Original Article

T-loop force system with and without vertical step using finite element analysis

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ABSTRACT

Objective: To investigate the effect of vertical steps on a T-loop force system at three interbracket distances (IBDs) and their association with V-bends.

Materials and Methods: Loop response during simulated loop pulling was determined for 18 T-loop configurations (6-, 9-, and 12-mm IBD with a 2.5-mm canine bracket (CB) end and 0- (plain), 0.5-, or 1-mm vertical step). Loop length-by-height was 8 $\times$ 8 or 10 $\times$ 10 mm. Horizontal load/deflection, vertical force (Fy), and moment-to-force (M/F) ratios at loop ends were determined for 100-g and 200-g activation by finite element analysis.

Results: Plain, 12-mm IBD T-loops showed similar force and moment responses as off-centered V-bends (greater moment close to V-bend) without change in moment direction at the premolar bracket (PB) end; plain, 6-mm IBD T-loop responses were similar to those of centered V-bends (equal, opposing moments at each end). Adding vertical steps to the T-loops raised the M/F ratio at the PB ends enough to produce root movement, while lowering the M/F ratios at the CB ends. Increasing the step bends for shorter IBDs increased Fys and caused rapid changes in M/F ratios. Unlike plain T-loops, increasing activation in stepped T-loops caused substantial variations in M/F ratios and in amount and direction of Fys.

Conclusions: Step bends can dramatically change the force system. Stepped T-loops display combined effects of V-bends and step bends. (*Angle Orthod.* 2016;86:372–379.)

KEY WORDS: T-loop; Vertical step; Force system; V-bend; M/F ratio; Finite element analysis

INTRODUCTION

Closing loops are used in orthodontics to generate forces to move teeth and close spaces between teeth or groups of teeth. In a clinical situation, closing loops are usually placed near the canine brackets (CBs). Clinicians can repeatedly activate a loop by cinching the wire end gingivally at the molar tube during subsequent visits as the space is closing. Inevitably, the resulting shift in loop position changes the forces and moments (herein denoted as a "force system" of a loop) and could thus also affect posterior anchorage in segmental and continuous archwires.

Clinicians adjusting loop positions off center are usually focused on the loop's desired effects at the shorter end, but moving a closing loop off center affects the force system on both ends. For a T-loop placed close to the CB end, the moment-to-force (M/F) ratio will be higher at the CB end, and the vertical force (Fy) will be extrusion. On the premolar bracket (PB) end, the M/F ratio will be low and the Fy will be intrusion.[1–3] The Fy generated in this situation can deepen the overbite. To reduce extrusive force, an anterior step bend has been suggested for off-centered T-loops (Figure 1).[4,5] This may be the easiest way to avoid extrusion at the CB end. However, such procedure is likely to affect both ends, as the moments are generated in the whole force system. This issue is rarely mentioned in the orthodontic literature. Considering the many complex interactions the addition of a bend can create, loop properties need to be investigated systematically.

The purpose of this study was to systematically evaluate how force systems of various T-loops change

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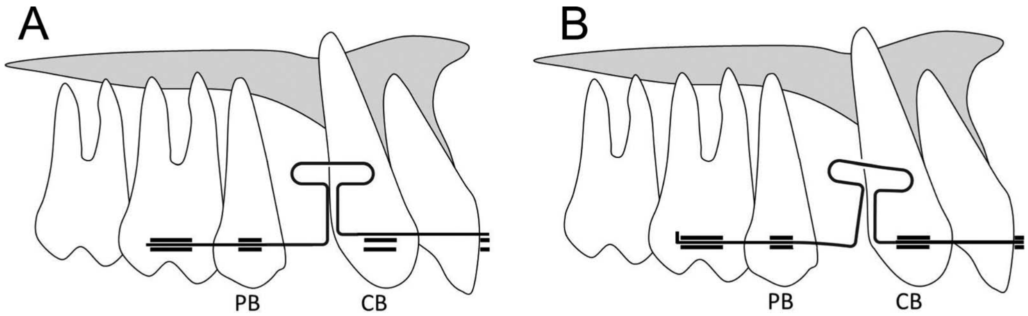

Figure 1. Off-centered, stepped T-loop (A) before and (B) after activation. PB is premolar bracket, CB is canine bracket.

with different amounts of vertical step and activation forces. Force systems can be studied with different methods, including mechanical experiments.[6] We chose finite element analysis (FEA) to systematically model loop shapes and calculate the force systems because it allows accurate control over loop shapes, properties, fixation, and loading.

MATERIALS AND METHODS

Eighteen T-loop variations were evaluated. The definitions of their dimensions and locations of PB and CB are shown in Figure 2A. T-loop sizes were 8×8 and 10×10 mm. Horizontal loop lengths (b) were 12, 9, or 6 mm. On the CB end, the distance to the center of the T-loop was kept constant at 2.5 mm to simulate space closing by shortening the PB end. Distances from the PB end to the T-loop center (a) were 9.5, 6.5 and 3.5 mm. The a/b ratios were 0.79, 0.72, 0.58 for the 12, 9 and 6 mm T-loops, respectively. Vertical steps (c) at the CB ends were 0 (no step), 0.5 or 1.0 mm.

Loop geometry was modeled in FEA software (Marc/Mentat, MSC Software, Santa Ana, CA) using beam elements with 0.016×0.022 inch rectangular cross-sections. T-loops were placed in one plane, and modeled with 520 three-dimensional (3D) elastic beam elements with transverse shear effects and linear interpolation for displacements and rotations. Curved sections used shorter beam elements (higher element density) to closely. Beam elements were given the material properties of stainless steel wire, consisting of an elastic modulus (157.6 GPa) and Poisson's ratio (0.3).[7] With 1400 MPa yield strength,[7] the yield strain was 8.88×10^{-3}.

Displacements of both closing loop ends were controlled in all 6 degrees of freedom (three displacements along and three rotations around the three orthogonal axes). During the analysis, the CB ends were fixed for the plain T-loops (c = 0 mm) or, in the

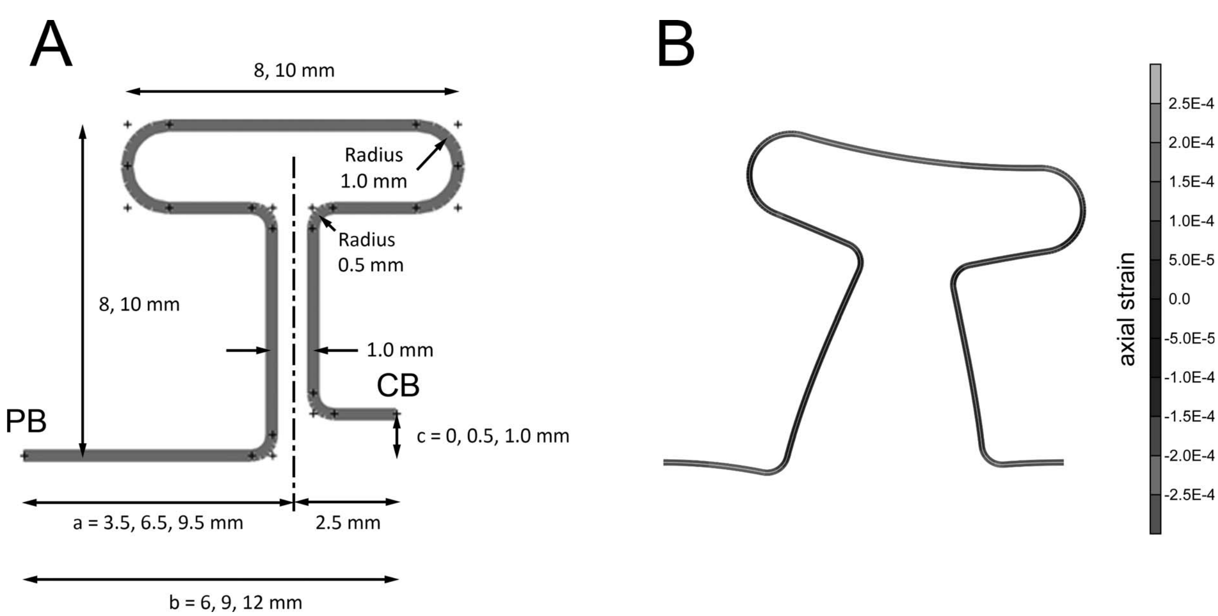

Figure 2. (A) Dimensions of the T-loop: distance from loop center to PB end (a), interbracket distance (b), and vertical step (c). (B) Axial strains in 8×8-mm T-loop with 6-mm interbracket distance and 1-mm step size at 4-mm activation displacement.

case of stepped T-loops, were moved to the same level as the PB ends and fixed in that position (Figure 1B). All loops were stress-free before activation (plain loops) or before step application. Next, the PB ends were moved in small increments to the left (posteriorly) toward the PB for a total horizontal activation (x) of 4 mm. For all tested activation distances and T-loop sizes, the axial strains were between -2.00×10^{-4} and 2.02×10^{-4}. The highest axial strain values occurred for the smallest T-loop with the shortest interbracket distance (IBD) and largest step size (Figure 2B). All strains were well below the yield strain, thus deformation during activation remained within the elastic range. This was consistent with an experimental study reporting that 3 mm of activation remained within the elastic range for a 6 × 6-mm T-loop on 0.016 × 0.022-inch stainless steel wires and 10-mm IBD.[8] During activation simulation, horizontal reaction force (Fx), Fy, and moment (Mz) were determined at both loop ends (PB and CB). Positive Fys were defined as forces directed away from the loop (extrusion), negative values were forces in the loop direction (intrusion). Positive moments were clockwise and negative moments were counterclockwise at PB and CB. Model design and procedures were validated against T-loop force system values published by Burstone and Koenig[1] by creating additional T-loop models using their loop dimensions and verifying the same outcomes.

RESULTS

Fxs, Fys, and Mzs were collected at the brackets (PB and CB ends) during the 0- to 4-mm activation displacement for the T-loops to create force and moment activation curves. Table 1 lists the M/F ratios, horizontal load/deflection, and Fys when the activation force was 100 g and 200 g. Three IBDs (Figure 3) simulated successive posterior cinching, while keeping anterior length constant (2.5 mm). Fx vs activation plots showed that at the same IBD, horizontal load/deflection rates were similar regardless of the vertical step size; only a slight increase was found with increasing vertical step size. The plots showed that a vertical step starts to provide a contraction force after the loop ends were moved apart over a small distance, thus not from zero origin. As the vertical step increased, more activation was required for the contraction force to start. The same response was found for the larger, 10 × 10-mm T-loops, but with load/deflection rates that were about half of the smaller 8 × 8-mm loops (Table 1).

Fys calculated for 0- to 4-mm activation displacements of the 8 × 8-mm plain and stepped T-loops show that without the vertical step, activation of the off-centered T-loop (12- and 9-mm IBD) generated extrusion at the CB end (Figure 4A,B) and an equal amount of intrusion at the PB end. When x was increased, the extrusive Fy generated by the off-center effect increased. Fy values decreased with decreasing IBD (6-mm IBD; Figure 4C). Adding a step bend produced a substantial opposite force component at both ends at all activation displacements: intrusion at the CB end and extrusion at the PB end. The resultant Fy was a combination of those two responses. The intrusive force generated by the step bend was nullified by the gradually increasing extrusive force of the off-center T-loop x. The force component introduced by the step bend increased with step size, and changed little with activation displacement; only a slight decrease was observed with increasing activation displacements. The larger, 10 × 10-mm T-loops showed a similar response but with force values lower than those shown by the smaller (8 × 8-mm) loops (Table 1).

M/F ratios at both loop ends were plotted with the Fxs (Figure 5). Without steps, the 8 × 8-mm T-loops showed nearly constant M/F ratios for Fxs of 50–250 g. For a plain T-loop (12- and 9-mm IBD without a step bend) placed off center next to the CB, the M/F ratio was higher on the CB end than on the PB end. M/F ratios on the CB and PB ends also had opposite directions (Figure 5A,B; Table 1). When loop length (interbracket space) was decreased at the PB segment, as for the 6-mm IBD, the difference in M/F ratios between both ends decreased as the loop position became more centered.

Adding an intrusive step to the T-loop changed the moment (and thus the M/F ratio) clockwise at both loop ends (Figure 5). Note that positive moments turn the loop clockwise; negative moments turn it counterclockwise. The step caused an increase in M/F ratios at the PB end, with the highest ratios found at low Fxs, and a decrease in M/F ratios at the CB end. Greater step sizes caused greater changes in M/F ratios. Shortening loop length further increased M/F ratios at the PB end and decreased M/F ratios at the CB end. In some instances (eg, the 6-mm IBD between 50–100-g activation), the 0.5- and 1-mm intrusive steps decreased the M/F ratio at the CB so much that it caused a directional change in the M/F ratio (Figure 5C). These effects were less for stepped T-loops when loop size was increased to 10 × 10 mm (Table 1).

DISCUSSION

Seemingly simple closing loops can have surprisingly intricate mechanical reactions when activated. Experienced clinicians can achieve desired tooth movements by estimating resultant forces and moments with closing loop geometry and activation. However, these forces

Table 1. Force System of the 8 × 8- and 10 × 10-mm T-Loops for 3 Interbracket Distances (12, 9, and 6 mm) and 2 Horizontal Force Values (100 g and 200 g)

		100 g			200 g		
Interbracket Distance (mm)	Vertical Step (mm)	M/F Ratio[a] (PB/CB[b])	Load/Deflection[c]	Vertical Force[d]	M/F Ratio (PB/CB)	Load/Deflection	Vertical Force
8 × 8							
	0.0	0.1/−5.6	156.5	43.8	0.1/−5.7	153.4	85.5
12	0.5	5.5/−2.8	169.6	−20.6	2.7/−4.1	167.1	22.9
	1.0	10.8/−0.2	182.0	−80.0	5.2/−2.6	180.6	−35.6
	0.0	2.0/−5.5	157.9	36.2	1.9/−5.6	154.3	71.8
9	0.5	8.9/−1.6	168.8	−74.2	5.2/−3.4	166.4	−33.4
	1.0	15.9/2.0	177.7	−175.5	8.6/−1.5	176.4	−130.8
	0.0	4.3/−5.0	174.1	10.2	4.3/−5.0	167.7	21.2
6	0.5	10.7/−0.1	183.7	−160.8	7.6/−2.3	177.3	−144.2
	1.0	17.7/4.6	187.9	−325.3	11.1/0.1	181.9	−303.7
10 × 10							
	0.0	1.1/−7.2	80.2	45.9	1.0/−7.4	76.4	89.7
12	0.5	5.3/−5.0	85.1	−2.2	2.9/−6.1	83.0	45.2
	1.0	9.5/−2.9	89.8	−47.0	4.4/−4.8	88.6	3.0
	0.0	3.5/−6.9	81.4	33.4	3.3/−7.1	77.7	67.7
9	0.5	8.3/−4.1	85.3	−39.9	5.6/−5.5	82.8	0.6
	1.0	13.2/−1.6	88.1	−108.9	7.9/−4.0	86.7	−63.1
	0.0	5.8−6.4	90.7	8.3	5.8/−6.5	84.9	18.0
6	0.5	9.8/−3.3	94.5	−91.9	7.9/−4.7	89.2	−77.1
	1.0	14.0/−0.3	96.1	−190.2	10.2/−3.0	91.3	−170.9

[a] M/F ratio unit is mm; + is clockwise; – is counterclockwise.
[b] PB is at premolar bracket end, CB at canine bracket end.
[c] Load/deflection unit is g/mm.
[d] Vertical force unit is g; + is extrusion; – is intrusion at anterior or CB end.

and moments need not be estimated because they can be relatively easily calculated by analytical or numerical methods. Finite element analysis used in this study is eminently suited for accurately calculating and optimizing complex loops.[9,10] We used this method to systematically analyze forces and moments at the ends of a ubiquitous type of closing loop. Before discussing the results, it is important to note that forces and moments encountered clinically may differ from the pure loop force system we calculated because they may contain out-of-plane curvature effects or the wire play of a 0.016 × 0.022-inch wire in 0.018 × 0.025-inch bracket slots. It can be shown that 0.002 inch bracket play (Figure 6) reduces the effectiveness of loops and step bends (Table 2). However, the primary objective of this study was to understand the basic properties of loops themselves. Therefore, we eliminated curvature effects and bracket play. Hence, loop ends were considered as if rigidly attached to notional brackets. The choice of these rigid boundary conditions was thus essential for determining the basic characteristics of stepped T-loops. Furthermore, no tooth movement was considered, and thus no effects of bracket angulation during loop activation were simulated. Translating the

Table 2. Force System of the 8 × 8-mm T-Loops with 0.002-Inch Wire Play in 3-mm-Wide Brackets for 3 Interbracket Distances (12, 9, and 6 mm) and 2 Horizontal Force Values (100 g and 200 g)

8 × 8 mm		100 g		200 g	
Interbracket Distance (mm)	Vertical Step (mm)	M/F Ratio[a] (PB/CB[b])	Vertical Force[c]	M/F Ratio (PB/CB)	Vertical Force
	0.0	0.8/−4.3	26.2	0.9/−4.7	55.6
12	0.5	2.4/−2.7	2.0	1.2/−3.8	38.0
	1.0	5.7/−1.1	−35.3	3.2/−2.5	−10.9
	0.0	1.1/−4.4	33.6	1.2/−5.0	71.3
9	0.5	5.3/−1.5	−37.8	3.4/−3.2	−3.0
	1.0	8.9/−0.1	−86.5	5.9/−1.5	−83.0
	0.0	2.6/−4.0	19.2	3.2/−4.4	29.8
6	0.5	6.5/−1.7	−69.6	6.0/−2.0	−104.7
	1.0	11.8/1.0	−188.3	7.9/−0.9	−185.2

[a] M/F ratio unit is mm; + is clockwise; – is counterclockwise.
[b] PB is at premolar bracket end, CB is at canine bracket end.
[c] Vertical force unit is g; + is extrusion, – is intrusion at anterior or CB end.

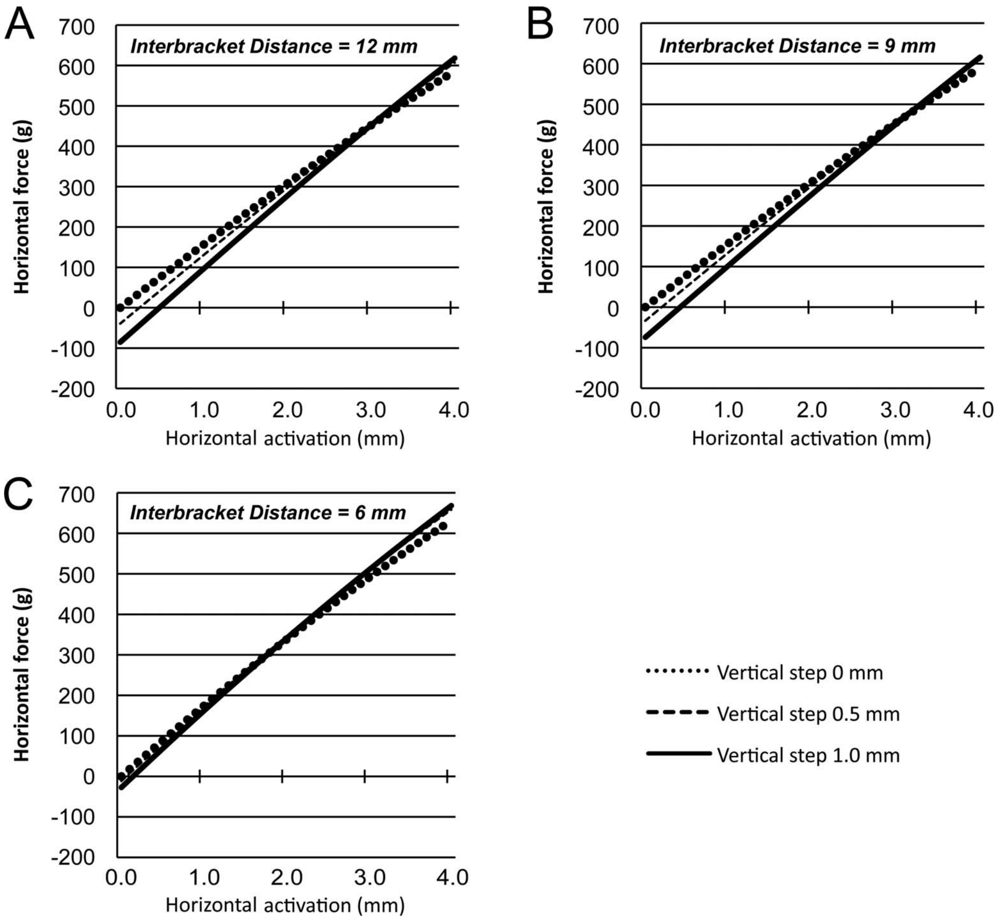

Figure 3. Horizontal force vs horizontal activation of 8 × 8-mm plain and stepped T-loops for three interbracket distances: (A) 12 mm, (B) 9 mm, and (C) 6 mm.

calculated properties to clinical conditions will therefore require taking the unique conditions of each individual case into account. Nevertheless, the general characteristics remain valid as a basis for individual application.

To study the effect of a step bend on T-loops, first the response of a plain T-loop needs to be understood. When a T-loop is placed off center, close to the CB for closing an extraction space, it affects the force system on both loop ends. For T-loops, off-center positioning had a significant effect on the moments produced, with the higher moment occurring at the bracket closest to the loop position.[11] Loop placement was suggested to resemble a V-bend, for which off-center positioning produced differential moments in which the greater moment acted on the tooth close to the V-bend.[12] A vertical extrusive force would occur at the short end, while the same amount of intrusive force occurred at the long end. Increasing x increased the Fy. For a center V-bend, the M/F ratio was equal in value but different in direction. Others reported similar reactions.[1–3,13]

Adding a step bend affected the force system of a wire in a different way. Step bends hardly affected horizontal load/deflection rates (Figure 3), but produced an opposite directional force on both sides of a step, while the effect on the moments at both ends were equal in magnitude and direction.[12] Unlike the closing loop or V-bend, a step bend generated forces and moments on both wire sides that were less affected by its position. A step in a wire between two brackets produced equal Fys in opposite directions and moments equal in magnitude and direction.

Our results show that step bends generated an almost constant Fy component along the activation distance (Figure 4). When x was increased, the change in Fys followed a nearly linear slope. To maintain force equilibrium, the vertical force should be s multiplied by x plus the Fy component due to the step bend (k): $Fy = sx + k$, where sx is extrusive. Using this simplified relationship, at the CB end, a plain T-loop has no vertical force component ($k = 0$) and thus the vertical force (Fy) is sx when x increases.

According to the orthodontic literature, M/F ratios of 1 to 7 produce controlled tipping, ratios of 8 to 10 (depending on root length) produce bodily moments, and ratios greater than 10 produce torque or root movements.[14] In the 12- and 9-mm IBD off-centered

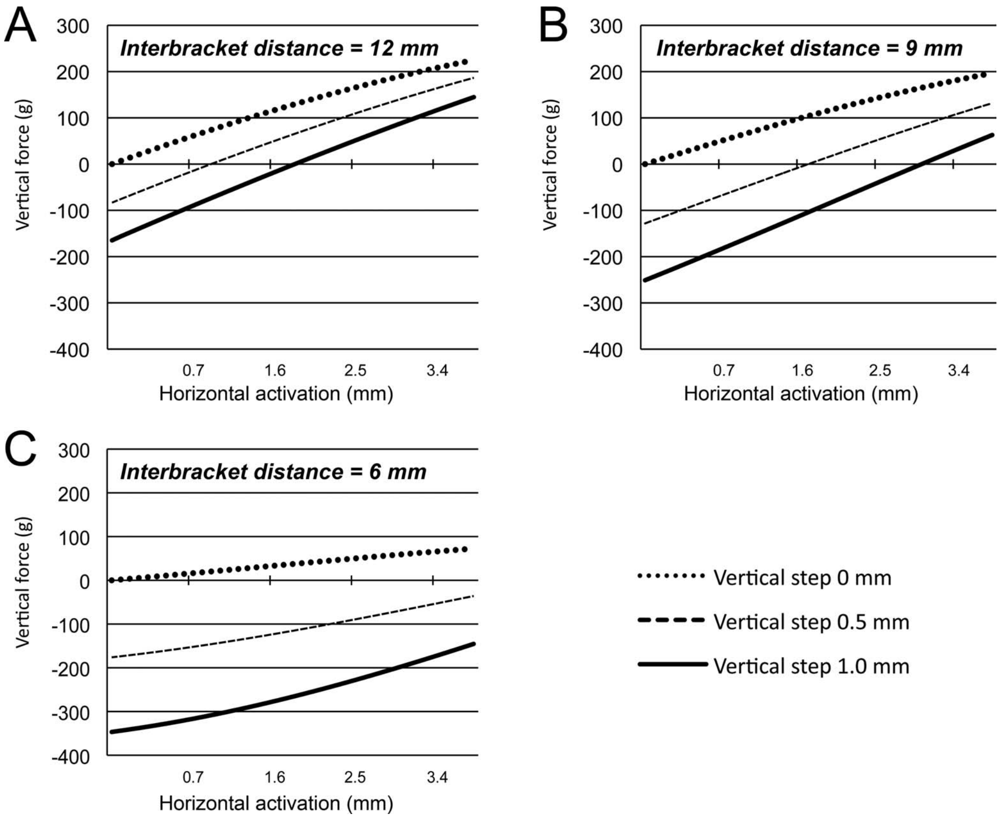

Figure 4. Vertical force at the canine bracket end during horizontal activation of 8 × 8-mm plain and stepped T-loops for three interbracket distances: (A) 12 mm, (B) 9 mm, and (C) 6 mm.

T-loops, the force system was a combination of the off-centered V-bend and step-bend effects. The longer the step, the more the step bends affect the force system. The M/F ratio at the PB segment rose under some activation conditions above 10 (Figure 5). Unlike the plain T-loop, for which the M/F ratio remained almost constant for 50 to 250 g horizontal activation, the M/F ratio of stepped T-loops decreased substantially with increasing activation force. A stepped T-loop may be good when maximal posterior anchorage is needed or when anterior protrusion in which tipping of the anterior teeth is allowed. A plain, off-centered T-loop may be good to upright anterior teeth that need more bodily movement, while posterior tooth anchorage is less critical or when crown tipping movement is needed. When a T-loop was more centered with a 6-mm IBD (a/b ratio = 0.58), the V-bend effect from activation provided less vertical force and more equal moment on both wire sides. The force system of the 6-mm, stepped T-loop was affected more by a step bend. While the space is being closed, clinicians should decrease the vertical step to lessen its effect on the force system.

This study demonstrated the situation wherein a step bend is used in an off-centered, closing loop archwire to avoid deepening the overbite. An easy application, such as an anterior, stepped T-loop, can provide effective intrusive forces on the anterior teeth. However, the other forces and moments can change substantially as a result of the combination of the position of the T-loop and the amount of step bend, potentially rendering the procedure inappropriate for the desired tooth movement. In this demonstration the step bend added a clockwise component that increased the clockwise moment at PB and decreased (but not eliminated) the counterclockwise moment at CB (Figure 7). The CB end generated an M/F ratios appropriate for tooth tipping while the M/F ratio at the PB end was suitable for bodily movement.

Avoiding deepening of an overbite may need other strategies. We suggest the use of an off-centered V-bend at the PB long end. Theoretically, such procedure provides a clockwise moment and extrusive force at the PB while the CB receives minor counterclockwise moments and intrusive force. The force system will become a center bend from two opposite off-centered V-bends; one V-bend from the off-centered T-loop and the other from the bend at the posterior V-bend.[15] Thus no extrusive force occurs. Martin et al.[16] tested 20–30-mm, IBD off-centered plain T-loop configurations with V-bends added at the long ends using loop software. Their data showed high M/F ratios on the posterior side for controlled tipping, bodily movement,

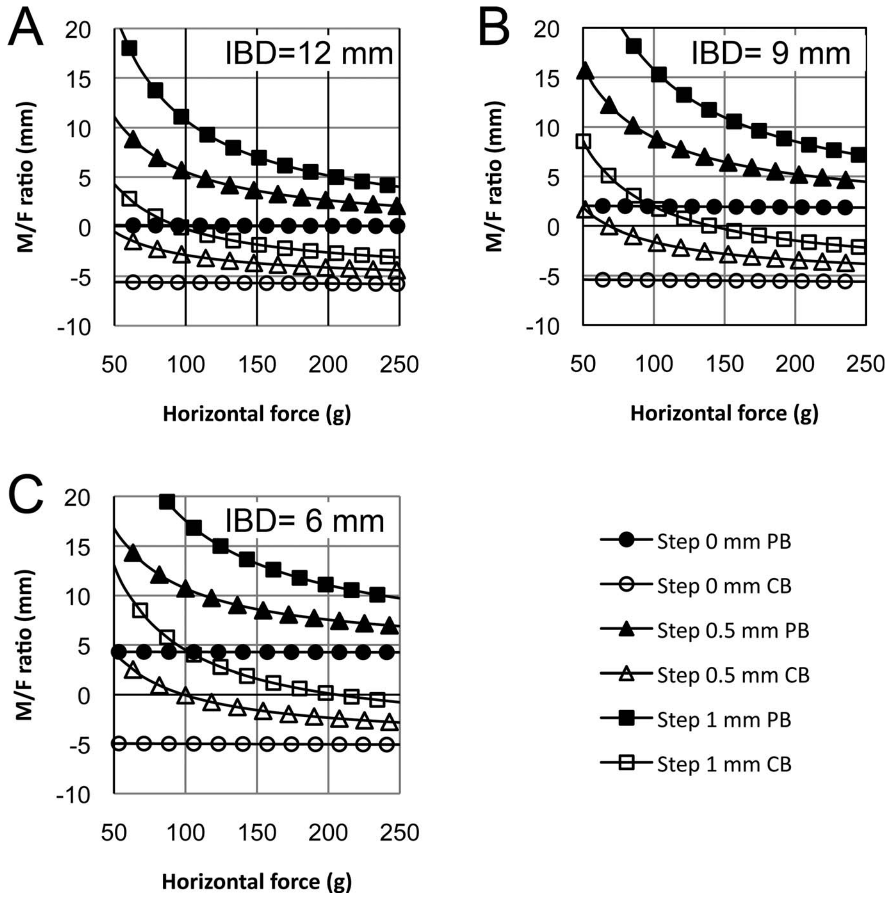

Figure 5. Moment-to-force (M/F) ratio for 50–250 g horizontal reaction forces of 8 × 8-mm plain and stepped T-loops for three interbracket distances (IBDs): (A) 12 mm, (B) 9 mm, and (C) 6 mm.

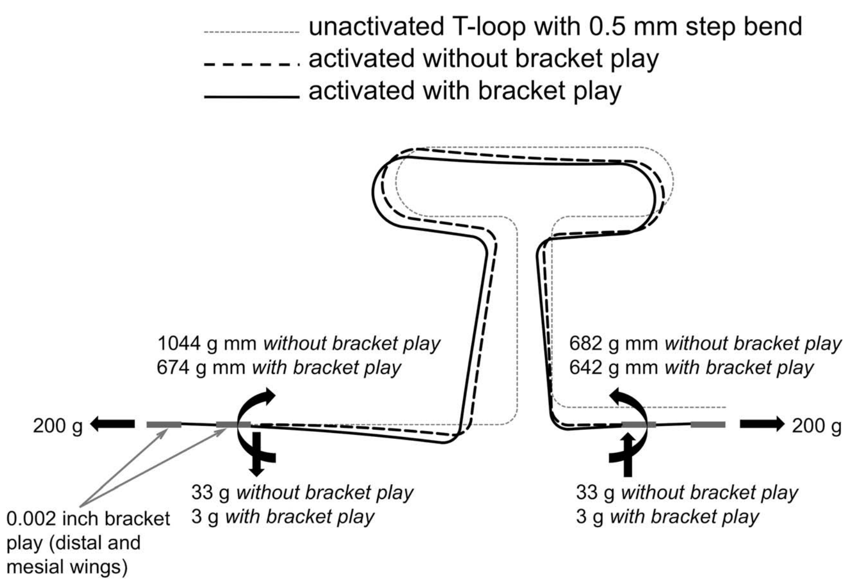

Figure 6. Comparison between 8 × 8 mm T-loops without or with wire play in 3-mm wide brackets at 200 g horizontal activation.

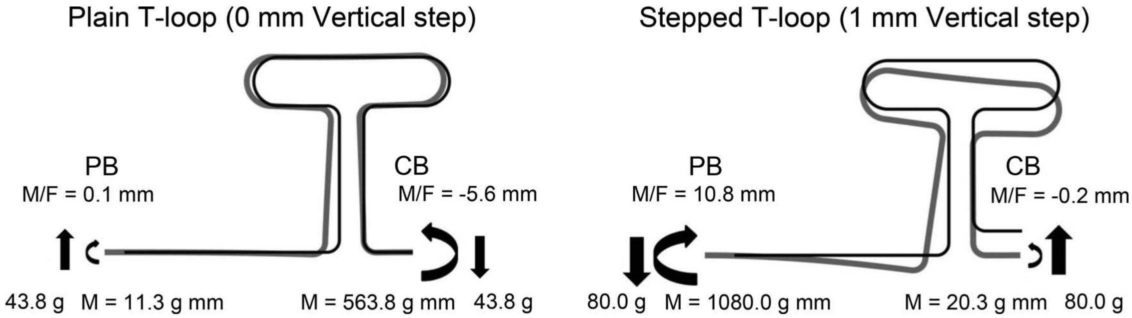

Figure 7. Comparison between forces and moments of plain and stepped 8 × 8 mm T-loops with 12 mm interbracket distance at premolar bracket (PB) and canine bracket (CB). During activation, the CB was moved inline and the PB was moved to the left until 100 g horizontal force was obtained. Deformed loop shapes are shown in gray.

and even root torque at 2-mm x. Although their study did not directly mention the vertical force, the 23–30 mm, off-centered, plain T-loop with gable bend close to the PB (<7 mm) showed higher M/F ratios at PB than at CB. It can be expected that with these configurations, vertical forces are extrusive at PB and intrusive at CB. It was also shown that L-loops always provide an intrusive force at the PB end.[2,3] If the L-loop is used in the reverse direction, an intrusive force may be obtained at CB. These are potential procedures that need scientific verification.

Considering the dramatic force system changes demonstrated for step bends, clinical implications can be summarized as: (1) when space is reduced, step bends should be reduced too since step bends increase especially the vertical force in shorter and smaller loops; (2) choose closing loops likely to give suitable force systems for each patient's condition; (3) consider other procedures for increasing vertical forces, such as gable bends in posterior legs or reversed L-loops.

CONCLUSIONS

- Step bends can dramatically change force systems (vertical force and M/F ratio) of off-centered closing loops by creating intrusive forces on the CB, extrusive forces on the PB, and clockwise moments on both CB and PB.
- The force system of a T-loop with a vertical step bend is a combination of the V-bend effect from the position of the T-loop and the step bend.
- Step bends affect the force system of closing loops more when the vertical step is increased, horizontal loop length decreased, or T-loop size reduced from 10 × 10 mm to 8 × 8 mm.

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