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# Finite element method (FEM) analysis of the force systems produced by asymmetric inner headgear bows

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*Background:* Extra-oral traction appliances were introduced more than a century ago and continue to be used to produce orthopaedic and/or dental changes in the maxilla. While force systems produced by asymmetric outer bows have been studied extensively, the force systems produced by asymmetric inner bows have been overlooked.

*Aim:* To analyse the forces acting on the maxillary first molars: when the size of one bayonet bend is increased; when the point of application of the distalising force on the inner bow is moved to one side; when one molar is displaced palatally.

*Methods:* Four FEM models of cervical headgear attached to maxillary first molars were designed in SolidWorks 2010 and transferred to an ANSYS Workbench Ver. 12.1. Model 1, each molar was 23 mm from the midpalatal line and the inner bow was symmetrical; Model 2: the left molar was displaced 4 mm towards the midpalatal line and the inner bow was symmetrical; Model 3: the molars were equidistant (23 mm) from the midpalatal line, but the left molar was engaged by a 2 mm larger bayonet bend; Model 4: the molars were equidistant (23 mm) from the midpalatal line but the join between the inner and outer bows was displaced 2 mm towards the left molar. In all FEM models, a 2N force was applied to the inner bow at the join between inner and outer bows and the energy transmitted to the teeth and the von Mises' stresses on the molar PDLs were assessed.

*Results:* There were marked differences in the strain energy on the teeth and the von Mises stresses on their PDLs. A 14 to 20 per cent increase in energy and force was produced on the tooth closer to the symmetric plane of the headgear. In addition, the increase in energy produced a 30 to 62 per cent increase in the von Mises stresses within the PDLs.

*Conclusion:* Small asymmetries in molar position, the size of a bayonet bend and the point of application of a force on an inner bow resulted in asymmetrical forces on the molars. These forces were higher on the molar closer to the symmetric plane of the headgear.

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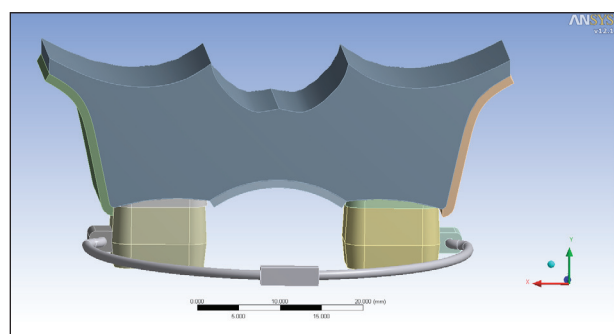
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## Introduction

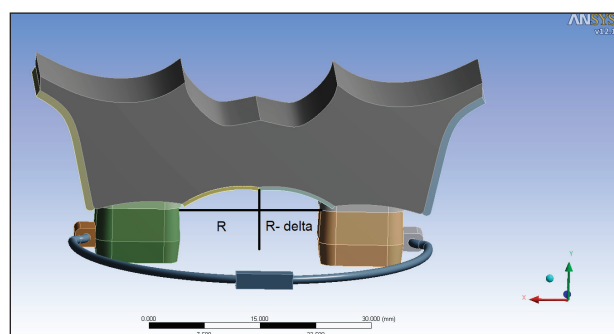
Headgear was introduced to the dental profession by Norman William Kingsley in the 19th Century.<sup>1</sup> In the early 1900s, Angle replaced headgear with intermaxillary mechanics which were considered to produce similar effects. Subsequently, Oppenheim promoted the use of headgear and described its mechanical principles.<sup>2,3</sup> Published reports have provided advice on the selection and use of the appliance while Oppenheim's original description

has been expanded to detail how the inclination and symmetry of the outer bows may affect tooth movement.<sup>4-14</sup> In spite of the wealth of information on the effects of different lengths and positions (angulations) of the outer bow on tooth movement, the effect of asymmetries in the inner bow on the molars has escaped attention.

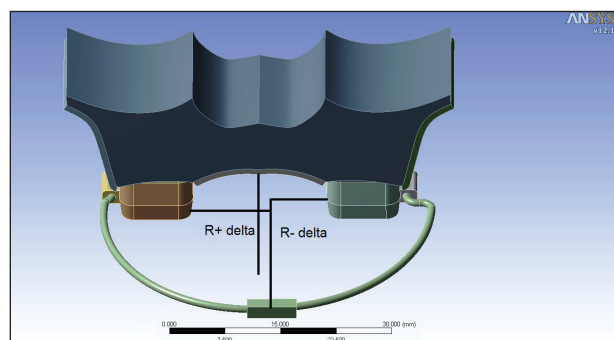
The finite element method (FEM) was introduced less than a century ago and has been adopted by the biologic sciences as a numerical means of finding answers to



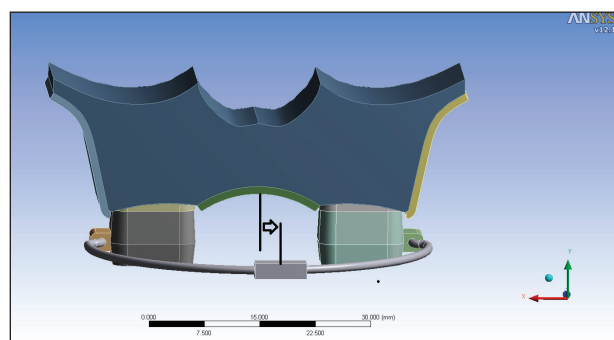
(a)



(b)



(c)



(d)

**Figure 1.** (a) Model 1, the positions of the molars and the headgear are symmetrical. (b) Model 2, the maxillary left molar is displaced 4 mm towards the palatal midline. (c) Model 3, the left molar is engaged by a 2 mm larger bayonet bend, shifting the symmetric plane of the headgear to left, thus reducing the left molar distance to this plane. (d) Model 4, the join between the inner and outer bows has been moved 2 mm to the left.

difficult questions. It consists of a computer model of a material or design that is stressed and analysed for specific results. The method involves the solving of partial differential equations by the use of a system of approximations which have been proven efficient in resolving the complex issues of structural analysis.<sup>15-20</sup>

It was considered that FEM would be useful in determining the force systems between the inner bow of a cervical headgear and the first molars when asymmetries were introduced into either the size of one bayonet bend, the point of application of the distalising force, or the position of a molar. In the FEM models under examination, the inner bows were passive before applying a force from a hypothetical neck strap.

## Materials and method

Four FEM models were designed. In Model 1, which served as a control, the maxillary first molars were equidistant (23 mm) from the midpalatal line and the inner bow was passive and symmetrical, while in Model 2, the left molar was 4 mm closer to the midpalatal line (19 mm) than the right molar. In Model 3, the first molars were equidistant (23 mm) from the midpalatal line, but the left bayonet bend was 2 mm larger than the right bayonet bend, simulating an inner bow bypassing a prominent canine. In the final model (Model 4), the molars were, again, 23 mm from the midpalatal line, but the join between the inner and outer bows was displaced 2 mm towards the left side (Figure 1).

The FEM models incorporated both maxillary first molars, their PDLs, a slice of the maxillae supporting the first molars, the tubes attached to the buccal surfaces of the molars and the inner bow of the headgear. It was assumed that the surface areas of the PDLs in each FEM model were equal throughout the experiment. The models were designed in SolidWorks 2010 (SolidWorks, Concord, MA, USA) and transferred to an ANSYS Workbench Ver. 12.1 (ANSYS Inc., Canonsburg, PA, USA) for solution. The headgear was considered to be made of 1.14 mm diameter stainless steel wire. The models were meshed in the ANSYS Workbench (Figure 2). Model 1 contained 49507 nodes and 25253 elements, Model 2 had 57172 nodes and 26241 elements, Model 3 had 53581 nodes and 24170 elements and Model 4 had 55825 nodes and 24898 elements.

The anterior and posterior surfaces of each model were fixed. The inner/outer bow connection was loaded with a 2N force at 20 degrees to the horizontal plane. The mechanical properties of the materials used are provided in Table I. The energy exerted on the molars and the von Mises stresses produced in the PDLs of molars were assessed by a defining probe (a post-processing tool in the ANSYS Workbench).

## Analyses of the force systems

### Model 1

In this control model, the molars were the same distance (23 mm) from the symmetric plane of the headgear and the midline of the maxillae. The force applied by the headgear was divided by two and the result applied to each molar.

### Model 2

The forces on the right and left molars are described by the following equations. Considering delta ( $\Delta$ ) the difference, in millimetres, in the bucco-palatal positions of the molars relative to the midpalatal line (and the symmetric plane of the inner bow, represented by the join between the inner and outer bows), the equilibrium equation used to explain the force applied to each molar is:

$$R \times F_{normal} = (R - \Delta) \times F_{near}$$

Where:

$R$  = The distance from the molar in the normal position to the symmetric plane of the headgear. This was assumed to be 23 mm.

$F_{normal}$  = The force applied to the normal side molar

$F_{near}$  = The force applied to the displaced molar.

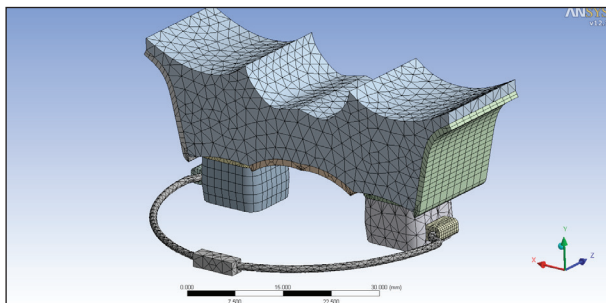


Figure 2. The meshed model.

Therefore:

$$\frac{R}{R - \Delta} = \frac{F_{near}}{F_{normal}}$$

Solving for  $F_{normal}$  we have:  $F_{normal} = F_{near} \frac{R - \Delta}{R}$

Since  $\frac{R - \Delta}{R} < 1$ , the solution gives  $F_{normal} < F_{near}$

From this equation, it is evident that the near side (displaced) molar is subjected to a larger component of the applied force than the normal side molar. Of the four elements in the above equation, two are unknown ( $F_{normal}$  and  $F_{near}$ ) and two are known ( $R$  and  $R - \Delta$ ) which makes the equation unsolvable. Therefore, to determine the forces present, the equation was rewritten thus:

$$\frac{R}{R + (R - \Delta)} = \frac{F_{(near)}}{F_{(near)} + F_{(normal)}}$$

Adding the denominator components produces:

$$\frac{R}{2R - \Delta} = \frac{F_{(near)}}{F_{(total)}}$$

Assuming a 200 g force for headgear and  $(2R - \Delta) = (2 \times 23) - 4 = 42$ :

$$\frac{F_{(near)}}{F_{(total)}} = \frac{R}{2R - \Delta} \rightarrow \frac{F_{(near)}}{200} = \frac{23}{42} \rightarrow F_{(near)} = \frac{200 \times 23}{42} = 109.523 \text{ g}$$

Therefore:

$$F_{(normal)} = F_{(total)} - 109.523 = 90.476 \text{ g}$$

The increasing nature of this force is shown in Figure 3.

### Model 3

The following formula was used to calculate the effect when one bayonet bend was larger than the contralateral bayonet bend. Delta ' $\Delta$ ' is the distance between the symmetric axis of the inner/outer bow and the midsagittal plane:

$$(R + \Delta) \times F_{(normal)} = (R - \Delta) \times F_{(near)}$$

Where:

$R + \Delta$  = The distance from the molar engaged by the normal bayonet bend to the symmetric axis of the inner/outer bow. Note,  $R$  equals 23 mm (half palatal

width) plus 2 mm (shift of the headgear symmetric plane to the left side) equals 25 mm.

$R - \Delta$  = The distance from the molar engaged by the large bayonet bend (near side) to the symmetric axis of the inner/outer bow.

$F_{(normal)}$  = The force applied to the normal-side molar.

$F_{(near)}$  = The force applied to the molar with the large bayonet bend.

Therefore:

$$\frac{R+\Delta}{R-\Delta} = \frac{F_{(near)}}{F_{(normal)}}$$

Solving for  $F_{near}$  we have:  $F_{(near)} = F_{(normal)} \frac{R+\Delta}{R-\Delta}$

Since  $\frac{R+\Delta}{R-\Delta} > 1$ , the solution indicates  $F_{(near)} > F_{(normal)}$

From this equation, it is evident that the near-side molar is subjected to a larger component of the applied force than the normal-side molar.

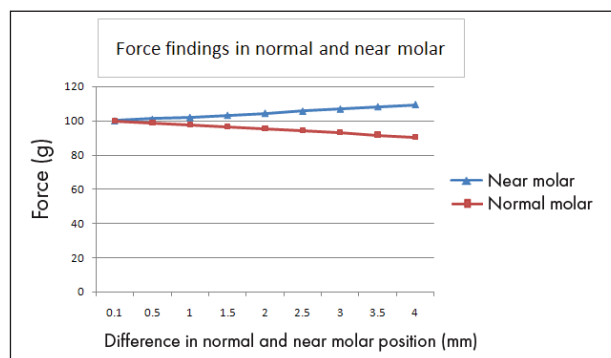


Figure 3. Force findings in the near (displaced) and normal molars.

Table I. Mechanical properties of the materials used in this study.

	Young's modulus (MPa)	Poisson's ratio
Tooth	20 300	0.26
PDL	0.667	0.49
Spongy bone	13 400	0.38
Cortical bone	34 000	0.26
Stainless steel	200 000	0.30

The equilibrium equation relative to the molar with the normal bayonet bend is:

$$[F_{(total)} \times (R+\Delta)] - [F_{(near)} \times (2R)] = 0$$

$$F_{(total)} \times (R+\Delta) = F_{(near)} \times 2R$$

$$\frac{R+\Delta}{2R} = \frac{F_{(near)}}{F_{(total)}}$$

Assuming a 200 g force applied by the headgear:

$$\frac{23 + 2}{46} = \frac{F_{(near)}}{200}$$

$$F_{(near)} = \frac{200 \times 25}{46} = 108.69 \text{ g}$$

$$F_{(normal)} = 200 - F_{(near)} = 200 - 108.69 = 91.31 \text{ g}$$

#### Model 4

The analysis is the same as Model 3.

## Results

The findings are provided in Table II.

### Energy

In Model 1 (the control model), the calculated energy was 393 nJ for both molars. In Model 2, the energy on the normal molar was 401 nJ and 460 nJ on the displaced molar, which represents a 14.7 per cent increase in energy on the displaced molar. In Model 3, a higher energy value occurred on the molar engaged by the larger bayonet bend (438 nJ) compared with the molar engaged by the normal-size bayonet bend (381 nJ). The energy difference in this model was 14.9 per cent more on the molar with the larger bayonet bend. In Model 4, the energy on the molar closer to join between the inner - outer bows was 544 nJ, and on the contralateral molar it was 377 nJ, representing a 44.2 per cent increase in energy (Figure 4).

### von Mises stresses

As it was assumed that the surface areas of the PDL in each model remained equal throughout each experiment, an increase in the von Mises stresses can be interpreted as an increase in the applied force. The stress value for Model 1 was equal to 0.95 MPa.

The differences in the stress (i.e. force/area) findings showed that a higher force was applied to the displaced

Table II. Numeric findings in two stages of the study.

	Model 1		Model 2		Model 3		Model 4	
	Normal molar	Normal molar	Normal molar	Near molar	Normal molar	Near molar	Normal molar	Near molar
Energy (Tooth, nJ)	393	395	401	460	381	438	377	455
Von Mises Stress PDL (MPa)	0.946	0.952	1.439	2.016	1.067	1.392	1.432	2.32

Model 1, control, both molars 23 mm from the midpalatal line, inner bow symmetrical; Model 2, left molar displaced 4 mm towards the midpalatal line, inner bow symmetrical; Model 3, both molars 23 mm from the midpalatal line, left molar engaged by 2 mm larger bayonet bend; Model 4, both molars 23 mm from the midpalatal line, inner - outer bow join displaced 2 mm towards the left molar.

molar (2.016 MPa) compared with the molar in a normal bucco-palatal position (1.439 MPa) in Model 2. Furthermore, the molar on the side with the larger bayonet bend experienced a higher stress (1.392 MPa) compared with the molar attached to the normal bayonet bend (1.067 MPa). In Model 4 (shift of the inner/outer bow attachment), the PDL on the side closer to the inner - outer bow join was subjected to 2.32 MPa whereas the PDL on the contralateral molar experienced 1.432 MPa, which equaled 62 per cent more stress than that received by a molar in Model 1 (Figure 5).

## Discussion

The present investigation aimed to determine the force systems generated between the inner bow of a cervical headgear and the first molars when either the bucco-palatal position of a molar, the size of a bayonet bend or the position of the join between the inner and outer bows was varied. Due to the limited space and the difficulty of clinical access in the maxillary first molar area, the FEM is the only method capable of analysing the force systems delivered by variations in the design of the inner bow and/or the position of a molar. The method assessed the likely generated force systems numerically and conservatively.

In the first FEM model, which was used as a control, the inner headgear bow and the position of the molars relative to the median axis of the inner bow were symmetrical. In the second model, a unilateral first molar crossbite was simulated by displacing one molar 4 mm towards the maxillary midline. In the third model, another common clinical problem found in headgear patients was simulated, that being a labially placed canine with both maxillary first molars in their normal bucco-palatal positions. In the final FEM

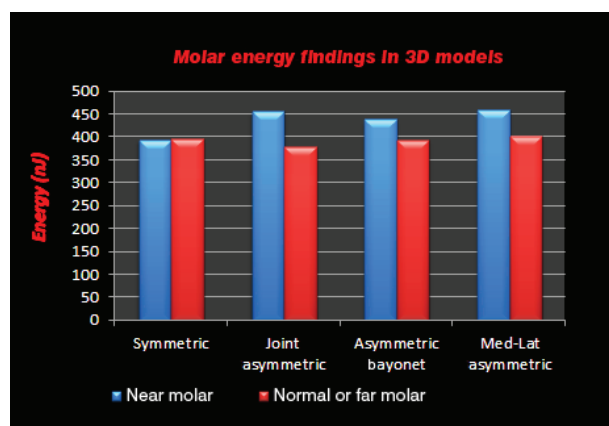
model, the join between the inner and outer bows was displaced to one side. In the three FEM models with asymmetries the inner bows were passive and did not deliver any force to the teeth until connected to a hypothetical neck strap. The models revealed that more energy and force were generated on the side closer to the asymmetries. These findings are of clinical significance because small asymmetries may be undetected and, as has been shown, can result in marked changes in the delivered force systems, which could affect one molar in an unwelcome manner.

In the second model (4 mm palatal displacement of one molar), the 15 per cent energy difference in the forces acting on the molars would be capable of moving the displaced molar further distally than the molar on the 'normal' side. Similarly, in the third FEM model with unequal bayonet bends, the symmetric plane of the headgear shifted towards the side with the larger bayonet bend and produced a similar effect as Model 2 (that is, a 15 per cent difference in energy on the molars). It was found that the largest side-to-side difference in force generation (20 per cent) was found in the fourth FEM model.

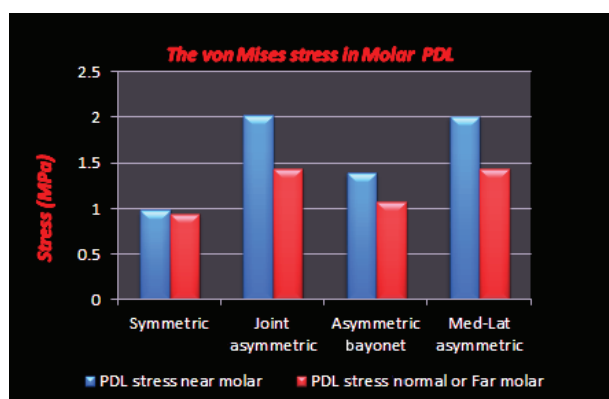
The literature lacks information on the effects of an asymmetry in a headgear inner bow. The present study suggests that, over time, unequal forces from an asymmetric inner bow could create an iatrogenic malocclusion. To avoid unwanted effects, it is suggested that clinicians use a symmetroscope to assess the symmetry of an upper arch before starting headgear treatment, and to reassess the form of the inner bow at adjustment visits. Clinicians may prefer to take photocopies of the headgear throughout treatment as these can be superimposed and differences in form easily detected.

The present findings may also be applied to a buccally





**Figure 4.** The molar energy findings in different 3-D models. Model 1, control, both molars 23 mm from the midpalatal line, inner bow symmetrical; Model 2, left molar displaced 4 mm towards the midpalatal line, inner bow symmetrical; Model 3, both molars 23 mm from the midpalatal line, left molar engaged by 2 mm larger bayonet bend; Model 4, both molars 23 mm from the midpalatal line, inner - outer bow join displaced 2 mm towards the left molar.



**Figure 5.** The PDL von Mises stress findings in different 3-D models. Model 1, control, both molars 23 mm from the midpalatal line, inner bow symmetrical; Model 2, left molar displaced 4 mm towards the midpalatal line, inner bow symmetrical; Model 3, both molars 23 mm from the midpalatal line, left molar engaged by 2 mm larger bayonet bend; Model 4, both molars 23 mm from the midpalatal line, inner - outer bow join displaced 2 mm towards the left molar.

placed maxillary first molar. In this case, the molar will receive less force than the molar in a normal position. To avoid unwanted side effects, it may be advantageous to correct a first molar in crossbite before starting headgear treatment. Unwanted side effects can be negated by ensuring that the inner bow is symmetric and that the bayonet bends are the same size.

Symmetry in the inner bow also includes the join between inner and outer bows. In the fourth FEM

model, it was found that if the join between the inner and outer bows was offset to one side, the molar on the side closer to the join was subjected to a markedly higher force. This finding is particularly important because this simple modification could be used to correct the mesio-distal position of a molar without the anchorage loss that accompanies other intra-oral appliances. In Model 4, the normal molar – near molar difference in von Mises stress was the highest found in the FEM models at 0.89 MPa. As the inner – outer bow join was only offset 2 mm, it could be postulated that a larger offset would have a greater effect on the near side molar.

The distance between the molars and the symmetric plane of the inner headgear bow directly affected the force delivered to the molars. In Model 2, the symmetric plane of the headgear coincided with the median sagittal plane of the hypothetical patient (represented by the slice through the maxillae), but the molars were at different distances from the median sagittal plane (as seen in a unilateral posterior crossbite). The circumstances were different in Models 3 and 4 in which the symmetric plane of the headgear was closer to one molar (near side), and the molars were not displaced palatally.

A small, but important, difference existed in the two asymmetric inner bow groups. When a molar was displaced towards the palatal midline to simulate a unilateral crossbite, a small millimetre decrease (delta) occurred in the ratio of the distance of each molar to the midline of the palate. But, when the inner bow was asymmetrical, delta (mm) decreased on the side with the bow closer to the molar and increased by a similar amount on the contralateral molar (Models 3 and 4). It appeared that the forces on the molars were more affected by an asymmetry in the inner bow than a palatal displacement of a molar. The shifts depicted in Models 3 and 4 were only 2 mm, whereas in Model 2, it required a 4 mm palatal displacement of one molar to produce the same effect. The findings in the present study suggest that the light, but unequal, forces generated by an asymmetric inner bow may be an effective method of distalising a maxillary molar.<sup>21</sup>

## Conclusions

1. A FEM analysis of the force systems revealed that small asymmetries in molar position, the size of a bayonet bend and the point of application of a force

on an inner bow resulted in asymmetrical forces on the molars. These forces were higher on the molar closer to the symmetric plane of the headgear.

2. These findings are of clinical significance because differences in headgear force systems have the potential to move molars asymmetrically.

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