Original Article

Effects of first- and second-order gable bends on the orthodontic load systems produced by T-loop archwires

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ABSTRACT

Objective: To measure the effects of first- and second-order gable bends on the forces and moments produced by a commercially available closing T-loop archwire.

Materials and Methods: A dentoform-simulated space closure case was mounted on an orthodontic force tester. Sixteen gable bend combinations were placed in the archwires, which were then activated using standard clinical procedures. At each activation, the three force components and three moment components on the maxillary left lateral incisor and canine were simultaneously measured.

Results: The first- and second-order gable bends showed low load coupling effects when used independently, but the load systems became unpredictable when bends were combined. Gable bends affect the magnitudes and directions of the forces and moments that are applied to teeth. The resulting moment to force ratios are sensitive to the bends.

Conclusion: Gable bends alter the orthodontic load systems; however, the three-dimensional interactions produce complex and unpredictable tradeoffs. (*Angle Orthod.* 2014;84:350–357.)

KEY WORDS: Orthodontic force systems; Biomechanics; T-loop archwire; Gable bends; Moment to force ratio

INTRODUCTION

Controlled orthodontic tooth movement relies on quantifiable load (force and moment) systems (Figure 1) and their manipulation in all directions. Loads, but more critically, moment to force (M/F) ratios, can produce different, often unintended, clinical outcomes.[1,2] Moreover, force magnitudes need to be maintained within some range for best clinical outcomes.[3]

The quantifications of segmental wire loading systems have been mostly under two-dimensional nonclinical conditions.[4–9] Recently, a three-dimensional (3D) clinical simulation of a commercial T-loop archwire[10] clearly demonstrated the necessity for modifications to achieve desired M/F ratios for translatory space closure.

A common way to adjust the M/F ratio is with first- (Figure 2a) and/or second-order (Figure 2b) gable bends. More specifically, the primary purpose of a first-order bend is to increase the anti-rotation M_z/F_y ratio during space closure. Similarly, anti-tipping is achieved by increasing the M_x/F_y ratio with second-order gable bends. However, the efficacies of these gable designs, particularly with continuous archwires in a 3D configuration, have not been reliably quantified. Thus, the objectives of this study were to determine the effects and interactions of first- and second-order gable bends on the load systems produced by a space-closing T-loop. The load systems were evaluated on their effectiveness in producing translatory tooth movements.

MATERIALS AND METHODS

The orthodontic force tester[10–12] (OFT; Figure 3) was used in this study. The left maxillary lateral incisor and

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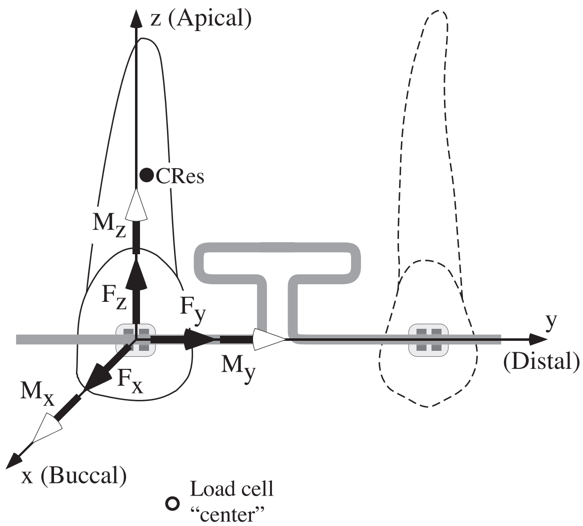

Figure 1. Schematic of complete generic load system acting on a maxillary left lateral incisor bracket. The $\pm F_x$, $\pm F_y$, and $\pm F_z$ force components act in the buccal/palatal, distal/mesial, and apical/incisal directions, respectively. The moment vector components' ($\pm M_x$, $\pm M_y$, and $\pm M_z$) directions are defined by the right-hand-rule convention: the thumb of the right hand points in the direction of the moment (open) vector arrow, and the fingers indicate the direction of rotation. Thus, as an example, $-M_z$ would produce a mesial-in distal-out (third order) rotation of the incisor.

canine were each supported by commercially available load cells (Multi-axis force/torque Nano17, ATI Industrial Automation, Apex, NC) that are capable of simultaneously measuring all three force (0–20 $\pm$ 0.025 N) and all three moment (0–100 $\pm$ 0.003 N-mm) components. A load cell's output is relative to its internal center, so routine equivalent system calculations[13] were performed to determine the reported loads at the teeth's respective brackets (Figure 1). Henceforth, all load systems refer to those that act on the bracket.

The tested T-loop closing archwires (0.016" $\times$ 0.022" Stainless Steel Natural Form Arch, Oscar,

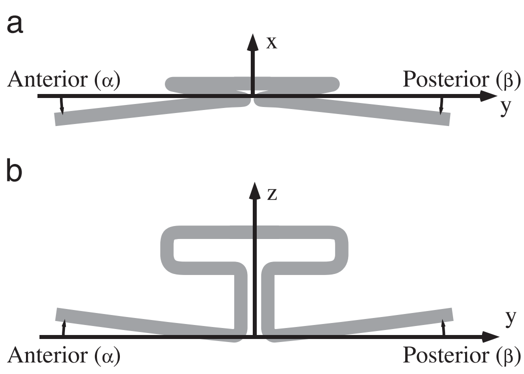

Figure 2. (a) Occlusal view of first-order gable bends. (b) Buccal view of second-order gable bends.

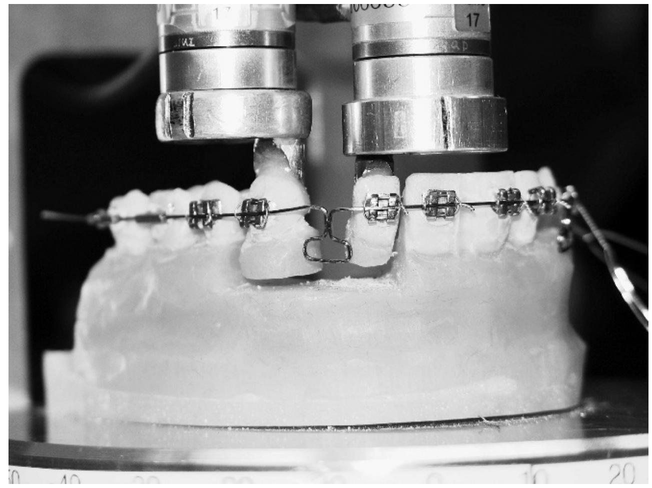

Figure 3. The OFT showing the load cells.

Inc, Fishers, Ind) with interloop distance of 42 mm centered the loop in the interbracket space between the lateral incisor and canine. The brackets, Pre-Adjusted Twin Andrews Formula Brackets, Oscar, Inc, had 0.018" slots. Using templates, the archwires were modified with 16 combinations of gable bend angulations. The variables were the gable type (first or second order), alpha (α) or beta (β) gable location, and gable symmetry (symmetric or asymmetric), shown in Figure 2 and Table 1. The total first- and second-order gable angulations were 0° or 20° each. The 20° individual totals were either entirely at one location or 10° at both locations. (All bends were mirrored on the contralateral side.) Thus, the 20° could be split evenly or unevenly while maintaining a sufficiently large minimum value, the 10°. Bigger angles might have potentiated permanent deformations.

To statistically account for inconsistencies in loop shape, ligature tightness, and activation, five wires of each specification were fabricated and tested. Averages and standard deviations were computed to determine the force and moment components and their variations. To assess the effects of (1 vs 2 mm) activation and gable angulations on the resulting loads on each tooth, a two-way full-factorial analysis of variance model was applied with a significance level of .05. (The normality was determined to be acceptable for these analyses.)

The previously used space-closing protocol[10] was adapted. The load cells were zeroed, the wire was inserted and ligated, the neutral position was established, and the 0-mm activation load cell readings were obtained. Then, after a 1-mm bilateral activation at the distal ends of the second molar tubes, the load cell readings were repeated. A third set of data was then obtained with an additional 1 mm of activation. Thus, the load systems on the teeth were obtained for 0, 1,

Table 1. Gable Type (First or Second Order) and Location (α or β)

Configuration	Designation	First-Order Bends		Second-Order Bends	
	α_1, β_1–α_2, β_2 (°)	α_1 (°)	β_1 (°)	α_2 (°)	β_2 (°)
1	0, 0–0, 0	0	0	0	0
2	0, 0–0, 20	0	0	0	20
3	0, 0–10,10	0	0	10	10
4	0, 0–20, 0	0	0	20	0
5	0, 20–0, 0	0	20	0	0
6	10, 10–0 ,0	10	10	0	0
7	20, 0–0, 0	20	0	0	0
8	0, 20–0, 20	0	20	0	20
9	0, 20–10,10	0	20	10	10
10	0, 20–20, 0	0	20	20	0
11	10, 10–0, 20	10	10	0	20
12	10, 10–10, 10	10	10	10	10
13	10, 10–20, 0	10	10	20	0
14	20, 0–0, 20	20	0	0	20
15	20, 0–10, 10	20	0	10	10
16	20, 0–20, 0	20	0	20	0

and 2 mm of activations. For statistical reasons, five archwires of each of the 16 combinations were tested, and the averages and standard deviations were computed.

RESULTS

The measured load component magnitudes acting on the left maxillary lateral incisor and canine are presented in Figures 4 and 5. Most zero and all nonzero activation F_x measurements (Figures 4a and 5a) were negative (lingual). First-order gable bends (configurations 8 and 9) affect this component but second-order bends alone (configurations 1, 2, 3 and 4) have little effect. Combined bends significantly altered F_x. α bends increased F_x on the canine, and β bends increased F_x on the incisor. In general, F_x on the canine (Figure 5a) was higher than on the incisor (Figure 4a).

F_y on the incisor was small (Figure 4b), much smaller than the concomitant F_x and sensitive to the bends. With activation, F_y on the canine was consistently negative (mesial) (Figure 5b). Combined first- and second-order bends significantly increased F_x. F_z on the incisor (Figure 4c) was mostly positive (intrusive). F_z on the canine (Figure 5c) was generally negative (extrusive), except with the second-order asymmetric α bends. The second-order asymmetric β bends created the largest extrusive force on the canine and the largest intrusive force on the incisor.

First-order bends had negligible effects on M_x, but overall, second-order bends increased its magnitude by 50% (Figures 4d and 5d). Except with second-order asymmetric β bends, negative M_x on the incisor supplied the desired anti-distal-tipping moment (Figure 4d). All but one M_x on the canine (Figure 5d) were positive, thus providing the intended anti-mesial-tipping moment. The largest M_x, a threefold increase, was produced by second-order asymmetric α bends. Thus, properly placed second-order bends can deliver M/F ratios that are sufficient in some cases.

Second-order bends generate the $-M_y$ that are needed to prevent the tipping produced by the lingual force, $-F_x$. ($+M_y$ are generated without the bends.) Second-order asymmetric β bends and second-order asymmetric α bends created the maximum M_y on the canine and incisor, respectively (Figures 4e and 5e). Even so, the M_y/F_x are generally too small ($<$8 mm) to avert lingual crown tipping.

M_z on the canine is predominantly negative, crown-mesial-in (Figure 5f). Except with first-order asymmetric α bends, M_z on the incisor is mostly positive, crown-distal-in (Figure 4f). In general, it appears that axial crown rotation of both teeth is inevitable because their respective M_z augment, rather than oppose, the F_y-produced rotations. The previously mentioned exception, first-order asymmetric 20° α bends, produce anti-rotation on the incisor. Figure 6 shows the typically emphasized M/F ratio (M_x/F_y) on the teeth.

DISCUSSION

Although the configuration is that of en masse tooth movements, only the leading tooth in each segment is instrumented. That is justified as follows. For a tooth to move in a specific direction (for example, translate into the extraction space), it has to experience a specific net load system on its bracket. That is, the appropriate force and moment vectors must be applied to its bracket. That necessary load system is determined by the constraints imposed on the root by the PDL-socket system, resulting in the characteristic location of a tooth's center of resistance (CRes), hence the required M/F ratios. Because the root/PDL/socket assembly is

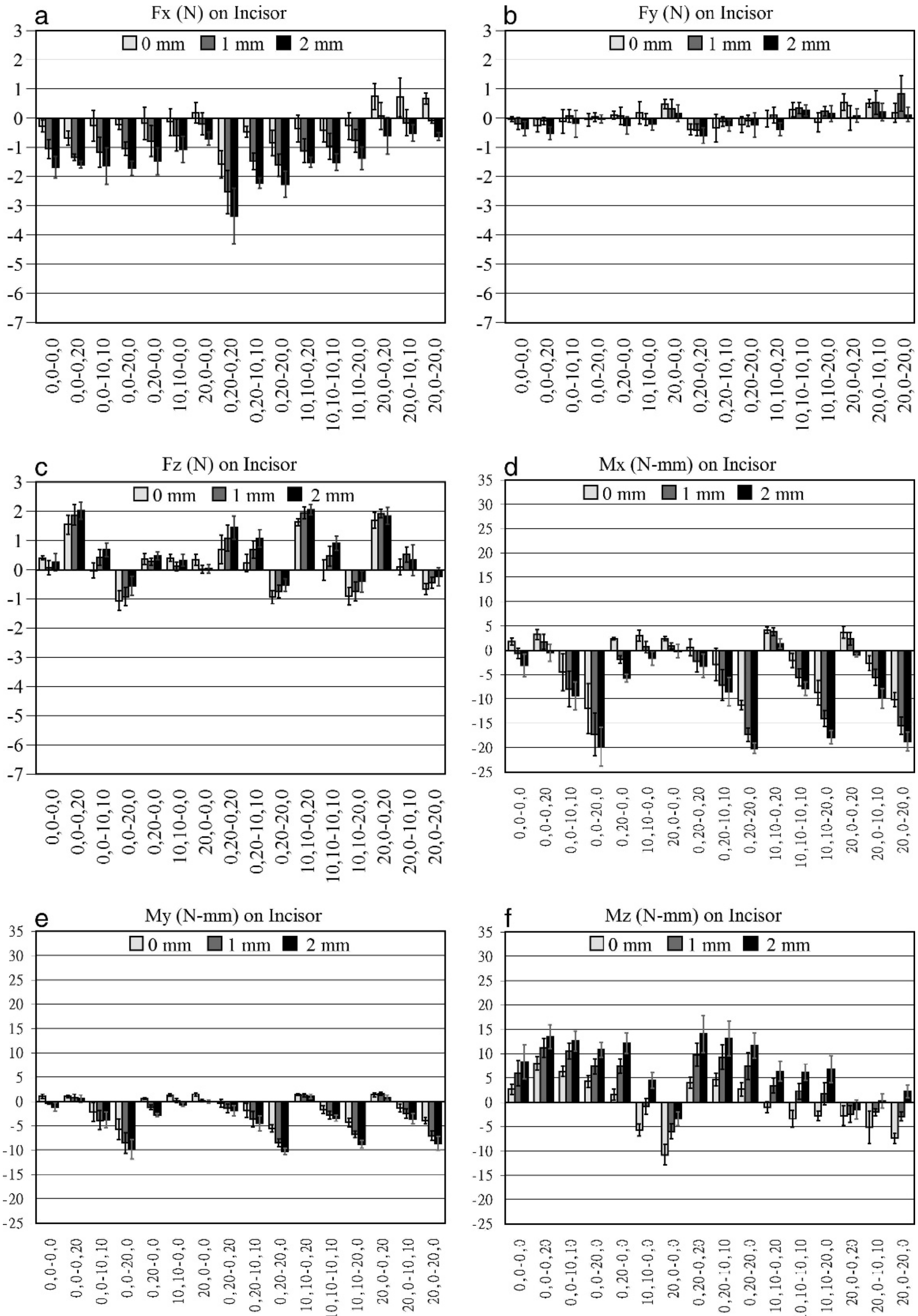

Figure 4. Load systems on the incisor. (a) F_x. (b) F_y. (c) F_z. (d) M_x. (e) M_y. (f) M_z.

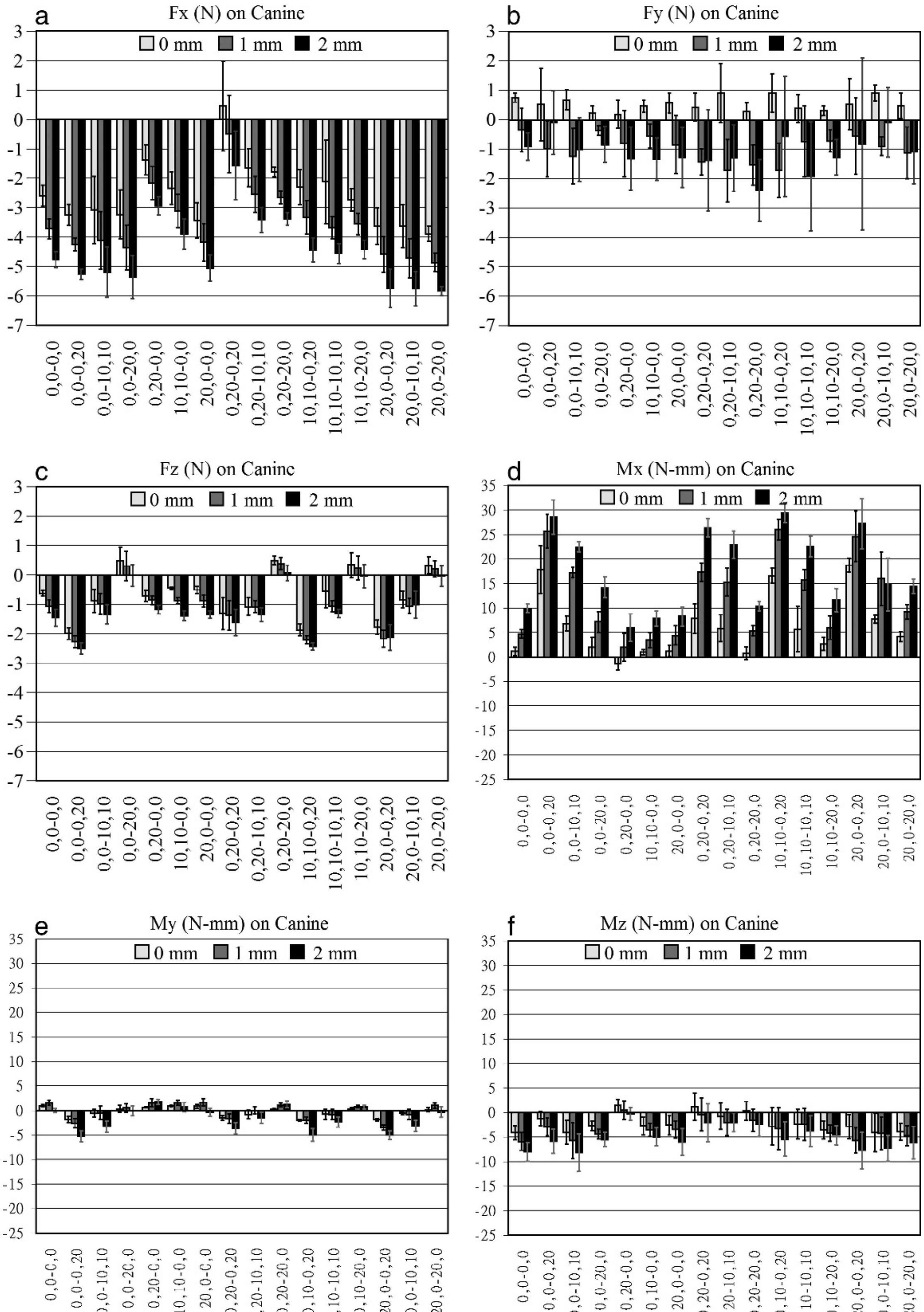

Figure 5. Load systems on the canine. (a) F_x. (b) F_y. (c) F_z. (d) M_x. (e) M_y. (f) M_z.

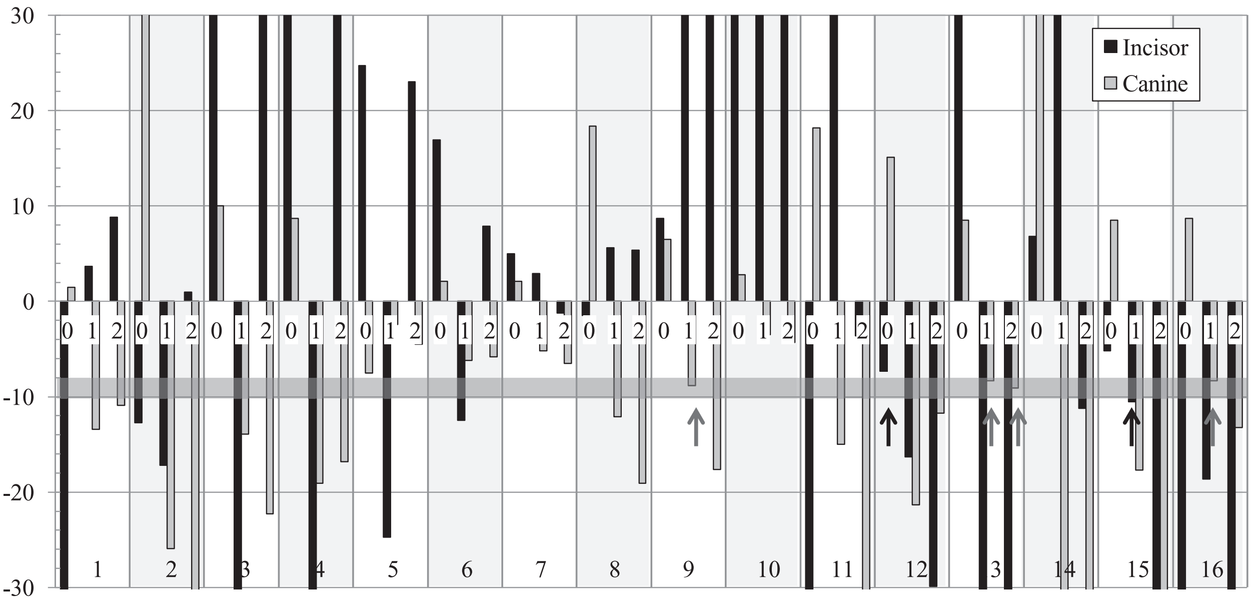

Figure 6. The M_x/F_y (mm) on incisor and canine for the 16 combinations of gable bends and 0 mm, 1 mm, and 2 mm of activation of each combination. The M/F ratios range between −578 and +788 and −303 to +35.2 mm on the incisor and canine, respectively. Ratios within or close to the ideal range, −8 to −10 mm (gray strip), are indicated by arrows.

the same when a particular tooth is moved individually or as part of a segment, it follows that the same net load system must be applied to its bracket in both instances. It is that load system that is measured by the load cell. With an isolated tooth, the load system is applied directly to its bracket by the spring. When part of a segment, that load system on its bracket is its share of the forces and moments that are distributed among all teeth in the segment. The net load system that is applied to the bracket, and therefore, what the load cell measures, are the same in both scenarios.

In the y-z plane (Figure 1), force components act in the +y/−y (distal/mesial) and +z/−z (apical/incisal) directions, and the moment acts in the +x/−x (buccal/lingual) direction (ie, second-order tipping). First-order tipping takes place in the x-z plane in which the forces act in the +x/−x (buccal/lingual) and +z/−z (apical/incisal) directions and the moment acts in the +y/−y (distal/mesial) direction. And in the x-y (occlusal) plane, the forces act in the +x/−x (buccal/lingual) and +y/−y (distal/mesial) directions and the moment acts in the +z/−z (apical/incisal) direction, or third-order rotation. (Thus, the most general plane model contains two force components, and a moment component that is perpendicular to both forces as defined by the right-hand rule [RHR].) Studies have focused predominantly on segmental wires in the y-z plane, involving force components F_y and F_z and moment component, M_x.

By components, there are nine possible M/F ratio permutations: M_x/F_x, M_x/F_y, M_x/F_z, M_y/F_x, M_y/F_y, M_y/F_z, M_z/F_x, M_z/F_y, and M_z/F_z. But M_x/F_x, M_y/F_y, and M_z/F_z are meaningless because a force cannot generate a moment in its own direction. In the customary (y-z plane) segmental view of space closure, F_y is the primary and largest force component, and it also has the longest (8–10 mm) moment arm relative to the tooth's CRes. That combination produces a substantial second-order tipping moment about CRes, so its counteraction has been the traditional focus of loop and (second-order) gable studies aimed at increasing M_x/F_y to the 8–10 mm level for typical tooth translation.[3] (In the literature, the generic ''moment-to-force ratio'' generally refers implicitly to M_x/F_y.) F_x is customarily considered to be zero, certainly smaller than F_y, but in the x-z plane, it also has an 8–10 mm moment arm relative to CRes, so it has the potential to produce considerable first-order tipping, which requires that the spring also produce an M_y/F_x = 8–10 mm as a countermeasure. (In actuality, the CRes in the two directions are not the same,[14,15] so $M_x/F_y \approx M_y/F_x \approx$ 8–10 mm.) In general, the other four M/F ratios (M_x/F_z, M_y/F_z, M_z/F_x, and M_z/F_y) are not emphasized, presumably because the relevant moment arms, hence the M/F, are less than ~2 mm for an upright tooth. (M_x/F_z affects second-order tipping while M_y/F_z influences first-order tipping. M_z/F_x and M_z/F_y produce third-order rotations whose control is the purpose of the first-order gable bend.)

The data should be approached from three points of view. One is to assess whether the spring design produces the load system that accomplishes the intended orthodontic tooth displacements, in this instance, translations of the incisor and canine into the extraction space. Second, it must be ascertained whether that design also generates loads that result in unwanted concomitant movements, for example, rotation about the long axis (first-order rotation) or extrusion of that tooth, or problematic movements of other teeth. If either requirement is violated, then gable design modifications become the third concern.

For space closing translation of the incisor, the following conditions apply:

- $F_y > 0$ (distally directed), and
- $M_x < 0$ (lingually directed as defined by the RHR) (Figure 1), and therefore,
- M_x/F_y should be between -8 and -10 mm.

For $-10 < M_x/F_y < -8$ on the incisor (Figure 6), the -7.3 mm (-2.11 N-mm/0.29 N) for configuration 12 at 0 mm activation and the -10.5 mm (-5.57 N-mm/0.53 N) at 1 mm of activation for configuration 15 are the closest, and both sets of F_y and M_x act in the correct senses (that is, $F_y > 0$ and $M_x < 0$; this is important because $F_y < 0$ and $M_x > 0$ can also produce the correct $-10 < M_x/F_y < -8$, but the tooth would translate away from the extraction space).

At the same time, on the canine for the space closing translation:

- $F_y < 0$ (mesially directed), and
- $M_x > 0$ (buccally directed by the RHR), and therefore,
- M_x/F_y between -8 and -10 mm.

Several configurations meet the $-10 < M_x/F_y < -8$ condition on the canine (Figure 6), and they also satisfy the $F_y < 0$ and the $M_x > 0$ conditions:

- -8.8 mm (15.3 N-mm/-1.73 N) for configuration 9 at 1 mm activation;
- -8.3 mm (6.0 N-mm/-0.72 N) at 1 mm of activation for configuration 13;
- -9.1 mm (11.64 N-mm/-1.28 N) at 2 mm of activation for configuration 13; and
- -8.3 mm (9.21 N-mm/-1.12 N) at 1 mm of activation for configuration 16.

Although the 1 mm and 2 mm activated 13 loop configuration provides ideal M_x/F_y for the canine, the corresponding incisor M_x/F_y equals -62 and -109 mm (Figure 6). The four other designs mentioned earlier, configurations 12, 15, 9, and 16, supply some appropriate M_x/F_y to one of the teeth.

Thus, our evaluation of the 16 wire designs demonstrated that some of the designs provided the required M_x/F_y for translation, but they were generally coupled with undesired load components in other directions. Although these designs do not fully meet the requirements for pure canine and incisor translation, the results clearly showed the effects of gable bend location and magnitude on the orthodontic load systems. This can provide guidance for improving and fine-tuning gable designs so as to bring the orthodontic load components on target.

There were initial (0 mm of activation) nonzero readings for all load components (Figures 4 and 5). These preactivation loads, produced by the nonpassivity of the wires during insertion, are of sufficient magnitudes to suggest that even when activation is exhausted, residual loads could continue to move teeth. This possibility is supported by the observation that none of the springs exhibited any visual evidence of permanent deformations.

In the present context, the sole purpose of a gable bend is to adjust an M/F ratio to a level that produces the desired tooth movement. As noted earlier, canine and incisor translation typically require that $M/F \approx M_x/F_y \approx M_y/F_x \approx 8$–10 mm. A loop that produces a smaller ratio may be incapable of keeping the tooth upright, while a larger ratio may overcompensate for the undesired tipping. Gable bends can be used to manipulate the load system; however, because of the extremely complex 3D interactions involving vector magnitudes and directions, a design that may improve the M/F ratio on a tooth in one direction may worsen it in another direction or with a different activation, or it can also be detrimental to the M/F ratio on another tooth.

In some instances, a spring that generates an out-of-range M/F ratio should not be summarily dismissed. Given the inherent limitations of spring design, the clinician may have to settle for a non-ideal M/F, and a large M/F can result from a relatively small F component magnitude in the denominator. A small force component may be unacceptable for space closure; however, in tandem with a large moment, it may be appropriate for root correction. Anchorage may require a higher M/F ratio than translation. Better understanding of the effects of the bends would help achieve desired clinical outcomes.

The data illustrate the intricate nonintuitive nature of statically indeterminate systems and the confounding effects of 3D. Furthermore, the clinical situation is more complex because the teeth move in response to the orthodontic loads, whereas static tooth positions are common shortcomings in studies of this kind. However, these experimental set-ups serve as good representations for treatment starting points or, if appropriately matched, intermediate treatment points. More studies of the sort presented herein (including the effects of wire materials, slot/wire sizes, asymmetry, etc) must be undertaken to qualitatively assess the loading characteristics of various loop configurations before evidence-based design criteria can evolve.

CONCLUSIONS

- Combinations of 3D gable bends on space-closing T-loops alter the load systems on teeth.
- The effects of gable bends on the 3D force and moment vector components and the various M/F ratios are complex, but they can be adjusted by varying the gable angle combinations.

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