Research Article

Force System Developed by Mushroom Archwires for Incisor Retraction: A Numerical Study

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ABSTRACT

Introduction: Mushroom archwires (MA) were developed to maintain incisor torque during retraction, i.e., control of root position via a generated couple while preserving posterior anchorage. This is achieved through a differential anchorage, either by translation or by controlled movement of the crown and root apex, in cases involving premolar extraction. Although their clinical application has been reported in the literature, the force system resulting from their activation has not yet been demonstrated. The aim of this study was to perform numerical simulations to analyze the force system generated by MA.

Materials & Methods: A MA was geometrically modeled using Autodesk Inventor, and finite element analysis (FEA) was performed in ANSYS Workbench to simulate its mechanical behavior. For this simulation, non-linear analysis was used in order to take into account the large displacements effects, which consisted of pre-activation at their posterior extremities by 45° gable bends; restriction of the posterior extremities to mimic the insertion in the molar tubes and spacing between the vertical extremities (legs) 2.5 mm apart. Loops were activated at 4.0 mm and at 5.0 mm.

Results: At 4.0 mm and 5.0 mm of activation, the archwire generated forces (Fx) of 184 gf and 251 gf, respectively. The corresponding Mz/Fx ratios were 12.9 mm and 10.6 mm, respectively.

Conclusion: MA could be activated up to 5.0 mm for incisor retraction, which may be compatible with the biological limits of tooth movement during incisor retraction.

KEYWORDS: Archwires, Finite Element Analysis, Titanium-molybdenum.

INTRODUCTION

Some malocclusions require premolar extractions as an option to resolve moderate to severe crowding. In more severe cases, maximum anchorage is necessary to prevent mesial movement of the molars into the extraction site. Treatment strategies identified so far include either frictionless or sliding mechanics. Examples of anchorage reinforcement include the use of palatal bars, sliding-jigs, headgears, and temporary anchorage devices (miniscrews)[1]. The sliding mechanics allow teeth to move over the archwire powered by coil springs or elastic chains, thus friction must be considered between archwire and bracket slot. Archwire-bracket interface has been studied aiming to obtain an adequate sliding surface to minimize friction.[2,3] The frictionless mechanics use looped archwires which should work in the elastic phase to produce space closure.[1,2] Vertical control during retraction is important to avoid anterior teeth's extrusion during space closure in sliding and in frictionless mechanics. Also, an auxiliary beta-titanium archwire for intrusion could be inserted over the incisors brackets, as a cantilever, to prevent anterior extrusion during retraction, in combination with palatal bars to stabilize molars[4]. In the frictionless mechanics, for anterior retraction, an option could be the Mushroom archwires (MA) originated from the T-loop archwires developed by Burstone[5,6] who later established the concept of differential moment strategy between the active and anchor units, which can be applied, also in the straight-wire technique. In this methodology, the anchor unit can remain stationary while the active unit moves. MA keep the same geometric configuration but the anterior segment (between loops) of the archwire as well as the superior part of the loop are rounded to obtain, respectively, vertical control to assure controlled torque and prevent extrusion and more wire and for consequence a low load-deflection rate. A 45° gable bend was placed on the posterior extremities for posterior anchorage control, since this archwire avoids posterior teeth to move forward preventing anchorage loss, because if molars move mesially, the extraction spaces may be lost and dental protrusion may not be perfectly corrected.[4-9] MA is made of titanium-molybdenum (β-titanium) CNAIII as prescribed by Nanda.[6-10] β-titanium has been used in clinic, since the first introduction in orthodontics because this alloy presents good mechanical properties as a good range and is about 42% less stiff than stainless steel (SS), with a nominal composition of 79% Ti, 11% Mo, 6% Zr and 4% Sn.[6] CNA III wire is nickel free, preventing allergies in some patients.[6] Some papers show clinical cases[8,9] dealing with MA showing good results, but no study demonstrates experimentally or numerically their force system when pre-activated and after activation. Only a numerical study[10] verified the von Mises stresses along the MA and found that loops could be activated up to 5.0 mm without plastification.

The finite element analysis (FEA)[11] is widely used, in many fields, including medicine and dentistry because it allows the analysis of a structure´s reaction to heat, vibration, fluid flow, stress-deformation and other physical properties, even before it is manufactured, thus avoiding unnecessary expenses. FEA is used in orthodontics for the numerical non-linear analysis of orthodontic springs[12-14]; finite element analysis of the effect of force directions on tooth movement in extraction space closure[14]; numerical simulations of canine retraction with T-loop springs based on the updated moment-to-force ratio[15], and finite element simulation of the behavior of periodontal ligament[16], among others. The von Mises yield criterion, employed in the present study through FEA, is used to predict the onset of yielding (i.e., start of plastification) in ductile materials under complex or multiaxial loading conditions.[10,17-19] Thus, the influence of geometric parameters, such as archwire shape and cross-sectional dimensions, on the resulting force system can be observed. These parameters may be adjusted to optimize the archwire design.The present study aimed to evaluate, through FEA, the force system resulting from the MA in pre-activation position and after activation.

MATERIALS AND METHOD

Tridimensional model

The prototype studied was modeled based on a previous study,[10] also from archwires commonly used in clinical practice[7-9] and activated at 4.0 mm and 5.0 mm. A 45° gable bend was also incorporated to prevent anchorage loss and to provide effective anterior torque,[6-10] thereby avoiding palatal (or lingual) inclination of the incisors during retraction. FEA employed to simulate the behavior of the prototype, is a numerical technique in which the body of interest (the archwire, in this study) is divided into smaller sub-regions called finite elements (FEs). For each element, an equation describing its mechanical behavior is formulated. These individual equations are then assembled, maintaining continuity at the boundaries, to produce a global system of equations that represents the entire body. In static structural analysis, used to calculate displacements and stresses, this system is represented by the algebraic equation $[K].\{u\} = \{F\}$, where $[K]$ is the stiffness matrix, $\{u\}$ is the nodal displacement vector, and $\{F\}$ is the nodal force vector. In the analysis of archwires, due to the large displacements involved, the stiffness matrix $[K]$ depends on the displacement vector $\{u\}$, resulting in a non-linear system of equations. Once the nodal displacements $\{u\}$ are obtained by solving the system, the internal stresses and forces can be determined. Autodesk Inventor software was used for geometric modeling, and the archwire's behavior was simulated using the FE code ANSYS Workbench (Swanson Analysis Systems, Houston, Pennsylvania, USA). Figure 1-A,B shows the isometric view and dimensions of the pre-activated archwire. Table 1 presents the mechanical properties of the archwire. The wire used in this study is a 0.017" X 0.025" inch, β-titanium alloy, with Young's modulus (E) of 69 GPa (10×10^6 psi), yield stress (σe or YS) of 1240 MPa (180×10^3 psi), and a Poisson's ratio of 0.3, obtained by mechanical tension tests[20]. In the simulation, a mesh consisting of 1884 elements and 5235 nodes was generated, and a large-displacement analysis was performed. The simulation was carried out using the ANSYS Workbench software and consisted of two steps. In the first step, the pre-activation of the archwire was applied. For this purpose, the archwire was subjected to prescribed displacements in its three-dimensional model, as shown in Figure 2.

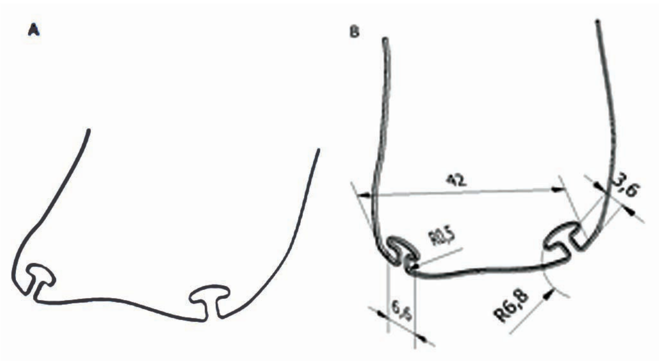

Fig 1: Mushroom Archwire.
A - Isometric view. B - Dimensions (in mm).

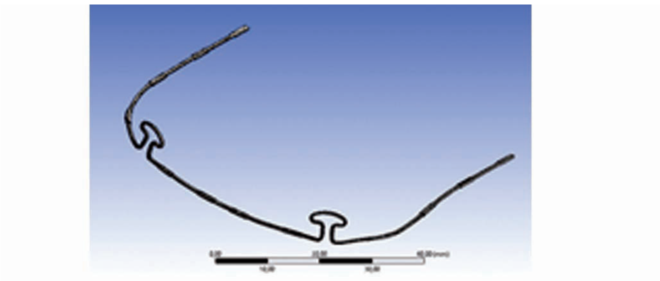

Fig 2: Mushroom archwire with restricted posterior extremities.

In order to evaluate the MA's mechanical behavior, the computational software Ansys® (Swanson Analysis Systems, Houston, Pennsylvania, USA) was used. This simulation by FEA sought to evaluate the force system in the archwire after activation over the anterior brackets. The MA must be activated within the elastic range, that is, they must not surpass the yield stress (YS) after being activated. To simulate the brackets, rectangular blocks were modeled with similar dimensions (4.0 mm) to those used in clinic, as well as the distance between them, considering the distance of 35.4 mm between loops. For this simulation, non-linear analysis was used in order to take into account the large displacements effects, which consisted of pre-activation at their posterior extremities by 45° gable bends; restriction of the posterior extremities to mimic the insertion in the molar tubes and spacing between the vertical extremities (legs) 2.5 mm apart and then activating them at 4.0 mm and at 5.0 mm. In the FEA, hexagonal elements of 20 nodes were used, as shown in Figure 3-A,B. The values of forces (F) and moments (M) in the anterior brackets can be seen in Table 2. Figure 4 illustrates the anterior brackets, represented by blocks (A, B, C, and D), where the F, M, and M/F ratio (Mz/Fx) were determined.

Table 1- Archwire mechanical properties

Young's modulus (E)	69 GPa
Yield stress (σe)	1240 MPa
Poisson's ratio	0.3
Bulk modulus	57.5 GPa
Shear modulus	26.54 GPa

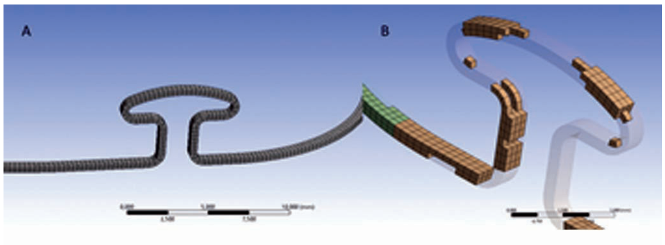

Fig 3: A - Finite element mesh (overview).
B - Shape details of the finite elements.

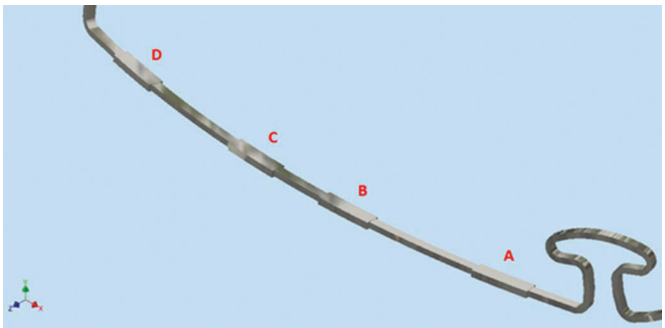

Fig 4: Representative illustration of the anterior brackets (A and D lateral incisors; C and B central incisors).

Translational and rotational movements of the brackets were restricted along and around the x-, y-, and z-axes. Once these constraints were applied to the anterior brackets (rectangular blocks), the force system was generated by distally pulling the extremities of the archwire (Fx direction). Table 2 presents the values corresponding to the resulting force system.

Table 2- Forces, moments and Mz/Fx for different activations

Force (N)	gram-force (gf)	Moment (N.mm)	Mz/Fx
Preactivated Archwire			
F_x = null	-	Mx = 4,45	-
F_y = null	-	My = 5,14	
F_z = 0,55	56	Mz = 1,08	
Activation at 4.0mm			
F_x = 1.81	184	Mx = 6.95	
F_y = 0.12	12	My = 33.26	12.9
F_z = -2.50	254	Mz = -23.32	
Activation at 5.0 mm			
F_x = 2.47	251	Mx = 8.74	
F_y = 0.17	17	My = 43.24	10.6
F_z = -3.42	348	Mz = -26.18	

RESULTS

The simulation for the pre-activation and activation at 4.0 mm and at 5.0 mm showed the specific influence of the force system and M over the archwire. Figure 5 shows the resulting force system obtained after distal pulling of the archwire extremities. In the neutral position, that is, with the archwire just preactivated, low magnitude forces were obtained. The values of Fx, Fy and Fz and Mz/Fx ratios can be seen in Table 2. For 4.0 mm activation, Fx force has a magnitude of 184 gf, while at 5.0 mm activation, a magnitude of 251 gf was observed. The Fy forces presented low magnitudes (12 gf and 17 gf for the activations of 4.0 and 5.0 mm respectively), while the Fz forces had magnitudes 254 gf and 348 gf for the activations of 4.0 and 5.0 mm respectively. In relation to the data in Table 2, there was a Mz/Fx ratio of 12.9 for 4.0 mm activation and 10.6 for 5.0 mm activation. Figure 6 shows schematically the planes formed by the axes x, y and z after activation. Consequently, in the frontal plane C (x-y plane) the force components are Fx, Fz and Fy, and the moment component Mz, that acts in the direction to compensate for second-order compensation (mesial-out, distal-in). Bucco-lingual tipping for third-order compensation takes place in the mid-sagittal plane B (y-z plane) with the force components Fy, Fz, Fx and the moment Mx. In the occlusal plane A (x-z plane), the forces are Fx, Fy and Fz, and the moment component My is associated with bucco-lingual rotation for first-order compensation. The moments follow the right-hand-rule convention[18]. With respect to Element Quality (EQ) most of the elements in the mesh of our study showed quality values above 0.84 (Figure 7). Figure 8 shows the maximum stress above 800 MPa, that represents a "peak stress"(PS), which does not represent the maximum stress (1240MPa). The von Mises stresses revealed a maximum tension of 1158 MPa at the whole part of the loop at 5.0 mm of activation. This result can be seen in an anterior study with the same modeled MA[10]. Localized PS may occur as a result of mathematical and numerical inaccuracies intrinsic to the simulation process. They typically appear in regions where forces or boundary conditions are applied. These non-physical stress concentrations are usually easy to identify and are commonly disregarded during result interpretation.

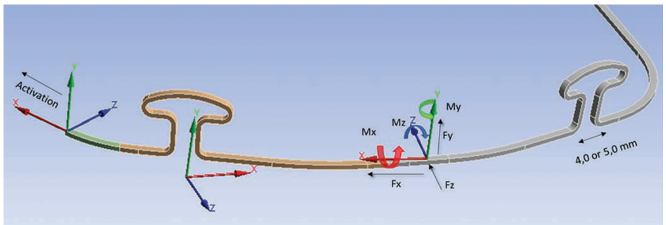

Fig 5: Resulting force system after archwire activation at 4.0mm and 5.0mm.

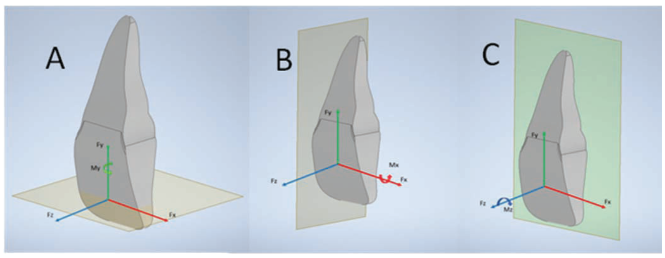

Fig 6: Planes represent schematically formed by the axes x, y and z after activation. A) In the occlusal plane (x, z plane) the force components are Fx, Fz and Fy, and the moment component My, that acts in the direction to compensate for first-order rotation. B) In the mid-sagittal plane (y-z plane) buccal-palatal rotation for third-order compensation takes place with the moment Mx. The force components are Fy, Fz and the Fx that represents activation direction. C) In the frontal plane (x-y plane), the components are Fx, Fy, and Fz. The moment component Mz is associated with distal-in/ mesial-out rotation for second-order rotation.

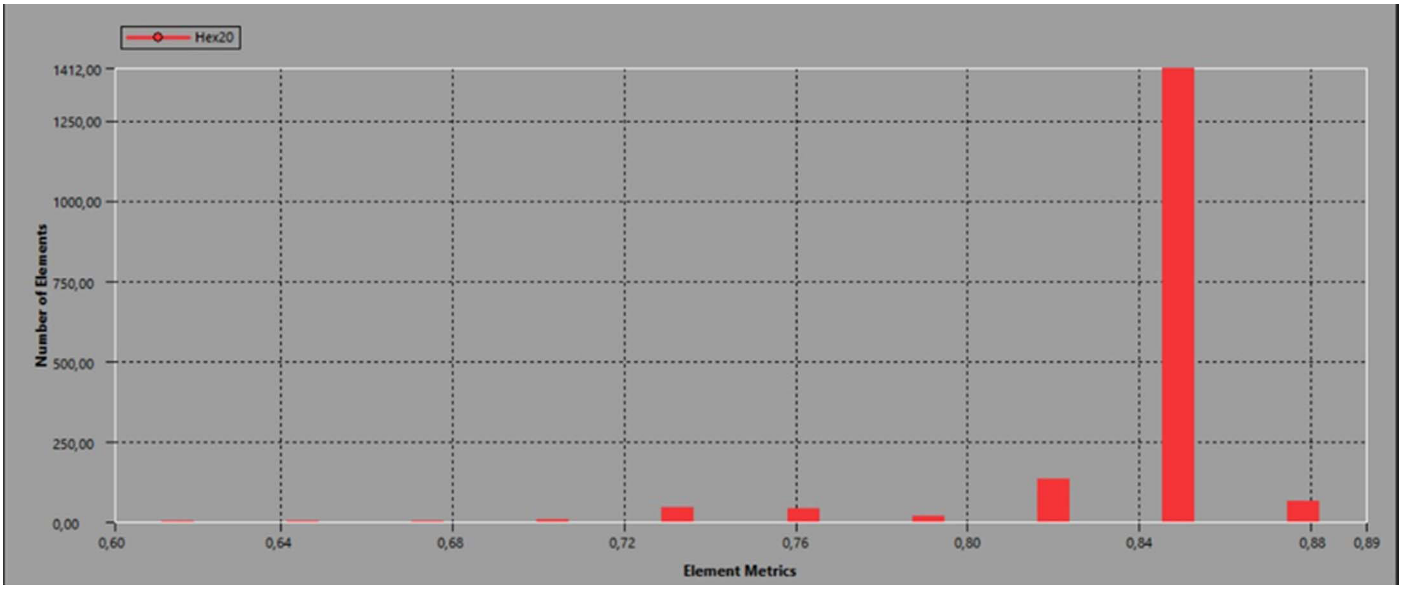

Fig 7: Quality of the FE generated in the mesh in the EQ metric study.

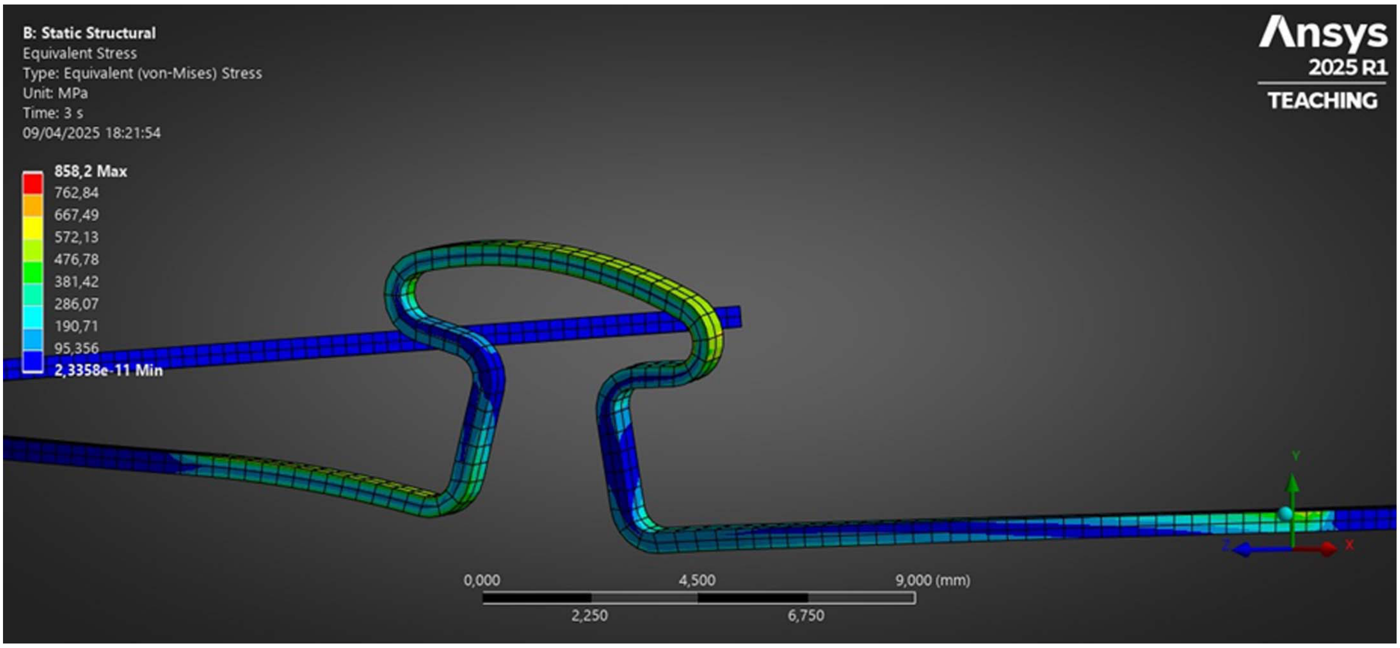

Fig 8: Von Mises "Peak Stress".

DISCUSSION

MA have been used efficiently in the clinic, maintaining efficient anchorage control during the retraction of the upper incisors[8]. No experimental or numerical study to date has verified the force system of these archwires, except some clinical studies[8,9]. A numerical study[10] recently verified the von Mises stresses over the MA. It was found that these archwires could be activated up to 5.0 mm without reaching the elastic limit (YS). However, no study obtained the force levels and the force system developed by them to validate the clinical findings. These clinical studies have demonstrated the versatility of these archwires as well as their efficiency in correcting dentoalveolar discrepancy with excellent torque control, so it becomes necessary to validate these good clinical results by means of numerical and experimental studies. In the experimental method, the body of evidence is submitted to mechanical tests, which might determine the force system more accurately, but the real behavior of an object and error can be verified statistically in order to certify that this error lies within certain limits. In addition to traction test, one of the most popular tests for evaluating orthodontic archwires is the three-point bending test; however, they are generally performed on pieces of straight wires. Although many transducers have been developed[13,18,20,21], they fail to mimic a clinical situation. Chen et al.[13] developed an orthodontic force-tester and a custom-made dentoform to measure the force system of T-loop archwires with three forces and three moments to obtain the coordinate system as defined clinically. The authors found that the activation in one direction (Fx) resulted in force and moment components in other directions (side effects) and that the archwires do not provide the force systems for pure translation; as a result, the quantification of the force system is critical for the selection of orthodontic appliances. Experimental and numerical tests are necessary to validate a safe device for use in both the medical sciences and engineering. FEA can be used to simulate the behavior of a body submitted to forces to obtain the resulting displacements and stress distribution. Some studies employed this method to understand the effects of archwire deformations[14-17]. As MA is derived from the T-loop archwires, comparisons can be made between them due to the lack of experimental and numerical studies with MA. Studies concerning geometrical parameters of SS and β-Ti T-loops have shown that the degree of activation influence the results of the force system, because deformation of the loop geometry occurs[21,22,23-27]. Another paper verified that T-loops without pre-activation, as the activation increases, the M/F ratio increase and the opposite was found when pre-activation is present[24]. Regarding the IBD, it was found[19] that as the space between teeth is closed the M/F ratio do not influence the force system significantly. However, this has less influence than other factors such as the loop position, height and width of the T-loop[16,20-31]. Burstone[25] developed the T-loop archwires, carrying out a series of clinical and experimental experiments in which different possibilities were verified regarding the parameters used and their effects on the force system, so the T-loops were checked with different heights, lengths and cross-sections. Different pre-activations were also verified and consequently the concept of differential moment mechanics was developed, also for looped archwires in the sense of producing retraction of the anterior segment while maintaining the torque of the incisors and at the same time maintaining the anchorage control of the posterior segment[7-10,30]. The present paper aimed to determine, the force system developed by pre-activated MA, in neutral position and at 4.0 and at 5.0 mm of activation, numerically, employing the FEA. It was revealed that three forces (Fx, Fy and Fz) and the three moments (Mx, My and Mz) act over the archwire. Fx forces that acts towards the loops were considered moderate at 4.0 mm of activation and acceptable[10] at 5.0 mm, if only the incisors were considered. The optimal force magnitude in the literature varies according to the type of tooth movement and the group of involved teeth. The literature[7,23,29] shows that the force levels for incisor retraction varies depending of the force application and center of resistance of the anterior segment. For incisor retraction the suggested forces could be about 300gf[30]. Park et al.[31] and Song et al.[32] applied a force of 200gf using coil springs for incisor retraction/intrusion using miniscrews. Ricketts[33] advised a force level of 320gf for incisor retraction. In the present paper the force levels for Fx that act towards archwire activation was 184 and 251 gf for 4.0 mm and 5.0 mm of activation, respectively (that would represent about 46 and 62gf per block). So it is important to check the compensatory curvature (Mx) in the anterior segment of the archwire in order to maintain torque control over the incisors. Fz forces that act bucco-lingually presented higher magnitudes 254 and 348 gf (63gf and 87gf per block that acts toward second-order rotation). Fy forces on the other hand showed low magnitudes. The moments (M) obtained showed rotational tendencies over the archwire compatible with first-, second- and third-order inclinations. According to Burstone[25] the M/F at bracket for maxillary central incisors could be 10/1 for translation and 12/1 for root movement. If extrapolating clinically, the Mx/Fz, in the present paper could produce a movement close to translation of the anterior teeth (lateral and central incisors) during space closure from 5.0 mm to 4.0 mm of deactivation (Table 2). Based on the results it can be inferred that MA developed a force system capable of producing incisor retraction with anterior vertical control and force magnitude compatible to induce tooth movement safely, if activated up to 5.0 mm. In ANSYS Workbench, EQ is a metric that evaluates the geometric quality of the FE generated in the mesh. This metric is particularly important because low-quality elements can compromise numerical accuracy and the convergence of simulations. The metric ranges from 0 to 1, with the following interpretation: 1.0: perfect-quality element (ideal shape, symmetric, and well-proportioned) and 0.0: very poor-quality element (distorted, collapsed, or with shapes unsuitable for numerical analysis), see Figure 7. An ongoing study attempts to measure numerically the force system on the beta side (posterior segment). A limitation of this investigation is that the numerical simulations were carried out with some simplifications, e.g., the periodontal ligament was not considered; the brackets were considered completely fixed (i.e., all movements constrained), which is not exactly the condition in a clinical situation, which depends on the tooth/bone relationship as well as the center of resistance and the center of rotation of the teeth. The IBD (inter-rectangular blocks) were based on estimated measures. Also, the numerical simulations involved certain simplifications. For example, residual stresses in the wire resulting from plastic deformation during the loop-forming process were not considered. Furthermore, the brackets were assumed to be completely fixed, which does not fully reflect clinical conditions, as tooth and bone properties may influence the outcome and introduce variability. The goal of the simulation is to obtain the three-dimensional force system, with three force components and three moment components acting at the anchorage points for each activation value. Studies are ongoing to refine the present model, also to test the MA experimentally.

CONCLUSION

The present study led to the following conclusions:

- MA could be activated up to 5.0 mm which may be compatible with the biological limits of tooth movement during incisor retraction.
- Extrapolating clinically, MA exhibited a Mz/Fx ratio compatible with translational movement of the anterior teeth.
- MA produced low-magnitude forces in the neutral (non-activated) position.
- The activation of these archwires generated a complex force system, with forces acting in three directions: Fx in the direction of activation toward the loops, Fy in the apical direction, and Fz in the bucco-lingual direction. The resulting moments acted in the first-, second-, and third-orders, corresponding to compensation for bucco-lingual inclination (occlusal plane), mesial-out/distal-in inclination (frontal plane) and bucco-palatal rotation (mid-sagittal plane), respectively.

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