COMPARATIVE EVALUATION OF THE DENTAL EFFECTS OF THREE BIOMECHANICAL CLASS II TREATMENTS USING THE FINITE ELEMENT METHOD

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Abstract

Objective: The aim of this study was to compare the stress distribution and the total strain in the dentition, PDL, cortical and trabecular bone from three Class II correctors (Class II elastics, Forsus Fatigue Resistant Device and the Carrier Motion appliance) by finite element analysis. **Material and Methods:** 3-dimensional finite element models of Class II elastics, Forsus Fatigue Resistant Device (Forsus FRD) and the Carrier Motion appliance (CMA) were constructed from a cone beam computed tomography (CBTC) image of an orthodontic Class II patient recreating the maxillo-mandibular dentition, the periodontal ligament (PDL) and alveolar bone. The distribution of stress (von Mises and principal stress) and the total strain (mm) at these areas were analyzed. **Results:** The highest von Mises stress and the maximum principal stress were found at the teeth, followed by the cortical bone, trabecular bone and PDL in the three models. The maximum stresses and total deformation were located at the upper canine and the lower molar in the Class II elastics and CMA models, in the upper first molar in the Forsus FRD and CMA and in the lower first premolar in the Forsus FRD. Additionally, the stresses were distributed in the anterior and posterior regions on the teeth and the total deformation in distal direction in the upper arch and in mesial direction in the lower arch. **Conclusions:** The stress concentration at the three models were located close to

the active components of each appliance producing different patterns of stress distribution and displacement.
Keywords: malocclusion, angle Class II, division 1, appliance, orthodontic, finite element analysis.

INTRODUCTION

Class II malocclusion is considered one of the most frequent problems found in orthodontics.(1) The prevalence can be up to 15% to 30% in different parts of the world.(2) A study in Colombia included 4,724 kids from Bogotá, between 5 to 17 years old, concluded that 20.8% of the population had Class II malocclusion.(3) The etiology is multifactorial and may be presented as an skeletal (maxillary prognathism, mandibular retrognathism or a combination of both) and/or dental malocclusion.(2) Class II malocclusion could have a negative social and psychological impact in the subjects,(4) and an increased overjet can cause a higher incidence of incisal trauma.(5) Different techniques and biomechanics to treat this malocclusion have been proposed through the years, between the more used treatment protocols of Class II malocclusions are orthopedic appliances, intermaxillary elastics, extractions and distalization of the upper dentition.(1,6–14)

Class II elastics are effective in correcting Class II malocclusions, and their effects are primarily dentoalveolar, including retroclination and extrusion of the upper incisors, proclination of lower incisors and mesialization and extrusion of the lower molars.(15) However, one of the factors that influence its effectiveness is the patient compliance, deficient cooperation of the patient in the use of the elastics can lead to an unsuccessful treatment.(16) Class II fixed correctors, as the Forsus Fatigue Resistant Device (Forsus FRD, 3M Unitek, Monrovia, Calif), are an alternative that overcome the need of patient compliance and effectively correct the malocclusion, producing overjet and overbite decrease, improving in the molar relationship, with retroclination of the maxillary incisors, proclination and intrusion of the mandibular incisors, and mesialization of the mandibular molars. On the other hand, the Class II Carriere Motion appliance (CMA, Henry Schein Orthodontics, Melville, NY) is a combined appliance with a fixed attachment in the upper arch but needs the use of Class II intermaxillary elastics in order to transmit the force to produce the distal movement of the upper maxillary first molars and canines. Usually, a lingual arch or an Essix appliance is added to the lower arch as anchorage to the intermaxillary elastics, producing mesial movement of mandibular molars and proclination of the mandibular incisors.(17,18) Another alternative is to use as anchorage in the lower arch a miniscrew in order to decrease in the amount of anchorage loss in the mandibular incisors.(17) However, this appliance still need the patients cooperation in the use of the intermaxillary elastics.

Diverse authors, have studied the dentoskeletal effects of these three Class II correctors,(18–23) but only few studies compares the effects between them. Jones et al.(24) evaluated in a clinical study the effects of the Forsus FRD and the Class II elastics finding no statistically significant differences in the clinical changes between the two therapies, but with greater mesial movement of lower molars and greater correction of the molar relationship in the Forsus FRD group. Aras et al.(25) compare the effectiveness of the Forsus FRD and intermaxillary elastics in Class II subdivision subjects, they found that the Forsus appliance was more effective for correcting Class II subdivision malocclusion. Yin et al.(26) evaluated in a retrospective study the treatment effectiveness of CMA in comparison to Class II intermaxillary elastics and Forsus FRD finding that the time of Class II correction for CMA was significantly shorter than that for Class II elastics and no difference in the length of Class

II correction between CMA and Forsus groups. Also, they found that the amount of Class II correction (canine/molar relationship) was significantly lower for CMA when compared with Forsus appliance.

To our knowledge, no other studies compares the biomechanics effects of these appliances that although may have similar clinical effects in the correction of Class II malocclusion, they have different elements that are anchored in different parts of the teeth, so it would be that the actions exerted on the dentition are different. The few comparative studies between these therapeutics, possibly due to the difficulty of conducting randomized controlled clinical trials and finding patients who lend themselves to this type of study. The finite element analysis method (FEM) then becomes, in these cases, an excellent instrument to simulate, under a mathematical model, the distribution of stress and strain on the dentition of these three therapies, allowing us to analyze these distributions in a systematic way, such that we show the possible biomechanical effects in areas of difficult clinical access and free of risk for patients, providing orthodontists with important information to make more accurate therapeutic decisions.(27,28) Then, the aim of this study was to compare the stress distribution and the total strain over the dentition, PDL , cortical and trabecular bone from Class II elastics, Forsus FRD and the Carrier Motion appliance (CMA) by finite element analysis (FEM).

MATERIALS AND METHODS

This in silico study was conducted in base of finite elements method building the maxillomandibular models from existing Cone beam computed tomography (CBTC) image of a 16-year-old female patient with Class II division 1 malocclusion with an overjet of 6 mm. The study meets the ethical principles from the Helsinki declaration (15) and was approved by the ethics committee of UNICOC with ethical guarantee XX act XX in Bogotá, Colombia.

For the finite element analysis, the following steps were applied as the solution procedure:

1. Imaging

a) Imaging and three-dimensional reconstruction:

The CBCT was taken using a Planmeca dental tomography equipment (Planmeca OY, Helsinki, Finlandia). Images were generated in standard digital imaging and communication in medicine (DICOM) format, reconstructed into continuous slices at 0.4-mm axial thickness.

b) Image processing:

Anatomical Structures Models: The 3D geometry of the teeth, mandible, PDL, cortical and trabecular bone, were reconstructed through a semi-automated process with the software 3D DOCTOR 4.0 (Lexington, MA, USA). Once the reconstruction finished, a stl file (point cloud) of each required geometry was generated, then this was converted it into a solid, such as the one shown in figure 1(mandibular solid model). The thickness of the cortical and trabecular bone is variable in each patient, therefore in this study these two structures were reconstructed according to the patient's morphology from the computed tomography.

Models of Non-Anatomical Structures: In this step, the mechanical elements of the three appliances: Class II elastics, Forsus Fatigue Resistant Device (Forsus FRD L pin model, 3M Unitek, Monrovia, Calif), the Class II Carriere Motion appliance (CMA, Henry Schein Orthodontics, Melville, NY) were modeled as computer design geometry through photographs and direct measurements of the appliances' components and imported into the program of SolidWorks 2018 (Dassault Systèmes, Surenes, France). For the simulation of the Class II elastics and the Forsus FRD appliance, a set of upper and lower brackets with slot 0.22x0.28-inch, MBT (Mclaughlin, Bennett, Trevisi) prescription and a passive stainless steel archwire of 0.19X025-inch were also modeled. For the CMA, it was also modeled an acetate plate of 0,060" (Leone S.p.a, Sesto Fiorentino, Firenze, Italy)(29) thickness and a tube for the lower first molar. Subsequently, the assembled appliances to be simulated were placed in their recommended positions in the arches.

2. Meshing

The PDL was modeled with a thickness of 0.25mm and was considered as nonlinear and viscoelastic according to the Mooney-Rivly theory as in previous studies,(30,31) the constants used for the Mooney-Rivlin equation are shown in table 1. The other components of the models were assumed to be linearly elastic, isotropic and homogeneous. The Mooney-Rivlin model was chosen since many researchers consider PDL to be a hyperelastic material like the Mooney-Rivlin model where the estimated stress corresponds well with the in vivo experiment. Models proposed by various other researchers, explain a time dependency by using viscoelastic models using up to four time constants, these models are known as Maxwell models(2). A.V Shutov (1) explains that the Maxwell model is widespread in material modeling phenomenology, and the Mooney Rivly model has become a method of choice in various applications, especially those requiring higher robustness and efficiency. Young's modulus (elasticity, represents the slope of the linear portion of the stress/strain diagram of the material) and Poisson's ratio (absolute value of the ratio between transverse and longitudinal deformations in an axial tensile axis) were set in each component as reported by previous authors,(32–35) as shown in table 2. The assembled finite element models of the three appliances were imported to the ANSYS software (version 13.1; Canonsburg, Pa) for analysis. The total number of nodes and elements for each model was 1,207,182 nodes and 748,983 elements for Class II elastics, 1,280,801 nodes and 771,350 elements for the Forsus FRD and 933,279 nodes and 599,868 elements for the CMA (Figure 2).

4. Boundary and load Conditions

The boundary conditions for the maxilla were the maxillary process until the anterior nasal spine and the zygomatic process. For the mandible the boundary conditions were the neck of the condylar process. For the three models the magnitude of the force was of 2N for each side, applying tension with the Class II elastics and CMA at upper canine and lower first molar, pushing for the CMA at the upper first molar and compression for the Forsus FRD at the first upper molar and the lower first premolar according to the assembled components of each appliance.

5. Types of solutions

To analyze the distribution of the stress (internal resistance of an object to a force acting upon it) in the structures the estimated von Mises and principal stresses values were measured in megapascals (Mpa). The von Mises stress is the combining three principal stresses in to one equivalent stress and the principal stress is the maximum or minimum stress that may developed on a loaded object.(36) The maximum principal stress helps us understand the maximum tensile stress induce in the part due to the loading conditions and minimum principal stress principal stress helps to understand maximum compressive stress.(36) The total deformation (displacements from stresses, it gives a square root of the summation of the square of x-direction, y-direction and z-direction) was measured in mm. The color scale at the left side of each figure was used to identified the maximum (red) and the minimum (blue) stress/strain values. The figures of total deformation were increased in a scale of $2.2X10^4$, in order to help to observe in a didactic form the results of the total deformation on the area of displacement.

RESULTS

The results of the von Mises and principal stresses values are shown in the Tables 3 to 6. In general, the highest von Mises stresses were found at the teeth, followed by the cortical bone, trabecular bone and PDL in the three models. The range of the maximum von Mises stresses values were from 1.8991 (CMA, teeth, upper canine) and 0.0014541(Class II elastics, PDL, lower second molar). Similar results were found for the maximum principal stress that was from 1.5163 (Forsus FRD, teeth, upper first molar) to 0.0016788 (Class II elastics, PDL, lower second molar) (Figures 3, Figures 4, Figures 5 and Figures 6). In the upper arch, these stresses were localized in the upper canine for the Class II elastics and the CMA and at the upper first molar for the Forsus FRD and CMA. In the lower arch, the von Misses stress and principal stress were observed in the lower first molar in the Class II elastics and the CMA and at the lower first premolar for the Forsus FRD.

The total deformation in the upper arch in all the studied structures showed that the maximum displacements in the Class II elastics and CMA were localized at the upper canine, but for the Forsus FRD it was localized at the upper first molar, all in the distal direction. The displacements at the upper anterior teeth were palatal for the three simulations, being the CMA the device that showed the greatest palatal displacement of the upper incisors, followed by the Class II elastics and the Forsus respectively. Also, the Forsus FRD and CMA showed greater distal movement of the upper first molar than in the Class II elastics model. Also, in the Forsus FRD a buccal displacement of the upper first molars were observed but no in the Class II elastics or in the CMA models. The total deformation in the lower arch at PDL showed the maximum displacement in the Class II elastics and the CMA at the lower molars with proclination of the lower incisors. In the Forsus FDR it was observed at the first premolar with lesser proclination of the lower incisors in this model (Figures 7 and Figures 8). Additionally, the total deformation showed vertical displacements in each FEM model. For the Class II elastics we observed extrusion of the upper anterior teeth, especially the canine, and extrusion of lower molars. In the Forsus FRD it was observed intrusion of the upper first molar and extrusion of the upper anterior teeth. At the mandibula in the Forsus FRD model was observed a intrusion of the lower anterior teeth. The Carriere showed extrusion of the upper anterior teeth, being grater on the upper canine, and on the mandible for the Carriere was observed extrusion of the lower first molar.

DISCUSSION

This study aimed to evaluated three Class II correctors from the biomechanical point of view with the hypothesis that having individual active components which are located at different places at the upper and lower dentition, they could have distinct distribution of the stresses and total deformation. Cattaneo et al.(28) highlighted the importance of the stress/strain distribution within the PDL and the surrounding alveolar bone when an orthodontic load is applied and the corresponding tooth movement that this entails. Diverse studies,(37,38) have shown that the compressive and tensile stresses from orthodontic forces are essential factors to remodeling of the bones, changing the cellular activity in the PDL and resulting in bone resorption or deposition and leading to the intra-alveolar displacement of the teeth. The FEM is an non-invasive method which allow to observe the stress/strain distributions in alveolar support structures and to analyze the possible biomechanical behaviors of different orthodontic appliances.(27)

In present study, we found that the highest stresses (von Mises and maximum principal stress) were located in the upper canine for the Class II elastics an the CMA and at the upper first molar for the Forsus FRD and CMA. In the lower arch, the maximum stresses were observed in the lower first molar in the Class II elastics and the CMA and at the lower first premolar for the Forsus FRD. Similar results were found by Akis and Doruk.(39) who investigated the biomechanical effects of the Forsus FRD with and without miniscrews in the maxillary and mandibular teeth, finding that the maximum and minimum principal stresses were observed in the neck areas of the first upper molars and in the buccal neck of the lower canine, which was the anchorage site at the lower arch for the push road, unlike in our study where the anchorage site was distal to the first premolar. Chaudhry et al.(40) evaluated the stress distribution on the mandible with the Forsus FRD comparing to the resting stage, finding the highest von Mises stresses in the cortical bone from the canine to the premolar area. Chai et al.(41) in a FEM study analyzed the stress distribution in mandible advanced with Forsus, they found that the concentration of the stress was observed in the anterior part of the condyle, mandibular notch and lower molars and the areas of maximum displacement were observed at the chin and lower incisors. Wang et al.(42) found in a FEM study of Class II elastics and clear aligners that the stress on the PDL was concentrated at the lower first molars with compressive stress in the mesial cervical region and tensile stress in the buccal-distal cervical region. In the present study, we also found in the Class II elastics model, the highest concentration of stress in the lower arch at the first molar but with the compressive stress in the buccal distal region and tensile stress in the mesial cervical region. Xie and Li.(43) also found that with the Class II elastics, the highest von Mises stress in the lower arch at the PDL was located in the distal root of the first molar and that the stress decreased gradually in the mesial direction.

We also observed in our study, that the stress were distributed in different regions of the anterior and posterior regions of the maxillo/mandibular dentition depending on the simulated appliance causing different patterns of total displacement, observing distal displacement of the upper dentition and mesial displacement of the lower dentition in the three models. However, the distribution of these total deformations were at different regions in the three models. In the upper arch, for the Class II elastics the displacements were from the upper first premolar and canine to the anterior teeth and almost no deformation was observed at the posterior teeth; with the Forsus FRD the displacement were from the first molar to the premolars to the anterior teeth and with the CMA the displacements were from the canine and premolars to the anterior teeth. The three simulations showed palatal displacement of the upper incisors and distal displacement of the upper posterior teeth with the greatest retroclination in the CMA model and the greatest upper molar distalization in the Forsus FRD appliance. In the lower arch, for the Class II elastics and CMA models the displacements were from second and first molars to the anterior teeth; for the Forsus FRD the displacement were from the first premolar molar to the anterior teeth. All the models showed mesial displacement of the lower dentition with proclination of lower incisors being the Class II elastics model the one that showed the greatest displacements both for the molars and lower incisors. FEM studies in Class II elastics have found similar results, Chang et al.(44) found that with Class II intermaxillary elastics the initial bodily displacements were concentrated in on the anterior part of the upper dentition. Wang et al.(42) evaluated the displacement and stress distribution of mandibular dentition by various positions of the Class II elastics during en-masse retraction in clear aligner therapy, they found lingual tipping of the lower central incisors and mesial tipping of the lower first molars producing mandibular anchorage loss. Xie and Li.(43) studied the influence of the cross-sectional shape of ribbon arch wires on intermaxillary traction in Class II malocclusion treatment, they found mesial displacement of the lower dentition and labial-oriented inclination of the anterior teeth. Also, FEM studies with Forsus FRD,(39,40,44) were consistent with our findings. Kumar et al.(45) evaluated the stress distribution and the displacements produced by a Forsus FRD anchorage to a mini-plate finding retrusive movements of maxillary incisors and mesial displacement of the mandibular molars but with less proclination of mandibular incisors. To our knowledge, until now no studies with CMA have been published.

In the present study, the Forsus FRD model showed stress in the buccal cervical region of the upper first molar indicating that distal and expansive force was produced in this region. Similar results were found by previous authors with Forsus FDR or similar Class II correctors in FEM studies.(39,46) Therefore, if this expansion effect in the upper molars is not clinical needed it is important to be controlled with a transpalatal arch or similar appliance.

Chaudry et al ,(43) explains that the Class II elastics generates extrusion movement on the lower first molar, and intrusion of lower anterior teeth. The present study had similar results on the Class II elastics and the Carriere, both models showed estrusion of lower first molar, being less on the Carrier model. Additionally, both models showed extrusion of the upper anterior teeth.

Few clinical studies,(24–26) have compared the dentoalveolar effects in some of the Class II correctors simulated in our study. Jones et al.(24) found in the Forsus group greater distal movement of the upper molars, retroclination of the upper incisors, mesialization of the lower molars and proclination of the lower incisors than the Class II elastics group. On the contrary, Aras et al.(25) in Class II subdivision subjects found that the Class II elastics produced more palatal tipping on the maxillary incisors and both the Class II elastics and the Forsus proclined the lower incisors, but the Forsus group showed significantly greater improvement in overjet. Yin et al.(26) compared the clinical effects of the CMA, Class II elastics and Forsus FRD finding greater Class II molar and canine correction in the Forsus group followed by the CMA and Class II elastics respectively. They also found that part of the Class II correction with the CMA is achieved by derotating the maxillary first molars distally

In our study the CMA showed the greatest palatal displacement of the upper incisors, this may be related that the CMA is used previous fixed appliances unlike the Class II intermaxillary elastics and the Forsus FRD which are assembled to the dentition over rectangular wires in to the brackets in full edgewise appliances, this could bring not only more anchorage as the dentition could move as an unit but also it could bring more torque control in the anterior teeth because the couple between the 019x025-inch stainless steel archwire in the bracket slot.(47,48)

These findings, could help to the clinicians to understand the different patterns of stress distribution and displacements from these Class II correctors that can lead to different biomechanics for the correction of the Class II malocclusion. Clinicians should choose between the different options of treatment based on individual patient needs and not only in clinician preferences or brand advertising.

This study considered the non-linear viscoelastic properties for the PDL as diverse authors,(49,50) have found that loading of the periodontium cannot be explained as the simple compression/tension along the loading direction but as a more complex structure that is in charge to transmit the orthodontic for the bone remodeling to allow the tooth movement. Then, a nonlinear analysis may provide us a more accurate and reliable results.(28,51)

This study have some limitations as the calculations are made using a mathematical model, it may not simulate with accuracy the complex biological dynamics of tooth movement. Other limitation is that FEM studies can record only instantaneous stress patterns and not the clinical situation in orthodontic treatment that is carried out in longer periods of time. Then, the results of the present study must take with caution and it is recommended to perform more randomized clinical trials to compare these effects in vivo.

CONCLUSIONS

- In the upper arch, maximum stresses were localized in the upper canine for the Class II elastics an the CMA and at the upper first molar for the Forsus FRD and CMA and in the lower arch were observed in the lower first molar in the Class II elastics and the CMA and at the lower first premolar for the Forsus FRD.
- The total deformation in the upper arch showed the maximum displacements in distal direction at the Class II elastics and CMA at the upper canine and for the Forsus FRD at the upper first molar.
- It was observed differences in the distribution of the total deformation between the three Class II correctors, with greater palatal displacement of the anterior teeth in the CMA model, greater proclination of the lower incisors in the Class II elastics model and greater distal movement of the upper first molar in the Forsus FRD model.

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FIGURE LEGENDS

Figure 1: *Mandibular solid model*

Figure 2: *Meshing* ***A****, Mesh Carriere, B, Mesh Forsus;* **C***, Mesh Class II intermaxillary elastics*