Original Article

Quantification of the force systems delivered by transpalatal arches activated in the six Burstone geometries

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ABSTRACT

Objective: To evaluate the force systems produced by transpalatal arches (TPAs) activated according to the six classes of geometries described by Burstone and Koenig.

Materials and Methods: Sixty appliances were tested for first-order activations using a mechanical force testing system. The TPAs were first checked for passivity in sagittal, transverse, and vertical planes at the measuring machine. Then 10 appliances per group were activated using a millimeter template to obtain the six classes of geometries, and the activated appliances were inserted into lingual tubes of the Force System Identification machine that recorded the deactivation forces and moments delivered by both terminal ends of the TPAs.

Results: The overall force system with the actual values of forces and moments recorded by each type of activation was illustrated and compared with the mathematical model reported by Burstone and Koenig. Although a great consistency of the direction of forces and moments were observed, the theoretically feasible force systems could not be fully accomplished by the TPA activated for the six classes of geometries.

Conclusion: The first-order activations of the TPA can deliver predictable force systems in respect to the direction of forces and moments attainable, but some unexpected forces and moments are also produced. Careful clinical monitoring is, therefore, strongly recommended when using this statically indeterminate system. (*Angle Orthod.* 2017;87:542–548)

KEY WORDS: Orthodontic appliances; Transpalatal bar

INTRODUCTION

The transpalatal arch (TPA) has been widely used for different purposes in the clinical practice. Normally this appliance is used as a soldered, passive orthodontic device to maintain leeway spaces during the transition of the dentition[1] to prevent rotation and buccolingual tipping of the molars[2,3] and also to maintain the transverse distance of the molars after rapid maxillary expansion.[4] However, the removable TPA allows for more versatile clinical applications than does its soldered counterpart.[5] The activations of the inserts of the TPA can generate specific configurations, which, in turn, are able to deliver a variety of force systems to move teeth in all three planes of space.[5,6] However, the appropriate prediction and achievement of the desired tooth movement using a TPA is not a simple task. Considering that both ends of the appliance are engaged in the tubes/sheaths of the teeth, the forces and moments applied on the teeth cannot be clinically measured. This system is called statically indeterminate because some of the unknown forces and moments cannot be calculated from the force and moment equilibrium formulas.[7,8]

Although complex, the force systems delivered by the TPA can be more easily understood if we follow the biomechanical principles of the six classes of geometries and the law of equilibrium.[7,9] The activated TPA represents a two-bracket system, therefore we can use the same principles studied in the past regarding the force systems delivered by a segment of a 0.016 inch

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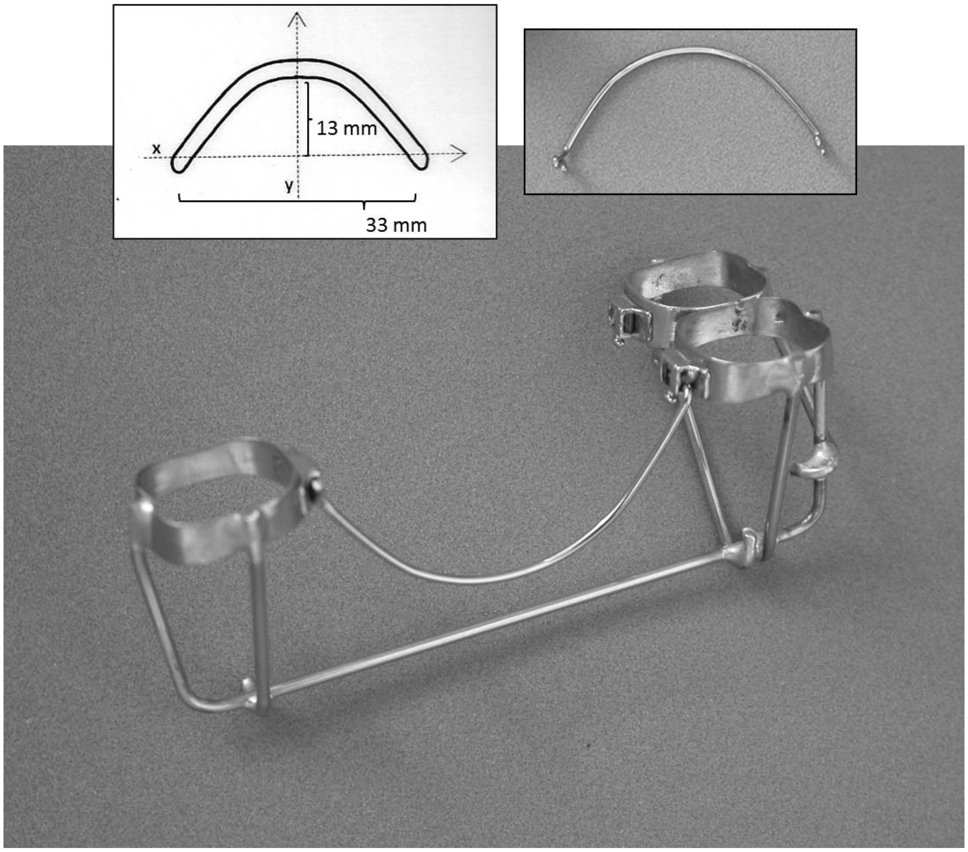

Figure 1. Template and structured model used to construct the customized transpalatal arches.

wire into two brackets with varying mutual angulations. In fact, several reports have applied these principles to obtain a specific tooth movement using the TPA, including the correction of molar symmetrical rotations,[3] unilateral crossbites[10] and mesiodistal asymmetries.[11] However, in a wide-range search of the literature, we were unable to find a controlled experimental study in which all six classes of geometries have been evaluated.

Therefore, the present study was designed to quantify in a laboratory setting the forces and moments delivered by transpalatal arches activated for the six classes of geometries, comparing the recorded force systems with those calculated by Burstone and Koenig.[7]

MATERIALS AND METHODS

Sixty TPAs (10 for each type of the six activations) were handmade from 0.032-inch stainless steel wire (Morelli, Sorocaba, Brazil) using a specific template and a structured model with bands and welded lingual tubes (Figure 1). The extended length of the bar except for the ends was 46 mm, the intermolar distance was 33 mm, and the height of the palatal vault was 13 mm.

The forces and moments delivered by the TPAs were measured using the Force System Identification machine developed for the Department of Orthodontics of the Royal Dental College, University of Aarhus (Figure 2). The machine uses six computer-controlled incremental motors that control the rotation and translation of two sensors in relation to each other. Sixteen strain-gauges inside the sensors measure deformations, which are amplified, converted into digital signals, and calibrated to forces and moments, and the computer then records and stores these data. The load cells were calibrated at the lingual tubes. The

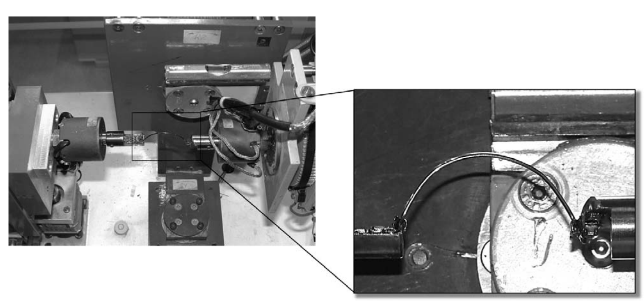

Figure 2. The force system identification testing machine showing the two sensors attached to lingual tubes in which the terminal ends of the transpalatal arches were inserted.

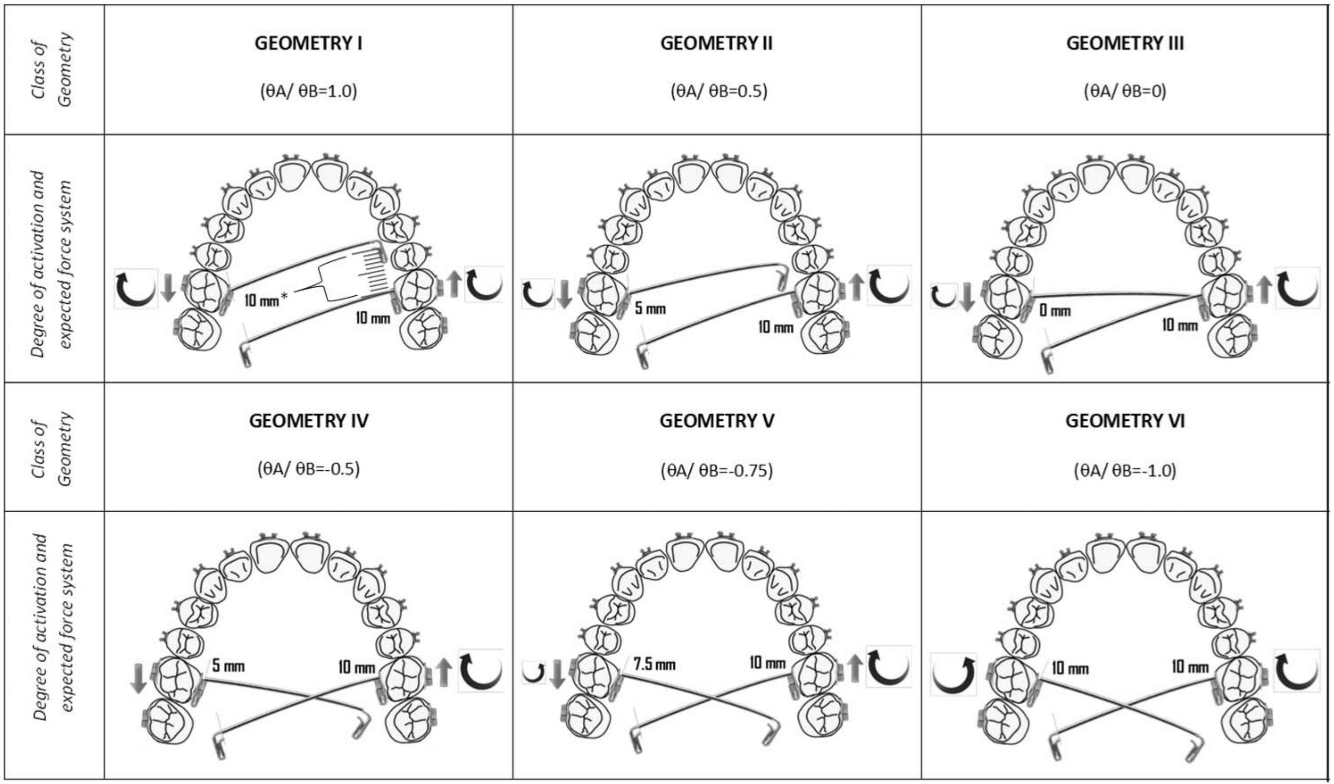

Figure 3. The two-teeth system obtained with the TPA. The geometry of activation is defined by the distances of the terminal ends measured with respect to the mesial part of the lingual tube. *The degree of activation in one side of the arch is represented by the distance (in millimeters) from the mesial part of the terminal end to the mesial part of the lingual tube of the opposite side. θA and θB are the angles of the terminal ends in respect to the intertube axis.

reproducibility of the system has been previously reported and was found to be within ±5%.[12]

After the bars were constructed in their passive form, the terminal ends of the bars were attached to the lingual tubes connected to the sensors, and the appliances were adjusted until they were totally passive. Then the TPAs were activated to obtain the six classes of geometries using a millimeter template. One terminal end was inserted into the lingual tube of the template showed in Figure 1, and the degree of activation was checked at the opposite end of the arch by measuring the distance from the mesial part of the terminal end to the mesial part of the lingual tube. The maximum activation (100%) was 10 mm at the terminal end, and the proper geometries were achieved according to the principle of truncated "V" bends[13] in which the degree of bending with respect to the tubes determines the geometry of activation (Figure 3).

The activated bars were then inserted into the lingual tubes of the measuring machine, and the records were taken at 0° deactivation, where the lingual tubes were parallel to each other. The moments in the clockwise direction were expressed as plus (+), and the moments in counterclockwise direction as minus (–). Only the force systems in the occlusal plane were evaluated in the present study — this means mesiodistal forces and rotational moments (first-order activations).

RESULTS

The forces and moments delivered by the TPAs activated for the six geometries are shown in Table 1. For a better comprehension and visualization of the whole scenario of the six geometries, a table was used to illustrate the forces and moments acting on the two-teeth systems (Table 2), comparing the values obtained by Burstone and Koenig with the present results. It is important to emphasize that the knowledge of the relative magnitudes of forces and moments and especially their directions are more relevant than the description of the actual values. If this knowledge is not reached, the orthodontists will obviously not be able to predict the tooth movements achievable by their appliances. The activations shown in Figure 3 and the force systems delivered by these activations (Table 2) can be useful guides to the clinician when using the TPA as an active appliance to obtain tooth movements in the occlusal plane (first-order activations).

Table 1. Means and Standard Deviations of Mesiodistal Forces (in cN) and Moments of Rotation (in cN.mm) Delivered by Transpalatal Arches (*N* = 10/group) After First-Order Activations for the Six Geometries

Type of Activation	Mesio-Distal Force	Moment in Unit A	Moment in Unit B	MA/MB Ratio
Geometry I	322.4 (35.0)	5183.8 (722.6)	4050.2 (425.3)	1.2
Geometry II	265.6 (29.7)	3615.2 (657.3)	4152.2 (364.9)	0.9
Geometry III	163.5 (20.3)	675.9 (390.7)	3968.6 (235.0)	0.2
Geometry IV	52.2 (25.6)	−2174.7 (506.2)	3617.5 (266.3)	−0.6
Geometry V	31.3 (14.3)	−2690.5 (205.6)	3561.6 (289.8)	−0.8
Geometry VI	19.5 (28.7)	−2897.8 (483.5)	3544.4 (531.7)	−0.8

DISCUSSION

All appliances reported in the past and all appliances that will be reported in the future must be in equilibrium once they are placed between two attachments.[9,14,15] The principle of mechanics states that the sum of all forces and the sum of all moments acting on a system must be zero. This concept can be clearly observed in the classic study of Burstone and Koenig, in which they reported the force systems developed by a 0.016′ round stainless steel wire inserted into two brackets with varying mutual angulations.[7] They used a mathematical approach to calculate the forces and mo-

Table 2. A. Force Systems Delivered by the Mathematical Model of Burstone and Koening Regarding a Stainless Steel Wire Segment With a 0.016-Inch Diameter. **B.** Force Systems Delivered by a Stainless Steel Transpalatal Bar With a 0.032-Inch Activated to Obtain the Six Classes of Geometries in the Occlusal Plane (First-Order Activations).

GEOMETRY	I	II	III	IV	V	VI
θA/θB	1.0	0.5	0	-0.5	-0.75	-1.0
MA/MB	1.0	0.8	0.5	0	-0.4	-1.0
RELATIVE FORCE SYSTEM ON TEETH	177.0 ↓ 177.0 ↑ 1860 1860	160.0 ↓ 160.0 ↑ 1488 1860	133.0 ↓ 133.0 ↑ 930 1860	88.6 ↓ 88.6 ↑ 1860	53.3 ↓ 53.3 ↑ 740 1860	1860 1860

A. Force Systems of a SS wire segment .016 with 21 mm length (Burstone and Koenig, 1974). Forces are represented by straight arrows and moments are represented by curved arrows.

GEOMETRY	I	II	III	IV	V	VI
θA/θB	1.0	0.5	0	-0.5	-0.75	-1.0
MA/MB	1.2	0.9	0.2	-0.6	-0.8	-0.8
FORCE SYSTEM ON TEETH	322 ↓ 322 ↑ 5183 4050	265 ↓ 265 ↑ 3615 4152	163 ↓ 163 ↑ 675 3968	52.2 ↓ 52.2 ↑ 2174 3617	31.3 ↓ 31.3 ↑ 2690 3561	19.5 ⇩ 19.5 ⇧ 2897 3544

B. Force Systems of a SS Transpalatal Bar, 0.032 (1st order activation); The unfilled arrows represent the unexpected forces and moments in relation to the model calculated by Burstone and Koening. Forces are represented by straight arrows and moments are represented by curved arrows.

ments acting on a two-bracket system in six particular situations, which were called the "six geometries." These configurations were established on the basis of the angles formed between a line connecting the center of the two brackets and the lines representing the slots of the brackets. The same force systems can also be achieved by placing specific bends (eg, symmetrical or asymmetrical v-bends, step bends, truncated bends) in a wire to obtain the desired geometry.[5,6,8,9,16] However, the theoretical values obtained by a mathematical model are not easily achieved in an actual clinical situation. Even in experimental controlled situations, it was not possible to achieve the exact force systems predicted. Two previous studies have tested the forces and moments delivered by TPAs symmetrically activated to derotate first molars symmetrically rotated.[17,18] Although the TPAs have been previously adjusted to deliver equal and opposite moments of rotation (activation for geometry VI), different moments were always obtained, and the sagittal forces were also produced as in Burstone's geometry V. These results are in accordance with the present study because the symmetrical activation of the TPA to obtain a geometry VI produced not only opposite moments but also opposite sagittal forces, which were not expected in this geometry. Although these sagittal forces are not too high as in the other geometries, some studies suggest that these forces could be clinically significant to move mesially the molar subjected to the largest moment, while the opposite molar is moved distally.[18,19] In fact, these unexpected mesiodistal forces occurred in a clinical study despite the precautions to obtain symmetrical moments with a TPA activated for geometry VI.[19] The magnitude of the unexpected sagittal forces on geometry GVI recorded in the present study (19.5 cN) were very similar to those previously reported by Ingervall (19.0 cN)[18] and Gunduz et al. (21 cN).[17] The mean values of the moments recorded in our study (3220 cN.mm) was also very similar to that reported by Gunduz et al. (2946 cN.mm),[17] but smaller than that reported by Ingervall (4472 cN.mm).[18] This last study tested a prefabricated stainless steel bar with a diameter of 0.036 inches, and the former has tested a Zachrisson-type bar made of a 0.036-inch Blue Elgiloy wire, whereas the present study tested a TPA made of 0.032-inch stainless steel wire. The similarity in forces and moments' magnitudes among the studies suggest that it is possible to achieve significant magnitudes with a smaller wire, which is easier to bend during the construction and activation of the appliances.

Another unexpected result was observed in the activation for geometry IV. In this configuration, two brackets are both rotated in opposite directions from the interbracket axis, where one is rotated half the amount of the other. In other words, to obtain this geometry with a TPA, one terminal end must be fully activated (100% or 10 mm) in one direction, and the other terminal end must have half of this activation in the opposite direction. In this case, a clockwise moment should be found at one terminal end, but no moment should be found at the opposite side.[7] This force system was not observed in the present study because an unexpected counterclockwise moment was also recorded at the terminal end, instead of only a single force. This finding is in line with the previous finding observed for geometry VI, which means that it is difficult to obtain an exact force system as described by the mathematical model of Burstone and Koenig.[7] The ideal expected force system could not be attained despite the precautions possible in the standardized conditions of the present laboratory experiment (Table 2).

There are several reasons for the dissimilarity of some forces and moments measured in the present study in relation to the values obtained by a mathematical model. As shown in previous laboratory experiments, it is difficult even under ideal conditions to attain the desired force system.[17,18] This difficulty is probably even greater in clinical practice. One reason for these dissimilarities could be the fact that the passivity of the appliances was checked and adjusted in the measuring machine before the activations. These frequent adjustments could have work hardened the wire to a different degree on the two sides, with possible changes in the limit of elasticity. This effect is most marked in appliances made from stainless steel,[17,18,20] the material used to construct the TPAs in the present study. Moreover, even if the degree of activation has been appropriately checked before the insertion of the TPA in the machine, the final insertion implies a risk of some permanent deformation at one terminal end. Finally, the mathematical analyses of Burstone and Koenig did not consider the actual play that exists between the appliance and the attachment in which it is engaged. Taken together, the present results reinforce the idea that TPAs are very sensitive to their shapes, as previously reported by mathematical,[7,8] laboratorial,[17,18] and clinical studies.[2,19] The careful determination of activations does not limit the need for clinical monitoring, but assures the minimizing of tooth movement that is unpredicted and undesirable.

The possibility to predict and apply a desired force system using the TPA can significantly increase its clinical applications. Ideally, an optimal force system should have the proper force magnitude, a low load-deflection rate, and the proper moment-to-force ratio. The most important requirement is that the moments and forces be in a proper direction.[6,8] If this aim is not reached, the teeth will obviously not move to the desired position. The present article demonstrates a significant consistency of the direction of forces and moments delivered by TPAs when compared with the force systems calculated by a mathematical model (Table 2). With the exception of some forces and moments that were unexpected recorded in geometries VI and IV, respectively, all activations achieved the expected directions of forces and moments. However, the exact proportions between the moments on the two teeth were not attainable probably because of the reasons already described in the previous paragraph.

The relative tendency of the two teeth to resist displacement is another important factor that must be considered for the successful application of the TPAs; in other words, the anchorage distribution. For example, if an orthodontist decides to apply a higher force and a larger moment to only one molar using a TPA activated for geometry I, it is obvious that the opposite molar will need an anchorage reinforcement to avoid the reactive forces of the active unit (Figure 3 and Table 2B). In this article, the TPA has been studied in only one plane of space. However, the concepts can be related to other planes as well. One limitation of the present study is that we evaluated the force systems only at the beginning of the activations (0° of deactivation), when both terminal ends were at the full activations in the attachments. Although these are the forces of greatest magnitude that are most responsible for the tooth movement, both force magnitudes and moment-to-force ratios change as the TPA works out.[3,17–19] For example, the geometries I, IV, and VI are considered to be punctual because they rapidly change to another geometry if one molar (eg, the active unit) moves faster than the opposite molar (eg, the reactive unit). On the other hand, the geometries II, III, and V present a large range of deactivation, and it takes more time for these force systems to change to another geometry. Because of their large working range, the activations in geometries II, III, and V are usually applied in clinical practice to keep a constant moment-to-force ratio throughout the entire range of tooth movement.

Future studies should also evaluate the force systems after different degrees of deactivation. This information will be relevant to help the orthodontist predict the changes in geometries during tooth movement and also to guide the reactivations needed to maintain the desired force systems during treatment.

CONCLUSION

- The present investigation demonstrated that the theoretically feasible force systems cannot be fully accomplished by TPAs activated for the six classes of geometries.
- The achievement of symmetric moments was not possible in the activations where they were expected, such as in geometry I (two equal and positive moments) and geometry VI (two equal and opposite moments).
- Unexpected mesiodistal forces or unexpected moments were also produced in geometries VI and IV, respectively, to maintain the system in equilibrium.

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