Original Article

Comparison of three-dimensional orthodontic load systems of different commercial archwires for space closure

Steven Gajda[a]; Jie Chen[b]

ABSTRACT

Objective: To experimentally quantify the effects of the loop design on three-dimensional orthodontic load systems of two types of commercial closing loop archwires: Teardrop and Keyhole.

Materials and Methods: An orthodontic force tester and custom-made dentoform were used to measure the load systems produced on two teeth during simulated space closure. The system included three force components along and three moment components about three clinically defined axes on two target teeth: the left maxillary canine and the lateral incisor. The archwires were attached to the dentoform and were activated following a standard clinical procedure.

Results: The resulting six load components produced by the two archwires were reported and compared. The results were also compared with those of the T-loop archwire published previously.

Conclusions: The three designs deliver similar loading patterns; however, the component magnitudes are dependent on the design. All of the designs result in lingual tipping of the teeth, canine lingual-mesial displacement, canine crown-mesial-in rotation, and incisor crown-distal-in rotation. (*Angle Orthod.* 2012;82:333–339.)

KEY WORDS: Orthodontic load system; Loop archwire

INTRODUCTION

Commercial archwires incorporating closing loops are widely used for orthodontic space closure because of their convenience as well as provision of favorable moments to control tipping.[1–3] The commonly used loops are T-loop (TL), Teardrop-loop (TD), and Keyhole-loop (KH). However, the difference between these archwires has not been evaluated reliably. The evaluation criterion should be the load systems on the target teeth by each of the archwires. Applied orthodontic load systems (forces and moments) determine the three-dimensional (3D) tooth movement pattern, which includes translation, rotation, or their combination in each of the three planes. Inability to control the orthodontic load system can result in undesirable tooth movement. Correction takes time, which reduces overall treatment efficiency.

Limited information on the load systems of these commercial archwires is available. Selection of the archwire has been primarily based on experience because the load systems of these appliances have not been provided. There are no quantitative data to be compared. A quantitative evaluation and comparison of various archwires will provide the scientific base for clinicians to select them based on the clinically desired load system.

The load system is 3D. Most previous studies were two-dimensional or were tested under nonclinical conditions,[4–6] which did not provide reliable load systems. Recently, methods to quantify clinically 3D load systems of archwires were reported.[3,7] The TL[3] and Triangle-loop[8] archwires were evaluated and all six load components quantified, which showed not only the force and moment components in the prescribed tooth movement plane but also the coupling effects in the other two planes. The results showed that different loop designs produced different load systems. Thus, other loop designs need to be evaluated.

The objectives of this study were to quantify the six force and moment components on two target teeth, the

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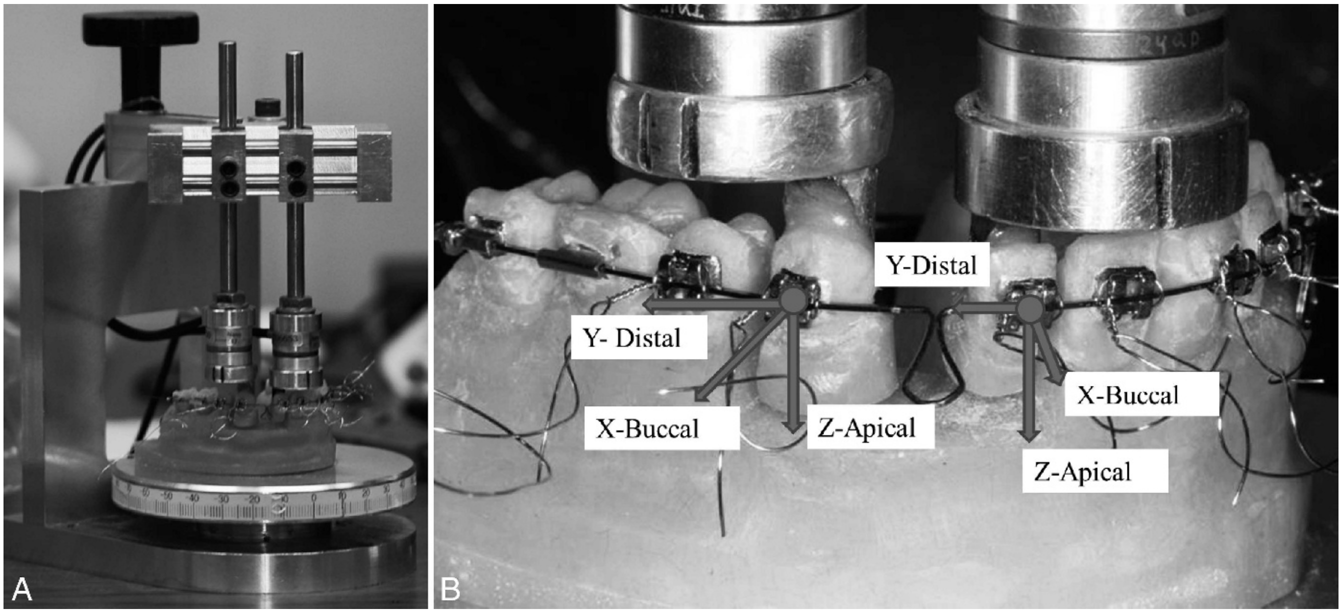

Figure 1. The orthodontic force tester used to measure three-dimensional load systems on the canine and incisor by either a Teardrop or a Keyhole archwire. (A) Orthodontic force tester. (B) The archwire ligated to the brackets. The experimental setup allows simulation of the space closure cases. The local coordinate systems used to describe the load systems. The positive F_x is directed buccally, F_y distally, and the F_z apically.

left maxillary canine and the lateral incisor, with commercially available continuous TD and KH closing loop archwires and to compare the results with those of the TL archwire published by Chen et al.[3] The purpose was to identify quantitatively the differences among the three types of archwires.

MATERIALS AND METHODS

The orthodontic force tester (OFT) published previously was used.[9] Together with a custom-made dentoform, treatment of a typical space closure clinical case was simulated (Figure 1). For this purpose, a clinically used orthodontic appliance was attached to the full dentoform. The appliance was then activated following established procedures. The load systems on the target teeth to be moved or to serve as an anchor were then measured.[3]

The dentoform with brackets simulating space closure after first premolar extractions and canine retractions was used. The dentoform was fixed to a platform (Figure 1A). The target teeth were attached to the load cells and were then separated from the dentoform following the published procedure.[3] In this way, their original positions and orientations with respect to the remainder of the dentoform were maintained. The design ensured that the boundary condition of the lab model was the same as that in the clinic.

The load cells were aligned with the clinically used coordinate system. The origin of the clinical system was at the center of the bracket. The x-axis was directed buccally (normal to the crown and pointing toward the cheek), the y-axis distally (tangent to the crown and pointing toward the molar), and the z-axis apically (perpendicular to the occlusal plane and pointing toward the root; Figure 1B). Thus, the buccolingual (BL), mesiodistal (MD), and occlusogingival (OG) orientations of each target tooth aligned with the x-, y-, and z-axes of the load cells, respectively. The directions (OG, BL, and MD) are clinical terms to describe force components and tooth displacements.

The load cells (multiaxis force/torque Nano17, ATI Industrial Automation, Apex, NC) report the load systems at their own coordinate systems, which are not on the brackets. Therefore, a transformation was performed to convert the load systems to the centers of the brackets based on the locations of the brackets in the load cell coordinate systems.[7] In our case, the xyz axes of the load cell and the bracket coordinate systems were parallel through the previously described alignment process.

Two types of continuous loop archwires, TD and KH, were used. The archwires (0.016 $\times$ 0.022 Stainless Steel Natural Form Arch, Oscar Inc, Fishers, IN) in interloop distances of 38 mm and 42 mm, commonly selected by the orthodontists based on the vendor's record, were tested. Both archwires corresponding to two loop locations, mesial (ME) and middle (MD), were evaluated. The 42-mm loop closing archwire (KH_{42} and TD_{42}) positioned the loops in the middle of the interbracket distance of the lateral incisor and canine

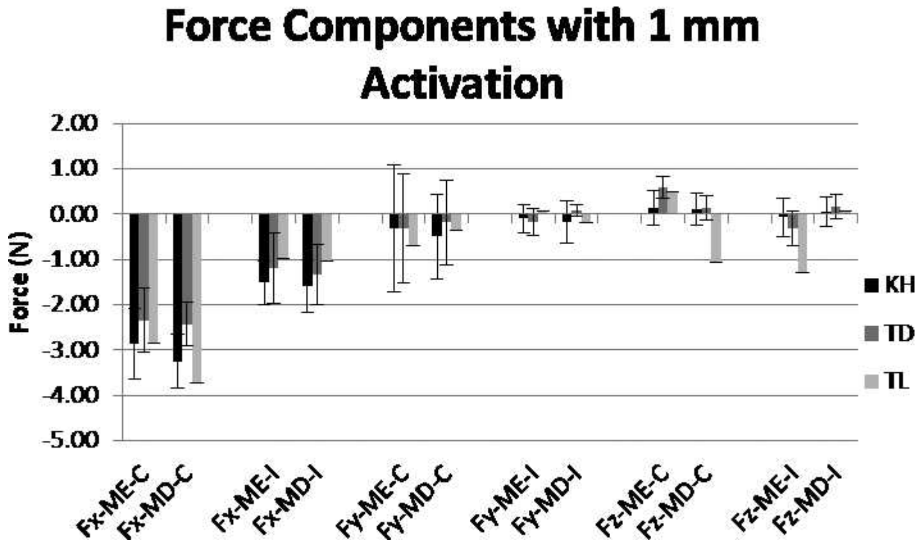

Figure 2. Three force components, F_x, F_y, and F_z, of the three types of the loop designs on the lateral incisor (I) and the canine (C) with the loop placed at two locations, mesial (ME) and middle (MD), corresponding to a 1-mm activation. Fx: (+ = buccal, − = lingual); Fy: (+ = distal, − = mesial); Fz: (+ = intrusion, − = extrusion). KH indicates Keyhole; TD, Teardrop; TL, T-loop.

brackets. The 38-mm (KH_{38} and TD_{38}) archwires positioned the loops 2 mm anterior to the middle of the interbracket distance. The archwire was secured to the brackets following clinically established procedures and was activated at the distal ends of the molar tubes. The resulting load systems on the target teeth were measured.

Three measurements were made for each archwire. The OFT was zeroed before placing each of the closing loops. An archwire was placed on the dento-form, with the vertical legs separated by a 0.05-mm metal shim[4] to maintain a consistent baseline. The closing loop archwire was secured to each bracket with 0.010-in. stainless-steel ligature wires (Figure 1). Crimpable stops were secured distally to the second molar tubes bilaterally. The resulting orthodontic load systems (F_x, F_y, F_z, M_x, M_y, and M_z) on the teeth were measured as the baseline. The closing loops were activated using 1-mm and 2-mm shims between the crimpable stop and the molar tubes bilaterally. The resulting load systems were measured and recorded.

To assess variation due to operating errors, such as variation of ligature tie tightness, activation level, and wire shape, experiments on each type of archwire were repeated on 10 wires with the same specifications. The average and standard deviation were computed to statistically determine the load components of the two loop archwires and their variations. A two-way full-factorial analysis of variance (ANOVA) model was used to assess the effect of activation amount (1 or 2 mm) and location of the loop on the resulting forces and moments. A separate analysis was performed for each tooth sensor. A significance level of .05 was used to test all hypotheses.

The article reports an in vitro study. There was no patient or patient record involved. Therefore, Institutional Review Board review was not required by the university.

RESULTS

The six load components were measured for both the left maxillary lateral incisor and the canine. The force and moment components corresponding to 1-mm and 2-mm activations and their standard deviations are shown in Figures 2 to 5 and Tables 1 and 2, respectively. The F_x was responsible for a buccal (if F_x was positive) or lingual (if F_x was negative) crown tipping (first-order tipping). Similarly, the F_y caused a mesial (if F_y was negative) or distal (if F_y was positive) crown tipping (second-order tipping). The F_z resulted in an intrusion (if F_z was positive) or extrusion (if F_z was negative; Figures 2 and 3). The moment components were responsible for tooth rotations. The moment about the x-axis, M_x, created a second-order rotation. The positive M_x rotated the crown distally. The moment about the y-axis, M_y, caused a first-order rotation. The positive M_y rotated the crown lingually. These two components are commonly used to counter tipping caused by F_y and F_x, respectively. Similarly, the moment about the z-axis, M_z, created a third-order rotation. The positive M_z caused distal-crown-in rotation (Figures 4 and 5). For comparison purpose only, the means of the force and moment components of the TL published previously were also incorporated into Figures 2 to 5.

Two commonly used moment-to-force ratios, M_x/F_y and M_y/F_x, primarily affect the tipping in the y-z and x-z planes; thus, only these two ratios are reported

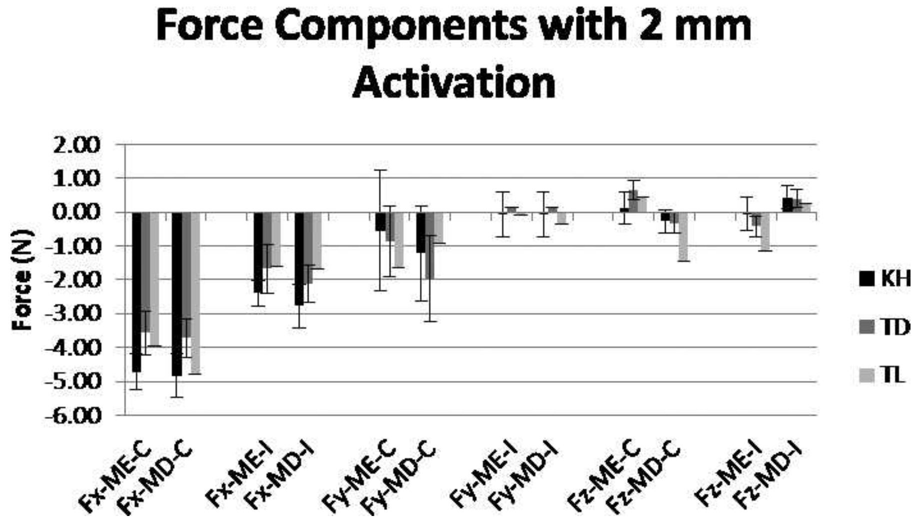

Figure 3. Three force components, F_x, F_y, and F_z, of the three types of the loop designs on the lateral incisor (I) and the canine (C) with the loop placed at two locations, mesial (ME) and middle (MD), corresponding to a 2-mm activation.

(Table 3). The signs of the M_y/F_x were consistent on both teeth. The large M_x/F_y values on the incisor were due to very small F_y; thus, the effects on the tooth movement would be determined by the moment component, M_x.

The level of activation affects the magnitudes of the load components. The force and moment components that are large enough to have clinical impacts are mentioned here. The force and moment components F_x, M_x, and M_z closely doubled their magnitudes when the activation increased from 1 mm to 2 mm. The loop position has less effect on these force and moment components, except for M_z of the KH wire on the canine. In this case, the KH_{38} archwire produced significant higher M_z than the KH_{42} archwire ($P < .001$; Figure 5). Neither activation nor loop location affected the directions of these components.

DISCUSSION

This study measured the load systems immediately sensed by the teeth resulting from different closing loop archwire designs in a simulated clinical setup. The initial load system would have clinical impact. One of the goals of this study is to make the treatment outcome (tooth displacement) predictable. To study the tooth displacement in response to the orthodontic load, only the initial load system is a controllable parameter because the load system will change as the tooth moves. As long as the final tooth displacement is

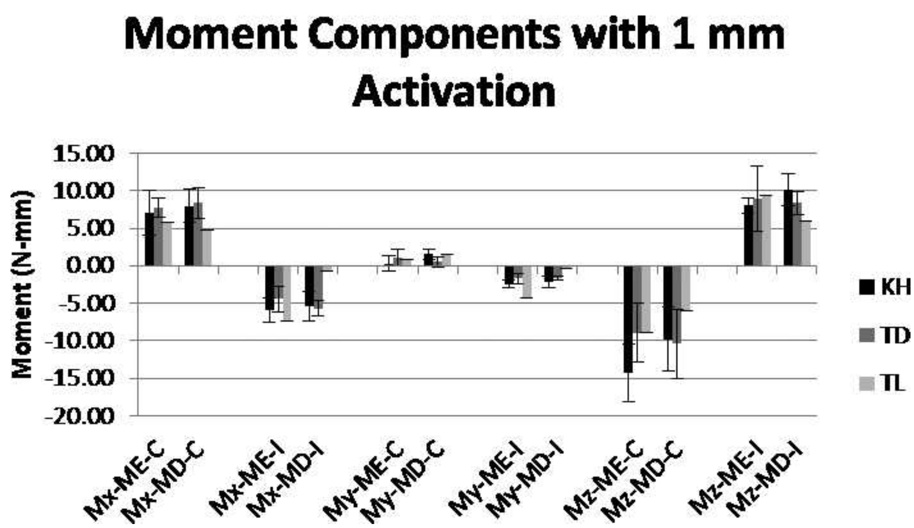

Figure 4. Three moment components, M_x, M_y, and M_z, of the three types of the loop designs on the lateral incisor (I) and the canine (C) with the loop placed at two locations, mesial (ME) and middle (MD), corresponding to a 1-mm activation. Mx: (+ = crown-distal rotation, − = crown-mesial rotation); My: (+ = crown-lingual rotation, − = crown-buccal rotation); Mz: (+ = distal-crown-in rotation, − = mesial-crown-in rotation). KH indicates Keyhole; TD, Teardrop; TL, T-loop.

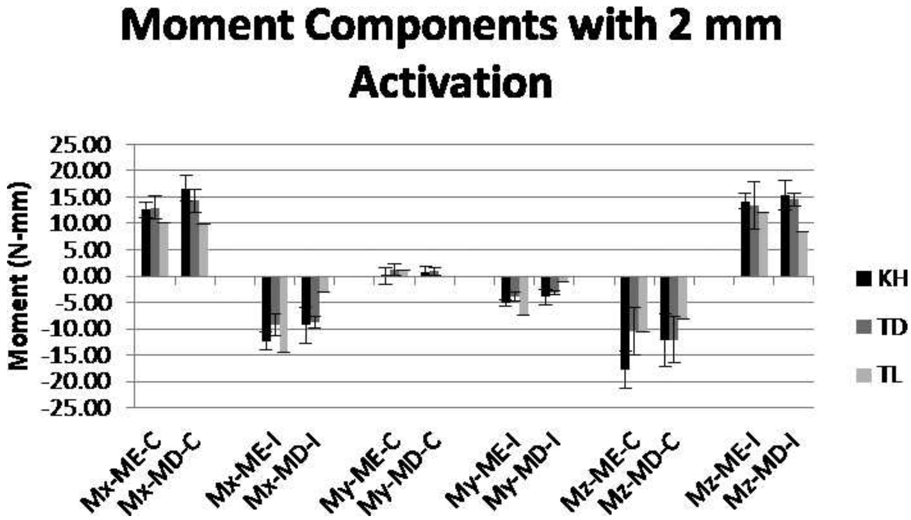

Figure 5. Three moment components, M_x, M_y, and M_z, of the three types of the loop designs on the lateral incisor (I) and the canine (C) with the loop placed at two locations, mesial (ME) and middle (MD), corresponding to a 2-mm activation.

related to the initial load system, this parameter is very useful to predict tooth displacement.

The measured load system is reliable. For a given closing loop (ie, size, material, and cross-section), the generated load system depends on the following factors: the location and orientation of the brackets, interbracket distance (IBD), activation, loop design, and ligation method. As long as these control factors in the clinical case and the corresponding experimental model are the same, the load system measured on the model accurately represents what happens in the clinic. Our experiment ensures that the control factors are close. First, the dental cast was used so that the spacing and locations of the brackets were close to the clinical case. Using the cast would maintain the relative positions and orientations of the teeth and the brackets. Second, the same type of brackets and closing loop as well as installation and activation procedures were used. It is understood that the dental model is different from the human dentition in many ways. The sole difference that influences force measurements, however, is the slight displacement of the patient tooth due to the initial compression of the periodontal ligament and, to some extent, of the bony structures, resulting in (1) a shortening of IBD and (2) slightly reduced activation. However, these displacements are very small compared with the IBD and thus have negligible effects on the load system. This level of simulation has never been achieved in previous studies. Furthermore, variations occurred in each of the load components. These came from human error

Table 1. Means and SDs of the Force Components on the Left Maxillary Canine and Lateral Incisor With 1-mm and 2-mm Activations When the Loop Was Placed at Two Locations, Mesial (ME) and Middle (MD), Respectively[a]

	Fx-ME	SD	Fx-MD	SD	Fy-ME	SD	Fy-MD	SD	Fz-ME	SD	Fz-MD	SD
Means and SDs of the force components on the canine corresponding to a 1-mm activation												
KH	−2.87	0.79	−3.25	0.59	−0.31	1.40	−0.50	0.93	0.13	0.38	0.10	0.35
TD	−2.34	0.72	−2.44	0.48	−0.32	1.19	−0.19	0.93	0.58	0.23	0.13	0.27
Means and SDs of the force components on the incisor corresponding to a 1-mm activation												
KH	−1.52	0.49	−1.59	0.57	−0.11	0.32	−0.18	0.47	−0.07	0.42	0.05	0.33
TD	−1.20	0.77	−1.33	0.67	−0.17	0.29	0.08	0.14	−0.32	0.38	0.16	0.26
Means and SDs of the force components on the canine corresponding to a 2-mm activation												
KH	−4.72	0.54	−4.84	0.65	−0.55	1.78	−1.21	1.40	0.13	0.48	−0.27	0.34
TD	−3.56	0.65	−3.73	0.56	−0.86	1.04	−1.98	1.27	0.65	0.30	−0.32	0.32
Means and SDs of the force components on the incisor corresponding to a 2-mm activation												
KH	−2.40	0.38	−2.77	0.63	−0.08	0.67	−0.08	0.67	−0.05	0.49	0.44	0.34
TD	−1.67	0.72	−2.12	0.54	0.13	0.15	0.13	0.15	−0.42	0.31	0.40	0.27

[a] KH indicates Keyhole; TD, Teardrop.

Table 2. Means and SDs of the Moment Components on the Left Maxillary Canine and Lateral Incisor With 1-mm and 2-mm Activations When the Loop Was Placed at Two Locations, Mesial (ME) and Middle (MD), Respectively[a]

	Mx-ME	SD	Mx-MD	SD	My-ME	SD	My-MD	SD	Mz-ME	SD	Mz-MD	SD
Means and SDs of the moment components on the canine corresponding to a 1-mm activation												
KH	7.08	2.93	7.97	2.16	0.30	1.08	1.53	0.71	−14.30	3.86	−9.78	4.29
TD	7.73	1.32	8.34	2.09	1.03	1.11	0.50	0.61	−8.91	3.99	−10.41	4.65
Means and SDs of the moment components on the incisor corresponding to a 1-mm activation												
KH	−5.91	1.69	−5.43	1.93	−2.42	0.58	−2.19	0.77	8.05	1.06	10.13	2.14
TD	−4.44	1.67	−5.67	0.97	−1.71	0.63	−1.63	0.28	8.99	4.33	8.42	1.53
Means and SDs of the moment components on the canine corresponding to a 2-mm activation												
KH	12.59	1.54	16.70	2.50	0.08	1.57	0.78	0.97	−17.75	3.50	−12.13	4.95
TD	12.99	2.15	14.36	2.21	1.14	1.07	0.91	0.80	−10.49	4.46	−12.07	4.49
Means and SDs of the moment components on the incisor corresponding to a 2-mm activation												
KH	−12.34	1.76	−9.35	3.38	−5.13	0.64	−3.99	1.48	14.25	1.38	15.31	2.83
TD	−9.24	2.06	−8.83	1.06	−3.91	0.90	−3.13	0.44	13.39	4.49	14.56	1.21

[a] KH indicates Keyhole; TD, Teardrop.

such as the tightness of the ligature wires. This kind of random error was dealt with statistically.

The components expressed in 3D are different from those in 2D. In a 2D system, all the forces are projected on the sagittal plane; thus, the forces can be described only in the MD or OG direction. Because of that, in a space closure case, the forces on the anterior teeth directed distally. In a 3D system, the coordinate system is attached to the tooth. The MD direction depends on the location of the tooth. The lingual direction of the incisor in 3D primarily corresponds to the distal direction in 2D, while the distal direction of a molar corresponds to the distal direction in 2D. Thus, the terms cannot be used interchangeably between the two coordinate systems.

The directions of the force and moment components of the three types of loops were consistent, except for the components with very low magnitudes, which were at the load cells' noise level and had negligible clinical impacts. Generally, a force less than 0.3 N is considered to have a negligible clinical effect. The load system on the lateral incisor was different from that on the canine for all the designs.

The force components tend to displace the brackets. In the BL direction, all three wires produced large lingual force, F_x, on the crowns, tipping the teeth lingually. The force components on the canine doubled that of the incisor ($P < .001$). In the MD direction, all designs produced clinically effective mesial forces, F_y, on the canine but very low F_y on the incisor. If not constrained properly, mesial displacement of the canine is expected. It is expected that, initially, the crown of the canine has the tendency to move lingually and mesially, while the crown of the lateral incisor tends to move lingually. In the OG direction, the KH and TD showed a different loading pattern from TL at the 1-mm activation. TL_{42} showed clinical effective extrusion forces on the canine, while TD_{42} and KH_{42} had small intrusion forces. Other designs produced negligible intrusion and extrusion force, F_z (Figures 2 and 3).

The moment components rotate the tooth. All three moment components had similar patterns for all three designs. They provided a distal tipping moment, M_x, on the canine; a mesial tipping moment, $-M_x$, on the incisor; a very low lingual tipping moment, M_y, on the canine; a low buccal tipping moment, $-M_y$, on the incisor; a large crown-mesial-in-moment, $-M_z$, on the canine; and a large crown-distal-in-moment, M_z, on the incisor (Figures 4 and 5). These components affect the moment-to-force ratios that control tipping.

Although the load patterns are similar, the magnitudes are different, with no clear trends observed. For

Table 3. The Moment-to-Force Ratios, M_x/F_y, M_y/F_x, on the Left Maxillary Canine (C) and Lateral Incisor (I) With 1-mm and 2-mm Activations When the Loop Was Placed at Two Locations, Mesial (ME) and Middle (MD), Respectively[a]

	Mx/Fy-ME-C	Mx/Fy-MD-C	Mx/Fy-ME-I	Mx/Fy-MD-I	MY/Fx-ME-C	MY/Fx-MD-C	MY/Fx-ME-I	MY/Fx-MD-I
1-mm activation								
KH	−22.6	−16.1	56.1	30.9	−0.1	−0.5	1.6	1.4
TD	−23.9	−43.9	26.5	−72.2	−0.4	−0.2	1.4	1.2
2-mm activation								
KH	−23.0	−13.8	154.8	117.3	0.0	−0.2	2.1	1.4
TD	−15.2	−7.3	−68.6	−65.5	−0.3	−0.2	2.3	1.5

[a] KH indicates Keyhole; TD, Teardrop.

example, KH_{42} provided the highest F_x at 2-mm activation, but TD_{42} gave the highest F_y ($P < .005$) on the canine at the same level of activation. Refer to Figures 2 to 5 for specific force levels.

The data in the figures help predict the resulting tooth displacement and provide guidance in selecting the archwire based on the desired load system. All three designs result in lingual tipping of the canine because of the large tipping force, $-F_x$, and the small lingual tipping moment, M_y. The correcting moment, $-M_y$, on the incisor is not large enough to produce a moment-to-force ratio, M_y/F_x, equal to 8 to 10 for translating the tooth. The small M_y on the canine even enhances the tipping (Table 3). Among the designs, TL_{38} provides the highest M_y/F_x ($\sim$4.4 mm) on the incisor.

In the OG direction, the KH and TD have very limited intrusion/extrusion effects compared with TL. TD_{38} provides the maximum intrusion force on the canine, while the TL_{42} delivers the maximum extrusion force on the canine (Figures 2 and 3). The force in the MD direction, F_y, is generally small on the incisor side, which is not sufficient to tip the tooth distally. This result is consistent with the common belief that the lateral incisor moves distally due to a distal force because, for the incisor, the 3D lingual direction orients closely in the distal direction in 2D. Using these designs, the incisor tends to tip mesially due to the large $-M_x$. Because of the constraint provided by the neighboring central incisor, it is expected that the root will move distally, which needs to be validated clinically. TL_{42} has the minimum effect on this.

The rotation of the tooth will be affected by these kinds of archwires. The mesial force, F_y, tends to rotate the canine mesial-in because it is applied to the bracket, which offsets to the center of resistance. To prevent unwanted tooth rotation, the moment, M_z, is expected to counter the moment due to F_y. Unfortunately, all the designs create M_z that enhance the moment; thus, crown-mesial-in rotation is expected for the canine. However, TL_{42} had the least effect on the rotation. On the incisor, the positive M_z produces a crown-distal-in rotation. The small F_y has little effect on this rotation.

CONCLUSIONS

- The component magnitudes vary with the level of activation primarily. There is no clear trend for the magnitudes.
- All the designs result in lingual tipping of the teeth, canine lingual-mesial displacement, canine crown-mesial-in rotation, and incisor crown-distal-in rotation.

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