Original Article

Unilateral Outer Bow Expanded Cervical Headgear Force System: 3D Analysis Using Finite Element Method

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Abstract

Objectives: Headgears are among the effective orthodontic appliances to achieve treatment goals. Unilateral molar distal movement is sometimes needed during an orthodontic treatment, which can be achieved by an asymmetric headgear. Different unilateral headgears have been introduced. The main goal of this study was to analyze the force system of unilateral expanded outer bow asymmetric headgears by the finite element method (FEM).

Materials and Methods: Six 3D finite element models of a mesiodistal slice of the maxilla containing upper first molars, their periodontal ligaments (PDLs), cancellous bone, cortical bone, and a cervical headgear with expanded outer bow attached to maxillary first molars were designed in SolidWorks 2010 and meshed in ANSYS Workbench ver. 12.1. The models were the same except for the degree of outer bow expansion. The outer bow ends were loaded with 2 N force. The distal driving force and the net moment were evaluated.

Results: A decrease in the distalizing force in the normal side molar from 1.69 N to 1.37 N was shown by increasing the degree of unilateral expansion. At the same time, the force increased from 2.19 N to 2.49 N in the expanded side molar. A net moment increasing from 2.26 N.mm to 4.64 N.mm was also shown.

Conclusion: Unilateral outer bow expansion can produce different distalizing forces in molars, which increase by increasing the expansion.

Keywords: Extraoral Traction Appliances; Asymmetric; Finite Element Analysis

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INTRODUCTION

Headgear is a well-known and useful appliance in orthodontic treatments. Several techniques use headgear as an auxiliary appliance for orthodontic treatment with different objectives [1-4]. Norman Kingsley is known as the earliest documented user of headgear [5].

It was revived by Oppenheim who described its mechanical principles after being ignored by Angle. Armstrong in 1971 published a comprehensive study in headgear [6] which was followed by other researchers [7-11]. The significant effects of inner bow length on treatment results were assessed in a recent study by Geramy et al. who explained the difference in the resultant force when adjusting a symmetric cervical headgear in a mediolateral asymmetric molar position [12].

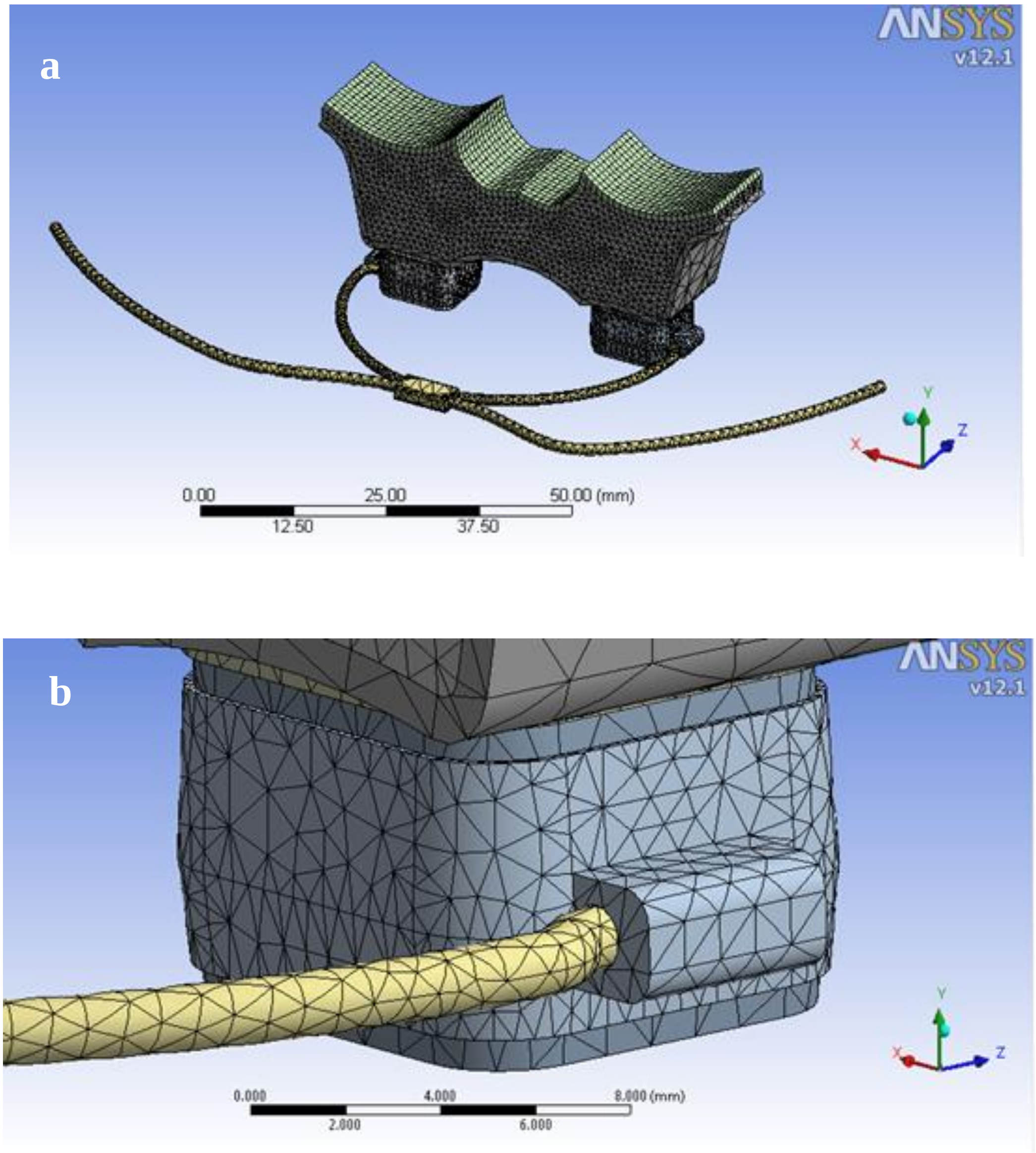

Fig. 1. **(a)** The meshed 3D model. **(b)** Closer view of the 3D model showing the connection between the upper left molar, its band, and inner bow end.

They reported different distal driving forces in different mediolateral molar positions. Different amounts of distal tooth movements are frequently required during treatment. Asymmetric force production has been the goal of different researchers [13-17]. Finite element method, as a numerical means of finding accurate answers to different questions, was introduced less than a century ago in aerospace industry and soon found its way through the bio logical sciences.

This method has proven its efficiency in different lines of investigations and questions [18-23].

The main goal of this study was to assess the effects of a unilateral outer bow expanded headgear on producing an asymmetric force to the molars.

In other words, this study tried to evaluate the nature of movements of upper first molars when loaded by a cervical headgear with a unilaterally expanded outer bow.

MATERIALS AND METHODS

Six 3D finite element models of a mesiodistal slice of the maxilla containing upper first molars, their PDL, cancellous bone, cortical bone, stainless steel molar bands fitted to molar crowns and a cervical headgear were designed. The models were the same except for the outer bow form, which was symmetric in model one and unilaterally (right side) expanded in models two through five. The right outer bow expansion was designed considering an arc drawn with the center in the anterior most point of the outer bow. Four different positions of the symmetric outer bow and the most expanded one were designed by dividing the angle difference between two extreme (the symmetric position and the most expanded one) outer bow positions. In this way, the gradual expansions of the outer bow were almost the same between models two to five. Wire diameter was 1.6 mm in the outer bow and 0.9 mm in the inner bow (Fig. 1). Due to the complexity of the molar shape, the results cannot be shown easily in the molar teeth. To solve this problem, molars were replaced by cubic parts in the last model to make it easy to show the displacements (model six).

The models were designed in SolidWorks 2006 (SolidWorks Corp., MA, USA) and were then transferred to ANSYS Workbench ver. 12.1 (ANSYS, Inc., PA, USA) for the solving process. To find the angles formed between the outer bow and its tangent to the neck, accurate trigonometric calculations were made using SolidWorks. Linear measurements were required to draw Fig. 2 and were derived from a volunteer dental student using a clinical vernier. In this way, the exact force components in the anteroposterior and mediolateral directions were found which were later used in the ANSYS Workbench for the analysis phase. Static analysis was done using force components found in the previous stage. The outer bow bending under loading was analyzed. In the final phase (model six), the teeth were replaced in the model five with two blocks to simplify presenting the displacement patterns.

Headgear was considered to be made of stainless steel. Meshing was done by a meshing program in Workbench. Meshed models contained 142,486 nodes and 84,023 elements (Fig. 1). Outer bow ends were loaded with a 2 N force in the horizontal plane decomposed in mediolateral and anteroposterior directions. The mechanical properties of the materials used in the models were defined (Table 1). The distalizing force to molars and moments were evaluated. The other part of this study involved finding the best position of the center of outer bow bending. In other words, a geometrical method was considered to find the center point of the favorable arc to place the outer bow in its most asymmetric position when expanded (Fig. 2a).

RESULTS

Distal component of force:

Force components to distalize molars were the same in the symmetric outer bow (1.9588 N in the left side and 1.9588 N in the right side). Proceeding towards outer bow expansion models, a difference between right and left side molar force findings was found. The outer bow expansion side (= right side) force increased gradually in models from the second model through the fifth one. The force was -2.1974N in the second model and increased to -2.4916 N in the fifth model (the negative sign shows the distal direction of force). At the same time, the force pattern in the normal side molar showed a descending trend from model two to five from -1.6984 N to -1.3789 N. The force patterns are shown in Table 2 and Fig. 3.

Moments:

Positive sign moments are clockwise while the negative ones are counterclockwise (based on Fig. 2). Moment findings were the same as force findings in the symmetric model (-12.393 N.mm in the left side molar and 12.399 N.mm in the right side molar).

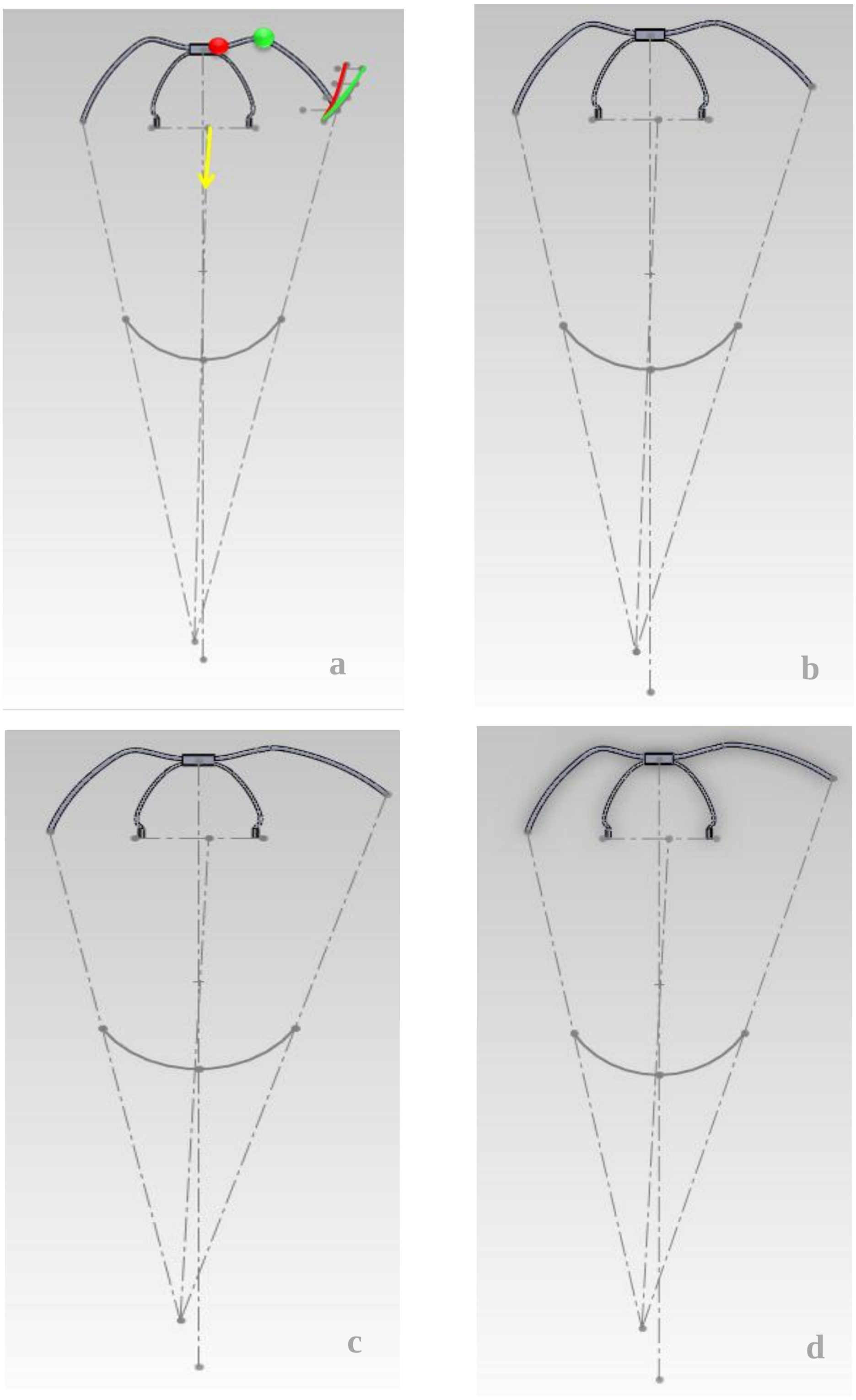

Fig. 2. Four asymmetric headgear models produced by expansion of the outer bow. a) The green curve is selected for the outer bow expansion (with the green point as the center) which can produce a greater difference in the neck tangent line angles than the red curve with the red point as the center. The yellow vector shows the asymmetric force production. b, c, and d) Progressive steps of outer bow expansion.

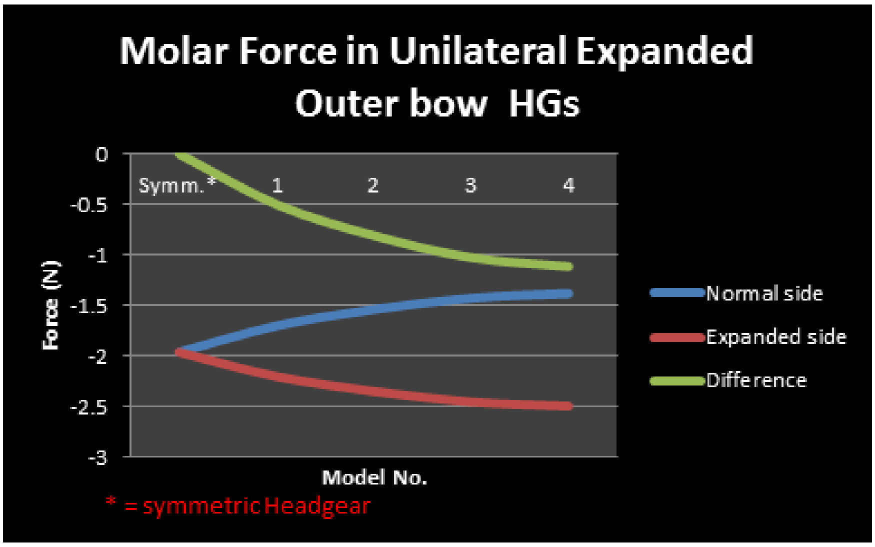

Fig. 3. The produced molar forces in the normal side, the expanded side and the difference of the forces.

A gradual decrease was shown in the expanded side molar moment between 11.171 N.mm and 9.906 N.mm in models two through five. An increase in the moment was shown from -13.434 N.mm in model two to -14.554 N.mm in the normal side molar (the negative sign shows the counterclockwise moment). A ∑M≠0 was found. This residual moment had an ascending trend (Table 3, Fig. 4).

DISCUSSION

This study assessed a unilateral outer bow expanded headgear to produce an asymmetric distalizing force to molars. Producing asymmetric forces to the molars and also understanding the side effects are challenging for practitioners and researchers. Different methods have been studied and published to produce such asymmetric forces [13-17].

Table 1. The mechanical properties of the materials used in the models

	Young's Modulus (MPa)	Poisson's Ratio
Tooth	20300	0.26
PDL	0.667	0.49
Spongy Bone	13400	0.38
Cortical Bone	34000	0.26
Stainless Steel	200000	0.30

Table 2. Force findings in the symmetric and asymmetric models (N)

	Normal side	Expanded side	Difference
Symm.*	-1.9588	-1.9588	0
1	-1.6984	-2.1974	-0.499
2	-1.5371	-2.3444	-0.8073
3	-1.4248	-2.4486	-1.0238
4	-1.3789	-2.4916	-1.1127

*= Symmetric Headgear

Table 3. Moment findings in the symmetric and asymmetric models (N.mm)

	Normal side	Expanded side	Difference
Symm.*	-12.393	12.400	-0.007
1	-13.434	11.171	-2.263
2	-13.69	10.822	-2.868
3	-14.423	10.062	-4.361
4	-14.554	9.906	-4.648

*= Symmetric Headgear

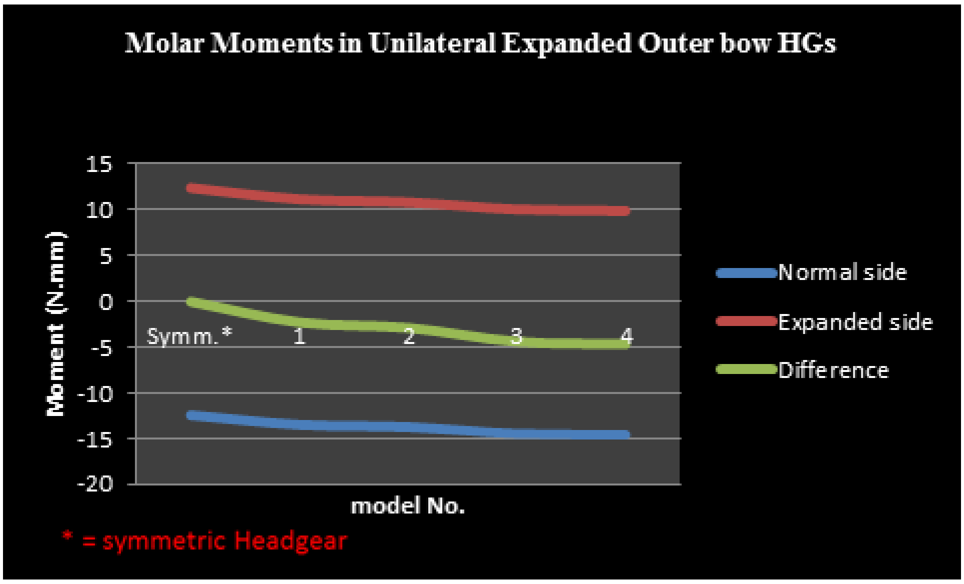

Fig. 4. The produced moments in the normal side, the expanded side, and the difference of the moments.

To analyze the force system of a headgear, tangent lines are drawn to the neck contour from the outer bow end points and continue posteriorly until crossing (Fig. 2). It must be necessarily drawn from different outer bow end positions.

Different outer bow positions are obtained by: a) different outer bow lengths; b) expanding one outer bow end; and c) incorporating a swivel joint in an off-axis-inner/outer-bow-connection-point headgear. The decomposition of force is the same for an asymmetric headgear position and depends directly on the degree of deviation produced in the contact point of tangent lines, regardless of the manner of inducing such deviation. Evaluation of moments is the important part of this analysis. When comparing different unilateral headgears, the only difference in the force system is the net moment. Comparing different outer bow lengths and unilaterally expanded outer bow, the net moment in the system is an important part. Finding the best position of the point of outer bow bend (to produce an effective asymmetric headgear) was another achievement of this study. This was done analytically by drawing arcs with the center in the inner/outer bow connection point (the red point in Fig. 2a) and also with the point of outer bow curvature (the green point in Fig. 2a). Comparing the curves, the green one was selected because of its ability to change the tangent line angle more than the other curve when viewed occlusally. Viewing the curves drawn in Fig. 2a (the green or the red one), it can be considered that outer bow end is moving away from its initial position, changing the tangent line angle up to a point and then the angle tends to return to its initial state (when viewed from the back of the neck in the mid-sagittal plane). The maximum shift of the connection point between the tangent lines is the midpoint of the start and end of outer bow path (Fig. 2a). In this way, the increase of the force difference is not directly related to the increase of the expansion. The force difference is increased up to the most prominent point of the path and will decrease afterwards. Considering the constant length of the outer bow, the position of the expanded outer bow end and the amount of deviation caused in the tangent line to the neck are mainly responsible for the produced unilateral force component.

The path is in the form of a curve (actually, it is an arc with the center in a definite point on the outer bow). Thus, it can be visualized to move away from its neutral position up to a definite point and then moving back toward its initial position when viewed from the back of the neck.

If the expansion is not enough to resist the traction load, the tangent line to the neck will almost be the same as in the other side; thus producing more or less symmetric force decomposition and the moment will act to make the unilateral headgear. This situation can be summarized as “a small amount of unilateral expansion that can be neutralized by the neck strap can keep the intersection point of tangent lines along the mid-sagittal plane (receiving equal force component in both side molars) and providing a yawing moment for the system”.

The asymmetric force production is not predictable in a unilateral outer bow expanded headgear. It is mainly based on the position of the outer bow after being flexed under the traction load and the difference produced in the angles of the neck tangent lines. This is a direct reflection of the flexibility provided by the outer bow. In this way, the role of the outer bow wire diameter is emphasized. Different molar distal forces are favorable to the clinician but the side effects are not ignorable and should be considered thoroughly.

Outer bow expanded headgears have a net yawing moment tending to rotate the dental arch clockwise or counter-clockwise when viewed occlusally.

This force vector, when analyzed in combination with the moment difference present in the system, can interpret different pure molar distal movements in both sides of the arch. Moments tend to rotate the system around the vertical axis. The clockwise/counterclockwise direction of rotation is decided by the side of outer bow expansion. In an apico-occlusal view, the direction of rotation is clockwise when the right side outer bow arm is expanded and counter clockwise when the left side outer bow arm is expanded. Combining the effects of force system decomposition and the residual moment present, it will be almost impossible to determine the final position of the molars with geometric analytical methods. In the limited space present and considering the complexity of the displacement pattern, FEM is by far the most acceptable discipline of gathering data on the events. Several points have been mentioned regarding the headgear form and the importance of its outer-bow position and length [5-9]. The literature lacks any detailed published data on the outer bow expansion and its force system analysis considering the flexibility of outer and inner bows.

Geramy and colleagues analyzed the mediolateral asymmetry in the molars being loaded by a symmetrical headgear [12]. They showed the difference in forces produced in molars, and explained some unwanted events in the process of treatment with a cervical headgear. These asymmetries can be considered to be unintentional. Analyzing the asymmetries produced by the outer bow expansion and those produced by the difference in outer bow length, it is revealed that they have different natures. The laterally directed force vector is an unfavorable side effect present in the headgears with different lengths of the outer bow [24] and is worsened by the presence of a net moment. As a whole, when reconsidering all findings, the response of upper molars can be summarized as a complex displacement shown in Figs. 5a and b.

To simplify presenting the displacement in molars, an alternate model (model six) was designed replacing molar teeth with cubic blocks and the axis of movements was drawn based on the analysis of the numeric findings. The movements traced in molar bands are shown in Fig. 5b. Focusing on the pattern of molar band displacements, a distal movement of bands combined with a yaw can be noticed.

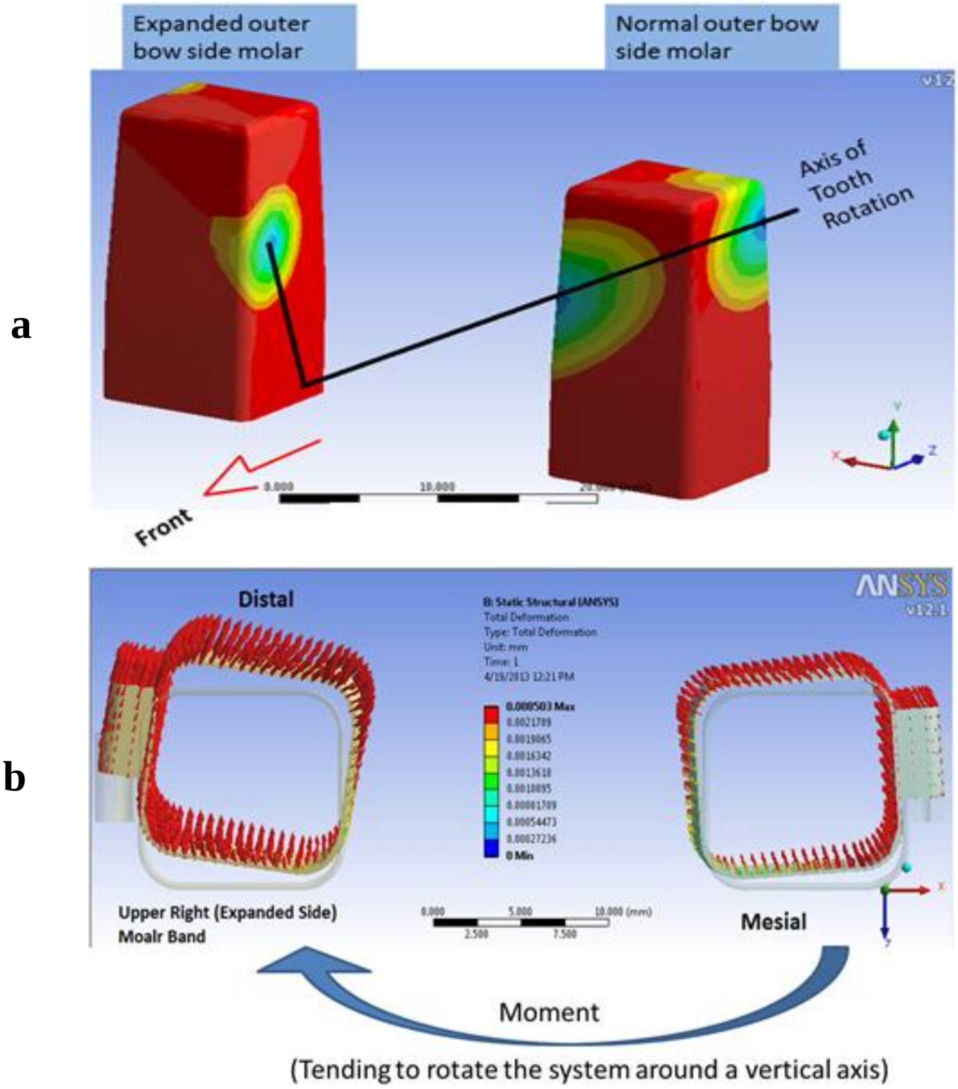

Fig. 5. (a) Blocks to represent teeth to simplify presenting the manner of tooth movements when a unilateral expanded headgear is applied (the simplistic model can make it easier to find out how the teeth respond to the applied force system). **(b)** The pattern of tooth movement shown in Fig. 5a is viewed occlusally by tracing the band displacements. A distal-ly driving force is shown to be combined with a yawing moment on molars.

CONCLUSION

1. A residual yawing moment was found, which tended to rotate upper arch (when applied to the entire arch) or upper molars (when applied to both side molars) clockwise/counter-clockwise according to the sign of the net moment (in an outer bow expansion head gear).

2. The amount of unilateral force produced by the outer bow expanded headgear increased up to a point and then decreased as explained.

3. In order to maximize the force difference in an outer bow expansion headgear, it is suggested to bend forward the outer bow with a center located in its curvature point (not the inner/outer bow connection point).

4. The net moment is expected to increase when the outer bow is expanded unilaterally and further increase as the expansion continues.

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