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SCIENTIFIC SECTION

Asymmetric headgear for differential molar movement: a study using finite element analysis

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Objective: To compare the effects of four different asymmetric headgear systems.

Design: A mathematical method for three-dimensional data called finite element analysis.

Setting: The Orthodontic Department, the Federal University of Rio de Janeiro and the Metallurgical Engineering Department of the Fluminense Federal University.

Methods: Four systems of delivering an asymmetrical force to headgear were studied: using face-bow arms of different lengths, a symmetric face-bow with one of the arms bent outward in relation to the internal arch, a symmetric face-bow used in combination with a transpalatal arch activated to produce an asymmetric force, and a symmetric face-bow with the outer bow soldered to the inner bow on the side where a larger force will be applied.

Results: All four systems were effective in promoting asymmetric distal movement of the molars. However, the symmetrical face-bow with the outer bow soldered to the inner bow (system 4) could be used in asymmetric mechanics if the bows are soldered on the opposite side to the proposed distalization. Lateral and occlusal displacing forces were observed in all systems as well as tip-back and rotational movements.

Conclusion: The simulated computer model used in this investigation suggests that a face-bow with a symmetrically soldered joint and arms of equal lengths used in combination with a transpalatal arch is the best headgear option when asymmetric movement of upper molars is desired.

Key words: Asymmetrical force, headgear system, class II malocclusion, orthodontic treatment

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Introduction

Headgear is a common option for the treatment of class II malocclusion.[1,2] Compared with other techniques used to distalize molars such as intra-oral appliances and mini-implants,[3] headgear is the choice when restraint of maxillary growth and dental movement are required. There is a consensus that headgear inhibits anterior growth of the maxilla, which contributes to the correction of the anteroposterior discrepancy between the maxillary and the mandibular dentitions.[1,4]

Headgear might also be adapted to correct an asymmetrical class II molar relationship. Various asymmetric face-bows have been designed to produce unilateral molar movements, including using different lengths of outer or inner bows (shortening or elongating one arm), alternative right/left angulations between the outer and inner bows, or by introducing a swivel offset or hinged inner bow, and other combinations.[5–8]

The finite element analysis, developed initially for studies in the field of the engineering, has been applied in dental biomechanical research since 1973, to analyse the stress and strain fields in the alveolar support structures.[9–11] This is a useful method to quantify forces, moments and tensions, as well as other variables that allow appliance activations to be simulated for distal movement according to coordinates X, Y and Z.[12] It is based on the separation of the analysis shape into subdomains through finite elements, allowing the prediction of the mechanical behaviour of the object under varied loading conditions.[12]

Several investigations have examined the use of asymmetric headgear systems; however there has been little consensus as to which method is the most

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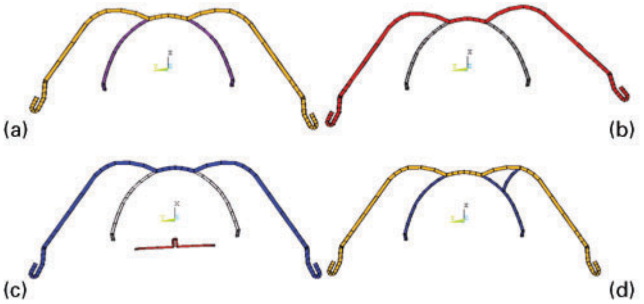

Figure 1 Asymmetric headgear systems studied: (a) face bow with arms of different lengths, (b) face-bow with one arm outward; (c) symmetric face-bow with asymmetric transpalatal arch and; (d) face-bow with outer bow soldered to the inner bow

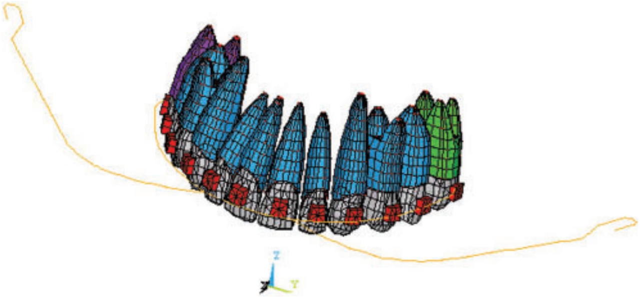

Figure 2 Finite element method applied to an asymmetric system. The coordinate X indicates mesial-distal movement, the coordinate Y indicates buccal-palatal movement and the coordinate Z indicates cervical-occlusal movement

effective.[8,13,14] The aim of this study was to compare the effects of four different asymmetric systems for applying forces to the maxillary first molar movement during headgear treatment using a mathematic method for three-dimensional data; finite element analysis.

Material and methods

The four asymmetric headgear systems (50.11.001; Morelli, São Paulo, Brazil) studied were produced by the same operator based on measurements made from the study casts of one patient. The upper first molars were asymmetric, with the right first molar more mesially positioned than the left one by 2 mm. These values were obtained with a digital calliper (797B; Starrett, São Paulo, Brazil) and then transferred to a schematic drawing on graph paper according to Cartesian coordinates (X, Y and Z). The zero point was placed at the centre of a tangent line placed on the distal face of the upper second molars.

The following headgear systems were analysed (Figure 1):

1. a symmetrically soldered face-bow with arms of different lengths. The modification (a reduction of 28 mm in length) was made to the left arm to produce more force on the right side (Figure 1(a));
2. a symmetrically soldered face-bow with arms of equal lengths, but with different angulations. The right arm was bent outward for application of larger force on this side. The angulation of the right outer arm was increased by 15° (Figure 1(b));
3. a face-bow with a symmetrically soldered joint and arms of equal lengths used in combination with a transpalatal arch made of 0.036″ stainless steel round wire (55.01.090, Morelli, São Paulo, Brazil) activated to produce an asymmetric force. In system 3 (Figure 1(c)), a modification was made to the transpalatal bar so that a 2 N force was applied to distalize the right molar. The transpalatal bar could not be simulated on a computer, therefore a 2 N force was added to the 4 N force applied to the right side of system 3, totalling 6 N distalization force;
4. a face-bow with symmetrical arms, but with the outer bow soldered to the inner bow on the asymmetric side.

The headgear was adapted in a patient and the obtained measures were transferred for a Cartesian system. Tube brackets were applied to the buccal surface of the first molars according to the model simulation, and facebows were connected to them. Elastics were placed on each facebow hook and then connected to cervical pull headgear. The centre of resistance for the molars was located in the apical third of the teeth, so that the cervical pull resulted in a line of force below the centre of resistance, with each side releasing a 4 N distal force.

The maxillary structures were created through ANSYS software, version 7.0 (Swanson Analysis System, Canonsburg, PA) using the finite element method (Figure 2). The finite element method was established based on the discretization of the geometrical model into several parts that were connected to each other through points called nodes. For each finite element, interpolation functions were established, which allow the structural behaviour of this area to be simulated according to the different properties of each element (teeth, alveolar lamina dura, bracket, headgear appliance, and periodontal ligament fibres) and their characteristic structural response. The mechanical properties of both organic tissues and orthodontic materials, particularly elasticity and Poisson's coefficient, were obtained from the literature,[15–18] thus characterizing the numeric module for finite elements. In order to simplify the model the properties of other structures, such as

Table 1 Resulting forces in the mesial direction (X-coordinate)

Asymmetric system of extra-oral force	Resulting distal force left side (26)	Resulting distal force right side (16)	Difference between right and left distal forces
1	2.68 N	4.42 N	1.74 N
2	3.20 N	3.28 N	0.08 N
3	3.21 N	5.24 N	2.03 N
4	3.57 N	2.87 N	−0.70 N

organic tissues and orthodontic materials were considered to be linear, homogeneous, and isotropic.[17–19]

For the purpose of initial dental movement and deformation of the periodontal fibres, the tooth was considered to be a rigid body that suffers no deformation. In addition, the differentiation between enamel and cement was not taken into account in order to simplify the model, and a single value was used to represent the tooth property. The values attributed for characterizing the tooth behaviour were 20,000 MPa for the modulus of elasticity[10,16,18] and 0.30 for the Poisson's coefficient.[20–22] The alveolar lamina dura (also considered a rigid body) was attributed the cortical bone properties with mean values of 13,800 MPa for the modulus of elasticity and 0.30 for the Poisson's coefficient.[10,17,20–22] The values attributed to orthodontic brackets, all made of stainless steel, were 180,000 MPa for the modulus of elasticity and 0.30 for Poisson's coefficient, whereas the periodontal ligament was attributed 0.05 MPa to characterize the finite element model, the smallest and more frequent value found in the literature.[10,16] A Poisson's coefficient of 0.49 has been used to characterize the incompressible materials in several studies.[21–23]

The computer simulations were performed on a desktop computer with the following configuration: Intel Pentium 4 with 2.8 GHz processor, 80 Gb Hard Disk, and 1 Gb RAM. The simulations were run by using the same ANSYS software. Each simulation was carried out once. Repetitions were only undertaken in order to adjust the developed model.

Statistical analysis

The simulations produced with the finite element method only represented the initial movement of the first molars. For this reason, the results do not exhibit significant quantitative differences in the distal molar movement and the values were not submitted to hypothesis testing, but are presented using a descriptive analysis.

Results

Table 1 shows the resulting forces on the upper first molars in the mesial-distal direction (X-coordinate). System 3 produced the greatest difference between the resulting distal forces on the right side and left sides: 2.03 N (3.21 N on the left side and 5.24 N on the right side). System 1 showed a distal force difference of 1.74 N of distal force between left and right sides, while system 2 produced a difference of only 0.08 N between both sides. Interestingly, system 4 had an unexpected result, with a smaller distalizing force of 0.7 N on the right molar as the left molar.

Table 2 shows the resulting forces on the upper first molars in the buccal-palatal direction (Y coordinate). Lateral displacing forces were observed in all systems: a force in the palatal direction on the right side and a force in the buccal direction on the left side. System 3, showed the smallest lateral forces (a buccal force of 0.25 N on the left side and a palatal force of 0.25 N on the right side) whereas system 4, showed the greatest lateral forces (a buccal force of 1.72 N on the left side and a palatal force of 1.56 N on the right side).

Table 3 shows the resulting forces in the cervical-occlusal direction (Z-coordinates). All systems tended to promote forces in the occlusal direction or extrusive movement. Application of a greater force on either side also resulted in a greater extrusive force, except for

Table 2 Resulting forces in the buccal-palatal direction (Y-coordinate)

Asymmetric system of extra-oral force	Resulting buccal force left side (26)	Resulting lingual force right side (16)
1	0.92 N	0.63 N
2	0.20 N	0.40 N
3	0.25 N	0.25 N
4	1.72 N	1.56 N

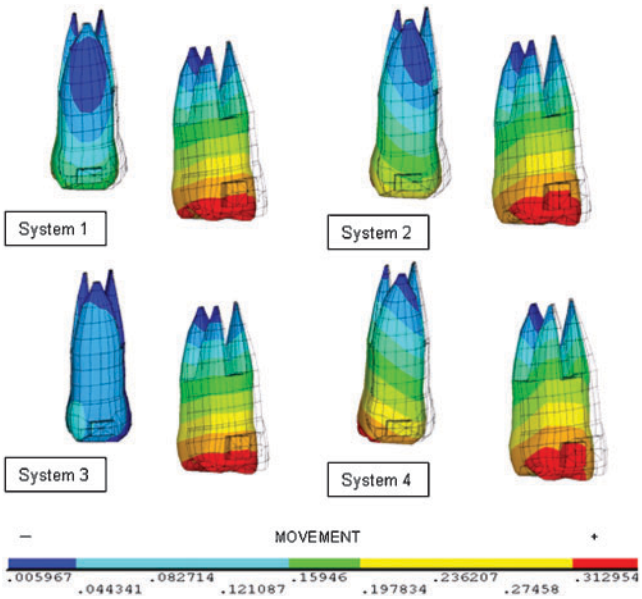

Figure 3 Computer simulation of the initial molar movement from the four systems after extra-oral force application. The degree of displacement is represented by the colour scale (blue: little or no movement; red: greatest amount of movement; molars in the right posterior view)

system 3, where the right side received an occlusal force of 1.19 N compared to 1.22 N on the left side.

Figure 3 shows that the displacement resulting from the activation of the four asymmetric headgear systems produced a distal movement of the crown in all systems. At the bottom of the figure is a colour scale representing the amount of molar movement. Blue shades to the left represent little or no movement and red shades to the right represent maximum movement. There is a colour gradation from the roots of the teeth to the crowns, which indicates a tip-back movement. Rotational movement was also present in all system after extra-oral force application (Figure 4), but this was smallest for the upper left molar in system 3.

Discussion

The application of computer simulations using finite element analysis showed to be an efficient method to study asymmetric headgear systems, being observed that the four researched types were effective in promoting asymmetric distal movement of the molars.

Analytical mathematical models can be criticized as not being true representations of dental structures, including the diversity of substances of tooth composition and anatomical irregularity. Experimental techniques in humans or animals are also limited because of the possible error caused by variables like tension and compression values in the periodontal ligament and individual variation. Finite element analysis is a possible solution to these problems because of the capacity to mathematically model complex structures with irregular geometries like teeth and biomaterials.[12] The technique has been use to produce models in several dental specialties[24,25] including orthodontics;[9,11,12,21] however as far as we are aware it has not been used to model orthodontic extra-oral systems. One major drawback is the inability to reproduce the cell functions and chemical mediators of inflammation during dental movement. In addition to the biological complexities, the variations of

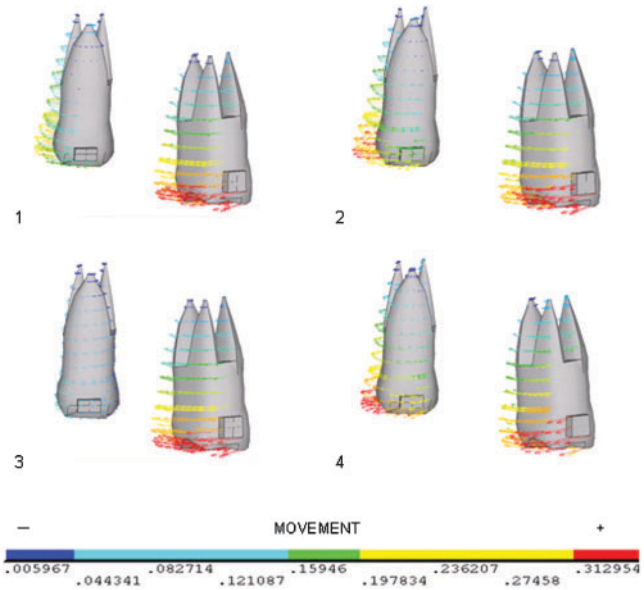

Figure 4 Rotational movement of the molars from the four systems after extra-oral force application. The degree of displacement is represented by the colour scale (blue: little or no movement; red: greatest amount of movement)

Table 3 Resulting forces in the cervical-occlusal direction (Z-coordinate)

Asymmetric system of extra-oral force	Resulting occlusal force left side (26)	Resulting occlusal force right side (16)
1	0.75 N	1.23 N
2	0.81 N	1.12 N
3	1.22 N	1.19 N
4	0.98 N	1.44 N

the individual response to orthodontic forces could not be observed through a computerized method.[26] Therefore, our analysis was based on the initial movement of the teeth in response to the forces exerted by each of the four systems studied.

In relation to the asymmetric distal movement of the molars, all systems were shown to be effective, but the best result was presented by system 3 (Table 1) which means that it was the best choice for producing asymmetric distal force. This result also reinforces the findings of Melsen *et al.*[14] who suggested using a transpalatal bar in associated with headgear and activating it on the side where a greater distal force is required. The headgear acts by neutralizing the mesial force on the opposite molar, thus controlling the rotational movement and optimizing the distal force on the desired side. System 1 was also effective in producing an asymmetric distal force. This finding is in accordance with other authors,[5,13,27] who recommend an increase in the outer bow length on the side needing greater distalization. System 2 was less effective in producing an asymmetrical distal force. Other authors[6,13] have also found that expanding one of the outer bow side without altering its length is ineffective, since the angulation between force line and sagittal median line is virtually kept unchanged. In addition, the authors have pointed to the fact that the lateral force component increases under such situations without favouring the antero-posterior position of the molar. Therefore expansion of one of the outer bow sides with no correspondent increase in length is not an appropriate choice for producing a greater distal force.

System 4 was based on work carried out by Jacobson[2] who modified the extra-oral arch by displacing the welded joint position attaching the outer and inner bows towards the side where distal molar movement is desired. He found a greater force on the side the welded joint was displaced toward, but he attributed this difference to the increased flexibility on the opposite side that, due to appliance activation, would suffer a greater deformation, reducing the angulation between the force line and sagittal plane and altering the resulting force vector. According to these findings, headgear system 4 was welded to a rigid wire segment, thus linking the outer arm to the inner one in order to make the extra-oral arch more rigid at the side where distalization is desired and consequently providing a greater flexibility at the opposite side; however, a lesser distal force was observed at the side where a greater distalization movement of the molar was expected. We can conclude that this system yields a discrete asymmetric distal force at the side having higher flexibility, a finding not corroborated by Jacobson. On the other hand same authors,[8,13] do not believe in the efficacy of this system in producing extra-oral forces asymmetrically.

Movements in the buccal-palatal direction are generally undesirable and very difficult to control.[27,28] Lateral displacing forces were found in all the systems in this study, with movement in the palatal direction on the right side and in the buccal direction on the left side. This has been found in other studies[5,29,30] and can result in a posterior cross-bite on the side receiving more distal force. According to Yoshida *et al.*,[29] the lateral dislocation is directly proportional to the asymmetry existing in the outer arch. That is, the more asymmetric the outer bow, the greater the buccopalatal movement of the distalized molars. Other authors[8,31] had observed buccal displacement on both sides, which could be attributed to discrepancies in the face-bow configurations.[29] System 3 showed the best results in the lateral direction, because the forces were low and equal on both sides. This result was expected since the transpalatal bar acts by controlling lateral movements.[14]

With regard to the occlusal or z-direction forces, we expected to observe extrusion of the first molars in all headgear systems studied as cervical extra-oral traction was employed and the greater the force applied, the greater the tendency for extrusion. According to this same rationale, it was possible to predict that the right molar (the tooth expected to undergo the greater distalization) might suffer an extrusion greater than that of the left molar. As expected in this study and previous studies,[1,28,30] we observed the predicted outcome on three of the four systems submitted to computer simulation. System 3 showed a similar extrusive force on both and this result was attributed to the transpalatal bar that equilibrated the system by promoting occlusal movements of similar intensity on the right and left sides. The control of vertical force can be achieved by altering the angulation of the outer arms of the facebow, although Altug *et al.*[28] advise that in such cases a decreased distal force will be achieved.

The line of force passed below the centre of resistance of the first molars in the model used in this simulation, therefore it was expected that these teeth would tip distally instead of moving bodily. This supposition was confirmed (Figure 3) and is corroborated in the literature[27] as the molar models made for this computer simulation had their centre of resistance located in the apical third of the root (this result was obtained by mistake in the elaboration of the drawing of the tooth molar in the computer model).

Distal rotation is another movement associated with the mechanics of distal movement, because the force application point is located on the buccal face of the crown.[5,14,29] In Figure 4, it can be observed that this rotational movement happened in all systems, but in system 3 this effect was smaller on the upper left molar. This was expected because of the role played by the transpalatal bar, which neutralizes the movements of distalization and rotation.[14] Although distal rotation is not desired, according to Yoshida *et al*,[29] it is not a reason for concern as this movement is favourable because the upper first molars in Class II malocclusions are frequently mesially rotated.

Conclusions

Computer simulations using finite element method for asymmetric headgear systems studied showed that:

- all systems were effective in promoting asymmetric distal movement of the molars;
- the symmetric face-bow, used in combination with a transpalatal arch (system 3) presented the best results;
- the symmetrical face-bow with the outer bow soldered to the inner bow (system 4) could be used in asymmetric mechanics if the bows are soldered on the opposite side to the proposed distalization.

Contributor statement

Luciana R. Squeff and Antônio Carlos O. Ruellas were responsible for the reproduction of the headgear systems and all the measures for the application of the finite element method, data interpretation and final approval of the article. Norman D Penedo was responsible for the elaboration and application of the finite element method. Eduardo F Sant′anna, Giovana R Casaccia, Janaína C Gomes, Carlos N Elias and Jayme P Gouvêa were responsible for critical revision. Luciana R. Squeff is the guarantor.

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