, aligner manufacturers, clinicians, and users must take responsibility and prioritize sustainable practices (Bichu et al., 2023).

2.5.2 Fabrication

The popularity of transparent aligners has increased due to drawbacks of fixed orthodontic treatment. Clear aligners are made from precise impressions or digital scans of the teeth, allowing for progressive dental alignment with different forces (Tartaglia et al., 2021).

Previously, only two manufacturing methods existed for CAT: vacuum forming and pressure forming. Vacuum forming applies pressures of 3-14 psi, while pressure forming applies pressures of up to 100 psi. The intimacy of fit and ability to generate forces depend on the air pressure used, with higher pressures resulting in improved precision and force generation (Weir, 2017).

Clear aligners were commonly produced using a thermoforming process, which tends to modify the material's properties (Figure 3). Fabrication of thermoformed clear aligners can vary in thickness. Thicker aligners provide enhanced force due to stiffness, but the thermoforming process can decrease these properties depending on the material and process used. The evenness of aligner thickness is also important for accurate and well-fitted alignment (Tartaglia et al., 2021).

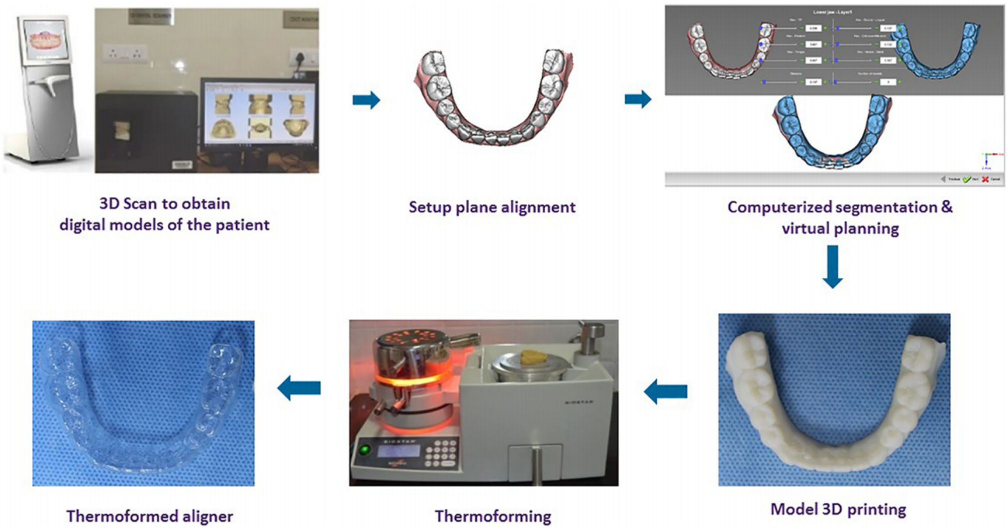

Figure 3- *The key stages of laboratory procedure in the manufacturing of thermoformed clear aligners.*

Source: (Rajasekaran & Prabhat Kumar Chaudhari, 2023) Integrated manufacturing of direct 3D-printed clear aligners. *Frontiers in Dental Medicine*, *3*.

Traditional manual fabrication of clear aligners is being replaced by digital methods using CAD/CAM technology. Digital images of the patient's teeth are obtained through intraoral or digital scanning of impressions (Figure 4). Treatment planning and tooth movement manipulations are done using CAD platforms, 3D models are printed using CAM technology and clear aligners are made on these models. Numerous materials can be used for 3D printing. The process is lengthy, requires significant labor, and entails high expenses (Tartaglia et al., 2021). Direct 3D printing of aligners offers a solution to the negative impacts typically associated with thermoforming, including changes to the material's mechanical, dimensional, and aesthetic properties. Direct 3D printing licenses the creation of precise aligners with soft edges, resulting in a better fit, higher efficacy and reproducibility (Figure 5) (Ryu et al., 2018).

The incorporation of Direct 3D printing, also known as additive manufacturing, enables the sequential production of components, distinguishing it from other conventional manufacturing techniques such as machining, molding, and subtractive methods. Additionally, direct 3D printing of aligners offers advantages such as improved accuracy, shorter supply chains and lower costs. Direct 3D printing is also a more sustainable process that generates significantly less waste than subtractive and thermoforming processes (Tartaglia et al., 2021). Overall, 3D direct printing of clear aligners offers a more efficient and customizable approach to orthodontic treatment (Figure 6) (Bichu et al., 2023).

Figure 4- *Digital 3D dental model impression by means of an iTero scanner*

Source: (Weinstein et al., 2021) Five-to-five clear aligner therapy: predictable orthodontic movement for general dentist to achieve minimally invasive dentistry. BMC Oral Health, 21(1).

Figure 5- *Direct 3D printed clear aligner*

Source: (Tartaglia et al., 2021) Direct 3D Printing of Clear Orthodontic Aligners: Current State and Future Possibilities. Materials, 14(7), 1799

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The use incorporation of attachments as auxiliaries in clear aligner therapy has been found to enhance the effectiveness of orthodontic movement. Composite attachments applied to the tooth surface improve aligner retention and enables more complex orthodontic adjustments (Upadhyay & Arqub, 2021). Type, shape, size, and number of attachments used in CAT are critical factors to consider in the overall assessment (Nucera et al., 2022).

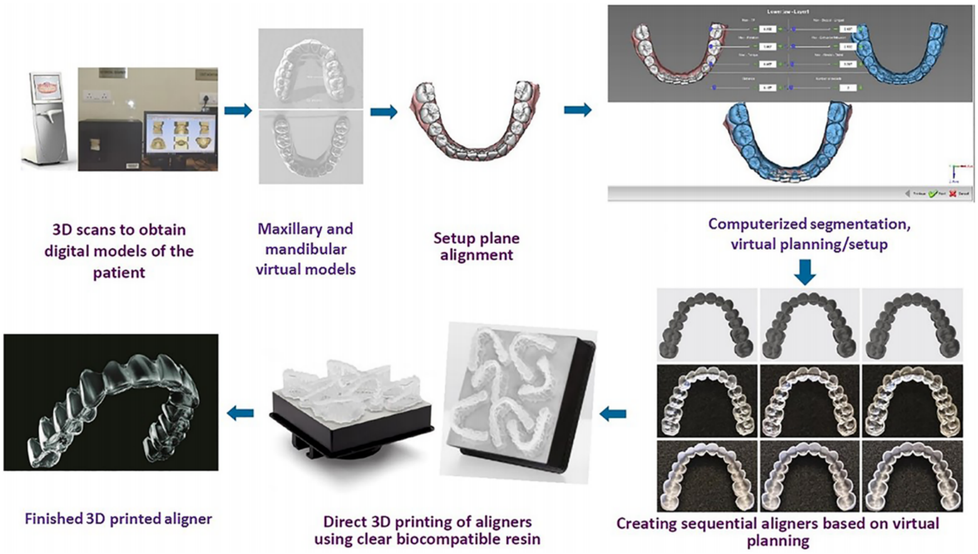

Figure 6- *The key stages of laboratory procedure in the manufacturing of direct 3D-printed clear aligners.*

Source: (Rajasekaran & Prabhat Kumar Chaudhari, 2023) Integrated manufacturing of direct 3D-printed clear aligners. *Frontiers in Dental Medicine*, *3*.

2.6 Aligners

Arrays of companies are manufacturing aligners today. Clear thermoformed plastic is the universal material used in all aligner systems (Ganta et al., 2021). The orthodontic industry offers numerous aligner brands, but their quality and features can vary significantly (Shi et al., 2022).

Align Technology introduced Invisalign® in 1997, and completely revolutionized the orthodontic field (Morton et al., 2017).

Invisalign® is a professional orthodontic treatment that utilizes patented SmartTrack® material. SmartTrack® is a thermoplastic polyurethane with integrated elastomer. This material applies continuous light forces to the teeth, enhancing predictability in orthodontic movements (Lombardo et al., 2015). Treatment involves scanning the teeth to promote a computer simulation of the final results. Invisalign® orthodontic treatment utilizes thermoplastic aligners for comfort and aesthetics, allowing precise control over tooth movement and reducing discomfort associated with orthodontic forces (Figure 7) (Tamer et al., 2019). Biomechanical principles utilized by invisalign enable precise tooth movement, including rotation and root adjustment, to achieve personalized results (Morton et al., 2017). Align Technology created attachments to aid in precise tooth movement for predictable treatment outcomes, offering flexibility in rotation, torque, and distalization rates (Figure 8) (Simon et al., 2014). Invisalign® has gained significant popularity among adults as a reliable and effective orthodontic treatment option (Weinstein et al., 2021).

Figure 7- *Invisalign* Clear aligner

Source: (Kaur et al., 2021) Invisalign. International Journal of Health Sciences, 46–52.

Figure 8- *Invisalign® clear aligner tray with attachments*

Source: (Weinstein et al., 2021) Five-to-five clear aligner therapy: predictable orthodontic movement for general dentist to achieve minimally invasive dentistry. BMC Oral Health, 21(1)

The introduction of Invisalign sparked the growth of various aligner manufacturers and systems (Hennessy & Al-Awadhi 2016). Following invisalign numerous companies have produced a range of aligners with diverse characteristics, including various materials, designs, and attachment shapes (Dasy et al., 2015).

ClearCorrect was established in 2006. This company manufactures clear aligners designed to improve aligner retention by overlapping the attached gingiva. Additionally, in order to achieve this enhanced retention precise impressions and scans of the gingiva are required (Weir, 2017). ClearCorrect aligners are a popular orthodontic treatment option that employs CAD-CAM technology to generate bonded resin attachments and promote precise tooth movement. These aligners have gained widespread acceptance and popularity due to their remarkable color stability (Kundal & Shokeen, 2020). ClearCorrect aligners are made using clear quartz material, providing a comfortable and steady force during teeth alignment. Compared to other aligners, ClearQuartz maintains its initial force and shape over time, ensuring consistent results (Bichu et al., 2023).

3M Oral Care Solutions launched Clarity aligners in 2017, this system allowed clinicians to plan and order aligners using web-based software. This software offered flexibility for orthodontists as they were allowed to use their preferred intraoral scanner for impressions (Grünheid et al., 2022). Clarity aligners are an effective treatment option for patients with mild to moderate malocclusions. This aligner system performs on par with other established aligner systems like invisalign. However, it renders limitations in vertical aspects of occlusion (Grünheid et al., 2022). According to Harandi et al. (2023), the use of clarity aligners for treating mild to moderate malocclusions, was a suitable treatment option. However, invisalign demonstrated greater rotational precision for specific teeth including maxillary central and lateral incisors, mandibular canines, and mandibular first premolars when compared to clarity aligners.

Clear aligner therapy (CAT) is a highly sought-after treatment option for moving teeth, known for its aesthetic appeal, cleanliness, and comfort. Sequential movements and elastic forces enable CAT precise tooth adjustment, making it an effective solution for complex orthodontic cases (Yao et al., 2023).

2.7 Orthodontic tooth movement with CAT

The development of clear aligners provided non-invasive solutions for tooth misalignment corrections. From their initial use in minor cases, clear aligners have now become a popular choice for treating moderate to severe malocclusions (Tartaglia et al., 2021). The stress between aligners, periodontal ligament and bone lead to movement in orthodontic treatment, with force transmitted through the periodontal complex (Upadhyay & Arqub, 2021).

Clear aligner therapy (CAT) is gaining popularity in orthodontics as it provides esthetic benefits, comfort, and better oral hygiene compared to traditional appliances. CAT can achieve different types of tooth movements, including intrusion, molar distalization, root torque, and incisor retraction. Nevertheless, the predictability and treatment complexity of tooth movements with CAT can vary across different cases (Liu et al., 2022).

Clear aligner manufacturing companies like Align Technology and ClearCorrect, have reported aligner predictability movements without attachment use (Table 1) (Weir, T. 2017). However, it has been vastly demonstrated that the inclusion of attachments in clear aligner therapy improves orthodontic tooth movement (Upadhyay and Arqub 2021).

Attachments can enhance the effectiveness of molar mesio-distal movement. Moreover, attachments bonded to posterior teeth can enhance posterior anchorage, with optimized and rectangular horizontal attachments yielding the most favorable outcomes. Correction of rotation is difficult to achieve in transparent aligners, especially in conical teeth. However, the use of attachments creates undercuts and enhances retention for more effective derotation movements (Nucera et al., 2022). A study by Cortona et al., (2019), suggests that using aligners and attachments effectively controls the rotation of lower teeth.

The use of attachments can also facilitate intrusions (Nucera et al., 2022). The use of particularly five attachments per quadrant can improve posterior anchorage, molar movement, and intrusion (Garino et al., 2016). Clear aligners can achieve significant incisor intrusion and palatal torquing in extraction cases, suggesting that overtreatment with aligners is justifiable. However, clear aligners alone have advantages but may be less effective in extraction cases due to unpredictable tooth movement, causing issues such as lingual tipping, incisor extrusion, and mesial tipping of posterior teeth (Liu et al., 2022).

Extrusion of the anterior teeth is necessary to treat the complex malocclusion known as anterior open bite (Savignano et al., 2019). Aligners are recommended for treating open bite malocclusion, which requires orthodontic movements such as the extrusion of anterior teeth, the intrusion of posterior teeth, or both (Giancotti et al., 2017). Inadequate maxillary arch width results in narrowed dentition and crossbite, impacting function and aesthetics. While CAT has been shown to expand the arch, its efficiency decreases with distal movement. Moreover, CAT tends to cause buccal tilt, which is associated with severe periodontal issues. Additional investigation is required to understand the potential of CAT for improving tooth movement efficiency and torque control (Yao et al., 2023).

Table 1
Tooth movement predictability

TOOTH MOVEMENT	PREDICTABILITY WITH ALIGNERS ALONE		
	Predictable	Moderate	Difficult
Crowding or spacing per arch	Up to 6mm	6-8mm	>8mm
Midline discrepancy	Up to 2mm	2-3mm	>3mm
Central incisor rotation	Up to 40°	40-50°	>50°
Lateral incisor rotation	Up to 30°	30-40°	>40°
Canine and premolar rotation	Up to 45°	45-55°	>55°
Molar rotation	Up to 20°	20-30°	>30°
Anterior extrusion per arch	Up to 2.5mm	2.5-3mm	>3mm
Anterior intrusion per arch	Up to 0.5mm	0.5-1mm	>1mm
Posterior intrusion per arch	Up to 0.5mm	0.5-1mm	>1mm
Posterior extrusion per arch	0mm	0.5mm	>0.5mm
Expansion per quadrant	Up to 2mm	2-3mm	>3mm
Anteroposterior correction	Up to 2mm	2-4mm	>4mm
Incisor lingual root torque	0-10°	10-15°	>15°
Posterior tooth lingual root torque	0-5°	5-10°	>10°
Posterior tooth distal movement (maxilla)	0-2mm	2-4mm	>4mm
Posterior tooth mesial movement	0-1mm	1-2mm	>2mm

Note. Tooth movement predictability with ClearCorrect and Invisalign™

Source: Weir, T. (2017). Clear aligners in orthodontic treatment. Australian Dental Journal, 62(S1), 58–62.

3 Finite Element Method

The finite element method (FEM) is a mathematical method for solving equations. FEM has the ability to solve complicated problems that can be represented in different equations that occur naturally in all fields of physical science (Baccouch, 2021). The finite element method is a strategy for obtaining a numerical solution to a specific problem (Bandela & Kanaparthi, 2020).

Finite element analysis (FEA) is a computer simulation technique that enables complex biomechanical analyses. It offers advantages such as the ability to create multiple simulations with controlled variables, ensuring high reproducibility. FEA also provides a valuable database for future clinical trials, minimizing the need for unnecessary duplication of studies (Song et al., 2023). FEA studies offer various simulation options, enabling the identification of the most suitable option for clinical validations (Liu et al., 2022). This numerical analysis technique has been successfully used in engineering and bioengineering since the 1960s to solve complex problems that cannot be analyzed using traditional analytical methods (Piccioni et al., 2013).

The finite element method (FEM) is a numerical technique used to perform finite element analysis (FEA) of any given physical phenomenon (Harish, 2016).

3.1 Finite elements analysis applications in dentistry

Dentistry is a continuously growing branch of medicine. Focusing primarily on the diagnosis, prevention, and treatment of oral cavity diseases and conditions. The law of physics can be used to describe natural phenomena, and finite element analysis is a similar computer-based method that breaks down structures into small elements for examination (Bandela & Kanaparthi, 2020).

Finite element analysis numerical method is used to simulate the behavior of a structure by breaking it down into small elements connected through nodes and subjecting these nodes to forces (Baccouch, 2021). The mechanical behavior of each element in a structure can be determined by analyzing the displacement of its nodes under specific loading conditions. By solving a system of simultaneous equations, it is possible to relate the forces and displacement of the nodes, enabling the calculation of stress and strain in each element and the overall evaluation of the structure. FEA provides mathematical conversions and analysis of mechanical properties of objects that have significant applications in the dental field. Licensing the study of mechanical aspects of biomaterials and human tissues is essential for gaining valuable insights that cannot be obtained in vivo (Bandela & Kanaparthi, 2020).

Moreover, a precise model is essential for reliable results in finite element analysis (Baccouch, 2021).

3.1.1 Finite element analysis in oral radiology

Radiology plays a crucial role in dentistry. Diagnostic images are used to interpret dental and craniofacial structures. Tools such as finite element analysis, help ensure accurate diagnoses and allow anticipation of any future potential iatrogenic effects (Baccouch, 2021).

According to Kihara et al. (2019), the longitudinal change in mandibular volume and configuration in a patient with craniofacial fibrous dysplasia (FD) using 3-D models with FEA, exhibits enlarged non-uniform lesions in the mandible. Suggesting that compression stress caused by occlusal force through the teeth may influence the direction and enlargement in fibrous dysplasia.

3.1.2 Finite elements analysis in dental ceramics and restorative dentistry

Dental ceramics is a delicate and inorganic material used in dentistry to replace missing or damaged teeth, and finite element analysis is a mathematical method used to foresee strength values and minimize errors in restorative dentistry (Baccouch, 2021).

Anticipating the behavior of materials and dental tissues is imperative to guarantee successful treatment outcomes. Composites have been demonstrated to carry compressive strength, abrasion resistance and high translucency. In restorative dentistry FEA is used as an aid to analyze stress generated to teeth and their restorations (Bandela & Kanaparthi, 2020).

Utilizing the power of FEA numerical simulation, the realm of mechanical stability and long-term success in post-and-core restorations is enhanced. Particularly for teeth with limited coronal dentin, it becomes crucial to reduce oblique forces and protect the remaining dentin from potential fractures (Trivedi, 2014).

3.1.3 Finite elements analysis in endodontics

Endodontics is the branch in dentistry that specializes in treating the health, form, disease, injury and function of the dental pulp and periradicular region. Through endodontic instrumentation the goal is to build preparations that preserve root canal anatomy and maintain an adequate apical seal. When apical pressure is applied to root walls during instrumentation, it may lead to inadequate canal preparations or microcracks, that furthermore lead to vertical fractures and tooth loss. FEA has demonstrated to be a reliable tool to examine treatment outcomes by analyzing the selected treatment technique and the properties of the material employed (Baccouch, 2021).

Finite element analysis (FEA) is an innovative method that uses computer aided design to mimic the mechanical behavior and stress distribution of endodontic rotary instruments under bending and torsional conditions (Roda-Casanova et al., 2021).

3.1.4 Finite element analysis in prosthodontics

Finite Element Analysis (FEA) is a method used to assess stress patterns and their distribution between a tooth and the material it is made of, with the goal of minimizing failure (Bandela & Kanaparthi, 2020).

According to Tatarciuc et al. (2021), dental prosthesis plays a crucial role in reestablishing the dental arch and restoring the functions of the dento-maxillary system. However, in order to evaluate the durability of prosthetic appliances, it is necessary to understand the differing responses of their structural elements and their behaviors over time. FEA, by incorporating certain assumptions and simplifications, allows us to evaluate the stability of dental bridges and the stress they impose on abutment teeth in scenarios of partial tooth loss. Finite element analysis, suggests stress resulting from the loading force does not harm the prosthetic device or abutment teeth; However, the connection area between bridge elements requires meticulous attention.

3.1.5 Finite element analysis in implantology

Finite element analysis helps in predicting stress patterns in dental implants and surrounding bone, aiding in designing appropriate implants and insertion techniques (Bandela & Kanaparthi, 2020).

The success of implants and posteriorly prosthodontics resides on the amount of stress transferred to the supporting tissue, consequently excessive forces produce higher stress resulting in bone resorption. Several methods have been analyzed to measure stress of dental structures displaying many disadvantages, however finite element analysis has proven to be a more accurate tool (Khurana et al., 2018).

The success of a dental implant relies on its biomechanical behavior, as stress distribution is different from that of a natural tooth. The presence of a periodontal ligament in natural teeth acts as a shock absorber, so the success of a dental implant depends on how stress is transferred to the surrounding bone. The use of 3D FEM provides a detailed analysis of the relationships between dental implants, teeth, periodontal ligaments, and bone. Validated 3D modeling shows that this technique can accurately measure stress distribution in bone. However, to improve dental implant success, clinicians must thoroughly assess the biomechanics of implants and understand the concept, methodology, benefits, and limitations of FEA. By incorporating computer technology and developing a deeper awareness, clinicians can enhance implant survival and advance the field of dental implantology (Reddy et al., 2019).

According to a study by Moraes et al. (2018), the finite element method is being used in dentistry to better understand the biomechanical behavior of dental implants. This method, when combined with well-designed clinical studies, could help develop new strategies for managing stress distribution in implant dentistry. However, caution should be taken when interpreting the results. More controlled and randomized clinical studies are needed to fully evaluate the clinical implications of biomechanical parameters in implant dentistry. The study found that increasing the diameter of implants improved stress distribution in the cortical bone region, regardless of the connection type.

3.1.6 Finite element analysis in orthognathic surgery

Orthognathic surgery is a dental procedure that restores the jaw and face, treating issues like growth modifications, joint disorders, sleep apnea, and skeletal deformities. Virtual planning tools like finite element analysis enable accurate preoperative planning for better outcomes (Bandela & Kanaparthi, 2020).

Repositioning the maxilla through orthognathic surgery serves functional and aesthetic purposes, and pre-surgical planning tools enable accurate prediction of 3D facial appearance by evaluating how soft tissue reacts to alterations in the underlying skeleton. Pre-surgical planning for maxillofacial and orthognathic surgery relies on skull radiographs and advanced imaging techniques to predict the 3D facial appearance after the surgery. Various computer software tools, such as mass-spring-models (MSM), mass-tensor-models (MTM), and finite element models (FEM), are used for soft tissue prediction. FEM approach offers insights into the impact of modeling inaccuracies and surgical planning uncertainties, helping patients and surgeons make informed decisions (Knoops et al., 2018).

3.1.7 Finite element analysis in trauma, fractures and reconstructive surgery

The use of finite element modeling has shown promise in the study of head trauma biomechanics over the past two decades. Researchers at Strasbourg University conducted a study using composite skull models to simulate skull fractures and contact forces. The results revealed significant similarities between the simulations and experimental findings. Suggesting the effectiveness of FEA in replicating real-world head trauma scenarios (Sahoo et al., 2016).

The Finite Element Method can be used to compare the elasticity and deformation of different bone types, aiding clinicians in understanding bone remodeling processes and enhancing surgical techniques. Additionally, FEM analysis in reconstructive surgery allows for assessing implant resistance to potential impacts estimating mechanical performance (Moncayo-Matute et al., 2022). Finite Element Analysis can also be used to estimate biomechanical responses of tissues and organs to specific conditions, including fracture. FEA provides valid models for analyzing facial trauma and can simulate injuries to the human skull. Additionally, FEA can estimate stress levels in different regions of the mandible and provides valuable information for surgical techniques and biomaterial development (Trivedi, 2014).

3.1.8 Finite element analysis in periodontics

The main function of the periodontal ligament is to support the tooth. The periodontal ligament (PDL) is an important aspect in finite element analysis designing as it affects the properties of a 3-D model. Overlooking the importance of the periodontal ligament may result in unreliable values of stress and force distribution (Bandela & Kanaparthi, 2020).

Proper balance and occlusion in the stomatognathic system are important for periodontal health, while imbalances can lead to periodontal disease. The FEM study found that higher occlusal loads and compromised bone levels increase stress on the periodontium, potentially causing periodontal destruction (Vandana & Reddy, 2018).

3.1.9 Finite element analysis in orthodontics

Three-dimensional finite element analysis has proven to be effective in complex biomechanical analyses and is widely used in orthodontics. FEA studies allow various simulations to be examined, helping to identify the most appropriate approach for future clinical validation (Liu et al., 2022).

Engineering, particularly in orthodontics, has made significant advancements with the use of FEA to calculate stress in biomaterials and human tissues. Applying force to the teeth during orthodontic treatment causes the surrounding tissues to undergo changes. This includes resorption and apposition of alveolar bone, resulting in tooth displacement. Various studies have explored these reactions, with finite element analysis being the most advanced and reliable method. This numerical analysis technique divides the structure into elements to determine stresses and displacements. Finite Element Method (FEM) involves three steps: pre-processing, processing, and post-processing. Pre-processing includes constructing a geometric model, converting it to finite element representation, defining material properties, boundary conditions, and loading (Singh et al., 2016). Overall, pre-processing is essential for obtaining reliable results in finite element analysis. The network model used for analyzing objects prioritizes non-overlapping neighboring elements with a simple structure. One-dimensional, two-dimensional, and three-dimensional objects are divided into finite elements connected by nodes. The body is represented by these elements and nodes, providing physical continuity (Aktı & Kaya, 2020).

Processing involves solving linear algebraic equations, while post-processing involves interpreting the results (Singh et al., 2016). The solution or processing stage is where the equations formed between the finite number of elements after the forces are applied are solved and resolved. Finally, the evaluation of the results or post-processing involves visualizing solutions through charts, figures, and color graphics (Figure 9) (Aktı & Kaya, 2020).

The integration of engineering knowledge and computational techniques in dentistry has provided insights into oral biomechanics and facilitated optimization of component strength and longevity. This method allows us to delve into the intricacies of the structures involved and gain insight into the dynamic relationship between compression and resorption, as well as tension and formation (Piccioni et al., 2013). Orthodontic tooth movement involves the delivery of force to the teeth, which causes changes in the periodontium. Finite element analysis stands out as the most advanced and reliable approach to measure orthodontic forces (Singh et al., 2016).

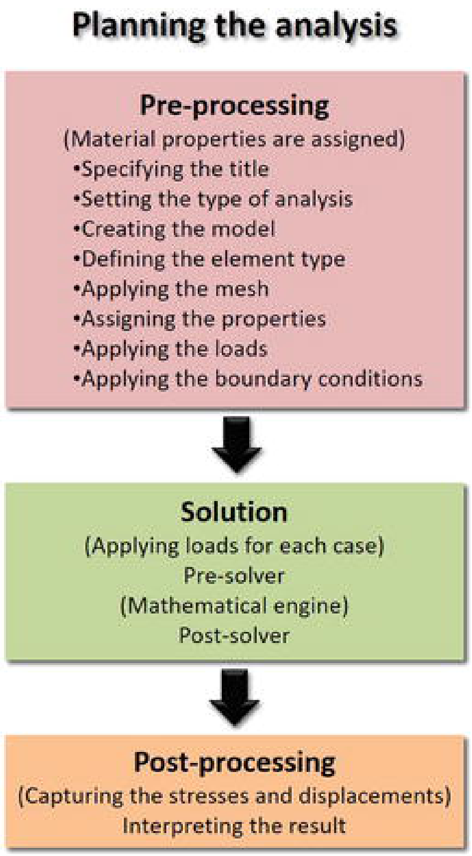

Figure 9- *Planning of analysis*

Source: (Bandela & Kanaparthi, 2020). *Finite Element Analysis and Its Applications in Dentistry*. Mahboub Baccouch. BoD – Books on Demand.

3.2 Finite Element analysis in CAT

Finite element analysis is an effective approach to examine the biomechanics of aligners (Song et al, 2023). It can be performed in one, two, or three dimensions, allowing for the evaluation of stress distribution and shape changes. This method is advantageous as it can model complex solids, analyze structures made of different materials, and provide real material definition. Additionally, it can also be repeated, resulting in shorter time compared to experimental research (Aktı & Kaya, 2020).

CAT is gaining popularity for its aesthetic and comfortable features; it employs tiny sequential movements with elastic force to gradually move teeth (Cortona et al., 2019). CAT customized appliance therapy offers a broad range of tooth movement options, allowing for complex orthodontic treatments such as intrusion, molar distalization, and root torque, thus enhancing clinical possibilities (Barone et al., 2016). Moreover, CAT has demonstrated effectiveness in arch expansion, but has been revealed to promote bucal tilt. A less predictable buccal tilt increases the likelihood of experiencing severe periodontal destruction, such as buccal gingival recession (Morris et al., 2017). Finite element analysis (FEA) creates multiple simulations with precise control over variables, while ensuring reproducibility (Liu et al., 2022).

The global use of clear aligners to treat misaligned teeth is increasing due to consumer demand, but concerns about the system's ability to effectively control tooth movement persist (Jiang et al., 2020). According to a study by Song et al. (2023), employing finite element analysis to examine movement strategies is a valuable tool.

3.2.1 Finite element analysis orthodontic tooth movement with CAT

Orthodontic movement is a biomechanical process involving the application of forces and moments to a dental structure, resulting in specific tooth movements determined by force systems. These force systems are referred to as the center of resistance. The type of tooth movement is determined by the location of the center of rotation (CROT), which is the point around which the movement occurs. The center of rotation can vary depending on the moment-to-force ratios. Tooth movements in clinical practice are mainly classified as translation and rotation, which can be combined in four distinct ways to achieve desired outcomes described as uncontrolled tipping, translation, controlled tipping and root movement. Uncontrolled tipping is observed when a force is applied to a tooth's crown, resulting in the tooth rotating around a different axis than its long axis. This differs from controlled rotation, where the tooth rotates around its long axis. When the center of rotation overlaps the center of resistance, the tooth experiences pure rotation around the center of resistance caused by a single moment. The translation movement occurs when the center of rotation and center of resistance are positioned at an infinitely distant point. The movement of a tooth can be achieved by applying a force moment on the crown surface, resulting in an equivalent force system at the center of resistance (CRES). The tooth then translates in the direction of the force. Furthermore, controlled tipping is a movement that occurs when the CROT is moved towards the root apex. The movement is caused by adding an anti-tipping force at the crown, resulting in a force and moment at the CRES and rotating the tooth around the root apex. Finally, root movement is when the force-moment system generates a tooth rotation around the crown tip (Figure 10) (Barone et al., 2016).

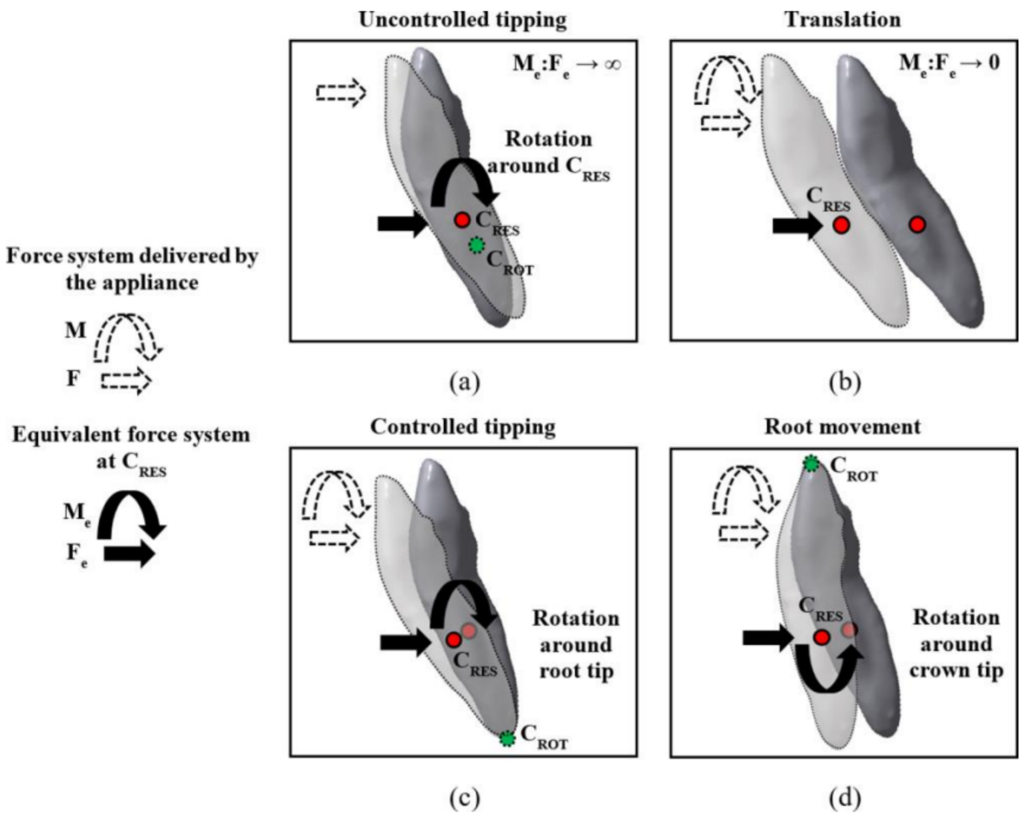

Figure 10- *Orthodontic tooth movements: uncontrolled tipping **(a)**, translation **(b)**, controlled tipping **(c)**, root movement **(d)**.*

Source: (Barone et al., 2016) Computational design and engineering of polymeric orthodontic aligners. International Journal for Numerical Methods in Biomedical Engineering, 33(8).

Dental attachments, made of dental composite material, play a crucial role in achieving specific orthodontic movements. However, a thorough analysis of their impact on dental movement is essential for effective treatment. Optimizing the placement, shape, and quantity of attachments can enhance treatment predictability and effectiveness (Barone et al., 2016). Computer-aided design (CAD) techniques are employed to generate the shapes of aligners and attachments in orthodontic procedures (Figure 11) (Barone et al., 2016).

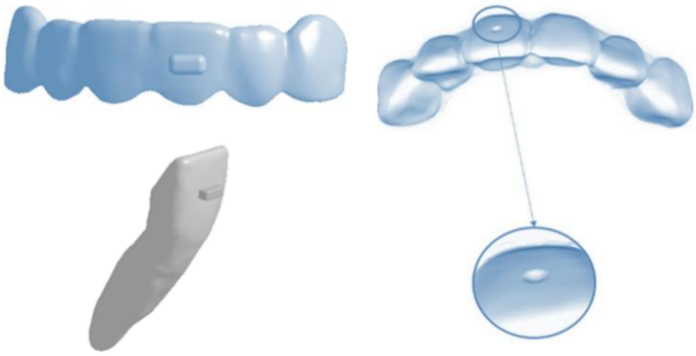

Figure 11- *Example of auxiliary elements used to enhance orthodontic movements: attachment **(a)** and divot **(b)**.*

Source: (Barone et al., 2016) Computational design and engineering of polymeric orthodontic aligners. International Journal for Numerical Methods in Biomedical Engineering, 33(8).

Complex dental pathologies require the use of full 3D digital dental models to predict the behavior of dental tissues and evaluate treatment plans. Computer-assisted dentistry requires accurate modeling of the tooth crown surface, soft tissue, bone structure, and tooth root geometry. Orthodontics specifically requires a full mouth model to improve functionality and appearance (Barone et al., 2013). Cone Beam computed tomography (CBCT) data is imported into software to generate models of the maxillary dentition, which are used to create a three-dimensional finite element model for FEA. This model is further optimized and expanded to accurately simulate the thickness of the appliance (Cheng et al., 2022). CBCT is widely used in dentistry and orthodontics due to its accurate diagnostics and lower radiation doses (Barone et al., 2013). The components are then imported into ANSYS Workbench to generate the final model, with specific boundary and contact conditions established (figure 12) (Cheng et al., 2022).

ANSYS is a comprehensive finite element analysis tool that includes pre-processing, solving, and post-processing functions. It allows user-programming through command language, which consists of a wide range of commands for meshing, geometry modifications, and boundary conditions. Interactive and batch modes are used for FEA analysis. Various computer software, such as ANSYS, Abaqus, SOLIDWORKS, and Inventor Nastran, are used for finite element analysis. However, despite the extensive list of available FEA tools on the market, they all serve the single task of problem-solving (Magomedov & Sebaeva, 2020).

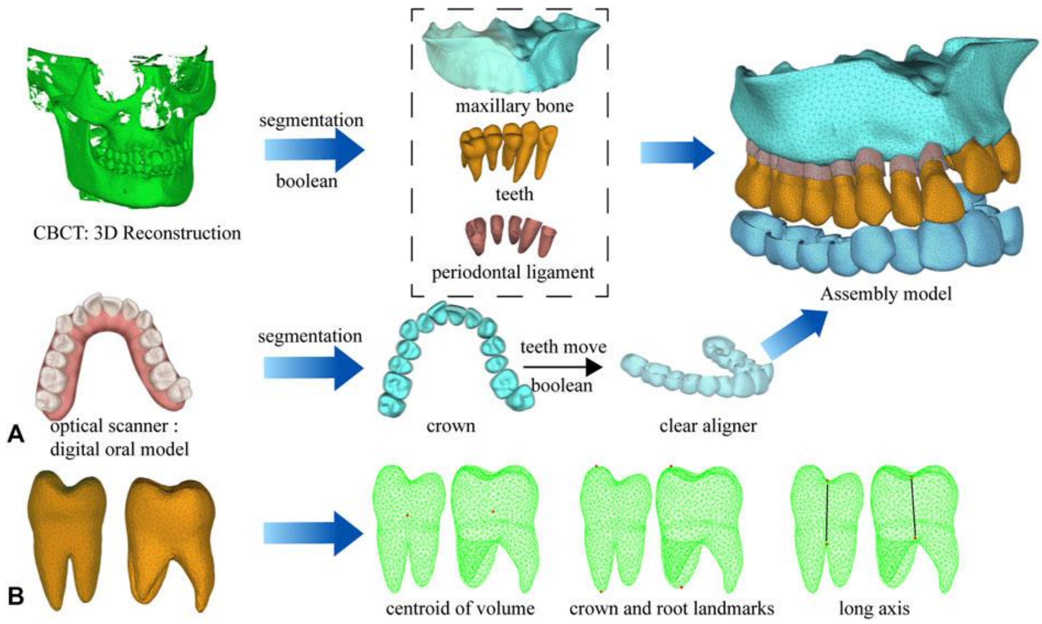

Figure 12- *Computer-aided design model and measurement points.* ***(A)*** *The process of model building and assembly.* ***(B)*** *Measurement points of tooth movement distance and torque change.*

Source: (Song et al, 2023) Improvements of tooth movement efficiency and torque control in expanding the arch with clear aligners: a finite element analysis. Frontiers in Bioengineering and Biotechnology, 11.

According to a study by Song et al. (2023), employing finite element analysis to examine movement strategies during arch expansion is a valuable tool. Models comprising the maxilla, dentition, periodontal ligament, and aligners are created and imported into a finite element analysis software and tested using different orders of tooth movement. Suggesting, clear aligners cause oblique movement and increase arch expansion efficiency while reducing anchorage loss. Proving FEA is a valuable tool for arch expansion evaluation.

Moreover, experimental studies on the biomechanics of tooth movement with clear aligners have used different approaches, including displacement measurements and strain gauge measurements. However, 3D FE analysis has the advantage of considering periodontal tissues and calculates stress, strain, and displacement for any part of the tooth and aligner. Nevertheless, most FE studies have focused on a single tooth or a segment of teeth. A study conducted by Jiang et al. (2020) used three-dimensional finite element analysis to investigate the behaviors and stress distributions of anterior and posterior teeth with clear aligners. Researchers utilized 3D FE models to simulate orthodontic treatment on the maxillary dentition. They reconstructed the teeth and bone using scans of a male subject and designed attachments for specific teeth. The study focused on various retraction and intrusion protocols and results indicate a transition in the behavior of incisors, progressing from uncontrolled tipping to controlled root movement through planned intrusion displacements. However, intrusion was consistently accompanied by a variety of movement types. These models were also analyzed using ANSYS Workbench.

Literature suggests that attachments aid in the extrusion process, which is a significant movement performed using aligners, particularly for central incisors. This is due to the aligners' limited ability to vertically deform and adapt to the teeth during this movement. However, the use of a palatal-side attachment improved incisor extrusion, as demonstrated through FEM analysis (Nucera et al., 2022). Numerical simulations, such as finite element analysis, offer valuable insights into the biomechanical response of orthodontic treatments, aiding in the optimization of design and analysis of orthodontic features (Savignano et al., 2019).

A study by Cortona et al., (2019), using FEA simulations demonstrated aligner deformation and ineffectiveness lead to greater rotation loss without attachment most predominantly in round teeth. Aligner stiffness and elasticity were important factors that influence treatment outcomes (Cortona et al., 2019). Furthermore, FEA is effective at analyzing force systems in orthodontics, but factors such as root length, root morphology, aligner material property, and aligner trim line design can impact the results and need further investigation (Liu et al., 2022).

Additionally, a study conducted by Fan et al. (2022), analyzed the impact of attachment position on maxillary molar intrusion in clear aligner treatment using finite element analysis. Cone-beam computed tomography images of a patient's maxillary second molars were used to construct three-dimensional models of the maxilla, periodontal ligaments, dentition, and clear aligner. The models were divided into four groups based on the attachment location on the first molar. After applying an intrusion on the second molar, displacements and stress distributions of the teeth, aligner, and periodontal ligament were analyzed using finite element software. The study concluded that using a combination of buccal and palatal attachments could effectively prevent buccal and palatal tipping. The bucco-palatal attachment group demonstrated the most favorable stress distribution. However, regardless of attachment position, the second molar exhibited a natural inclination to tip mesially, which should be taken into consideration for future treatment planning.

Furthermore, Cheng et al. (2022), investigated the impact of torque compensation using clear aligners of varying thickness on tooth displacement following tooth extraction. Three-dimensional finite element models of the maxillary dentition with extracted first premolars, maxilla, periodontal ligaments, attachments, and aligners were constructed and subjected to Finite Element Analysis (FEA). The study constructed three-dimensional finite element models of the maxillary dentition, incorporating extracted first premolars, maxilla, periodontal ligaments, attachments, and aligners. These models were then subjected to Finite Element Analysis (FEA) to analyze their behavior and performance. ANSYS software was used to analyze the initial displacement of teeth and stress on the PDL. The findings revealed that clear aligners caused retraction, tipping, and extrusion of teeth. Thicker aligners demonstrated higher tipping and intrusion forces, resulting in decreased incisor extrusion. Thicker aligners with torque compensation resulted in increased tipping and intrusion of canines and second premolars. The study underscored the importance of considering root resorption, as well as the necessity for proper anchorage control in cases involving tooth extraction.

Numerous studies were conducted to investigate the effect of aligner edge design on force transmission using 3D digital models and testing different trimming line designs and thickness. Consequently, results showcased that the design of the trimming line, the extension of the aligner edges, and aligner thickness significantly influence the magnitude and distribution of the resultanting force. Showcasing that the straight extended trimming design exhibited superior force distribution, potentially facilitating bodily tooth movement in CAT (Elshazly et al., 2023).

Traditional aligner treatments involve the sequential replacement of aligners until teeth reach their desired positions, with each set of aligners moving about 0.2mm respectively. A recent study simulated how a 0.2mm diastema closure could be performed using only one set of aligner trays with and without attachments (Figure 13). Results indicated that a 0.2mm diastema was successfully closed using an aligner by moving each central incisor 0.1mm towards midline. The movement of the incisor was magnified 20 times to show its displacement and regardless of the attachment, the central incisor tipped and rotated. Additionally, increasing the aligner's Young's modulus to 2000 GPa resulted in the incisor moving entirely to the desired position, disregarding the attachment. Aligners with attachment showed nearly 100% effectiveness in shifting the incisor to completely overlap the target position (Yokoi et al., 2019).

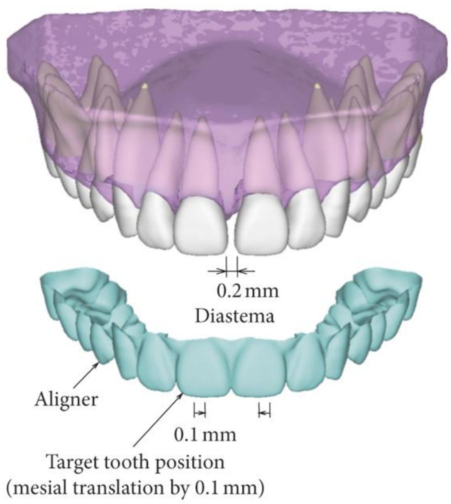

Figure 13- *Closing of diastema with a plastic aligner.*

Source: (Yokoi et al., 2019) *Effects of Attachment of Plastic Aligner in Closing of Diastema of Maxillary Dentition by Finite Element Method*. Journal of Healthcare Engineering

3.2.2 Limitations

Singh et al., (2016), recall limitations exist regarding the use of FEA, claiming results are dependent on the modeling system used, making the modeling step crucial. Expert operators are required for accurate modeling, and attention must be given to material properties, load applications and boundary conditions.

3.2.3 Advantages

FEM is a reliable and efficient experimental analysis tool that has revolutionized orthodontics and is widely used in other areas of dentistry and medicine. FEM has greatly improved understanding of tooth movement biomechanics in dentistry, particularly in treatment planning, bone remodeling, resistance, rotation and retraction. Its practicality makes it a reliable analysis system (Singh et al., 2016). Additionally, finite element analysis allows for repeated study at the operator's discretion, even with complex structures, while remaining time-efficient (Bandela & Kanaparthi, 2020). FEA can be consistently repeated resulting in a shorter time, offering a more efficient alternative to experimental research (Aktı & Kaya, 2020).

3.2.4 Disadvantages

The finite element method uses assumed shape functions to model internal nodal displacements, but its accuracy depends on the type and location of support. It may give incorrect results for certain configurations (Chopade SR et al., 2014). This is a mathematical method that leads to approximated results. FEA fails to consider important parameters such as anisotropy and heterogeneity of bone, periodontal structures, and the viscoelastic response to stress. Also ignoring coefficients of thermal expansion, fatigue effects of prosthetic materials, and complexity of masticatory forces (Tatarciuc et al., 2021).

According to Song et al., (2023), finite element analysis is limited in accurately replicating the oral environment and biological changes in bone. The study suggests using stress distribution to infer tissue changes, but emphasizes the necessity of refining parameters for more accurate clinical simulations. Furthermore, Aktı & Kaya (2020), highlight additional drawbacks of FEA, include high software costs, skilled personnel requirement, software updates, and limitations in representing material properties.

Aligner plastic waste has negative consequences on the environment and human well-being, as shown by the presence of microplastics in oceans. Addressing this issue requires responsibility and sustainable practices from aligner manufacturers and users (Bichu et al., 2023).

4 CONCLUSION

The clear aligner market has experienced significant growth in recent years, with more patients opting for this aesthetic alternative to traditional braces. However, the success of clear aligner treatments relies heavily on the accuracy of the aligner design and the predictability of tooth movement.

The use of finite models in transparent aligners offers a promising path for improving the effectiveness and efficiency of orthodontic treatments, as it is a powerful tool for simulating and analyzing the mechanical behavior of materials and structures. Moreover, finite models have enabled orthodontists to simulate and predict the biomechanical effects of different aligner designs and treatment protocols before they are applied to the patient. This allows for virtual trial and error, minimizing the need for extensive clinical adjustments during treatment.

This narrative review has provided a comprehensive overview of the application of finite element analysis and the finite element method in the design and optimization of clear aligners. Much more studies and finite element analysis are needed to validate biomechanics in aligners as also the analysis itself.

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