Original Article

Effects of T-Loop Geometry on Its Forces and Moments

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Abstract: The moments and forces produced by various orthodontic T-loop spring designs were measured. The effects of dimension changes (within clinically used ranges) and the addition of gable bends with heat treatment were assessed. Increasing the vertical or horizontal dimension reduced the spring's load-deflection rate and its moment-to-force ratio. Gable preactivation with heat treatment had the opposite effects. (*Angle Orthod* 2000;70:48–51.)

Key Words: T-loop spring, Force, Moment

INTRODUCTION

Quantitative knowledge of the forces and moments generated by orthodontic springs is crucial for understanding tooth movement. Controlled spring loads are required for controlled treatment. For proper spring design, the factors that affect the forces and moments must be known.

In 3-dimensional space (x, y, z), general loading on a bracket consists of 6 components. They are 3 forces (Fx, Fy, Fz) and 3 moments (Mx, My, Mz). In a 2-dimensional plane problem (Figure 1), the number of components is reduced to 3 (Fx, Fy, and Mz) on each bracket. That is, Fz, Mx, and My are zero if the spring and its activation are in the x-y plane.

The load components tend to move brackets along their respective directions. Fy intrudes/erupts along the y-axis, Fx translates (mesiodistally) along the x-axis, and Mz rotates about the z-axis. It is critical to recognize that these loads are applied to brackets and therefore the described movement tendencies are those of the brackets. In actuality, as an example, an intrusive force (-Fy) on the bracket would also produce a moment (Mx) about the tooth's center of resistance and therefore a tipping of the crown out of the x-y plane. This movement, and the nonzero Mx, violates the plane problem assumption. (The contributions of Fx and Fy to Mz, and the Mz generated by spring activation, are consistent with the 2-dimensional assumption.) Thus, all discussion is restricted to the 2-dimensional plane problem of the forces (Fx and Fy) acting on the brackets, and the effects of Mz.

Further simplification is possible if the spring geometry, its placement, and its activation are symmetric. In such cases, equilibrium requires that the Fy on each bracket be zero. Furthermore, the Fx on the right and left sides must be equal in magnitude, opposite in direction, and act along the same line. Similarly, Mz on the 2 brackets are parallel to each other (perpendicular to the x-y plane), equal in magnitude, but in opposite directions. Thus, in a symmetric plane problem, only 2 load components, Fx and Mz, are nontrivial.

It is clear that the level and direction of forces and moments generated by springs depend on many confounding factors. The influences of spring material and shape, end conditions (ligation methods), and activation direction and magnitude make analysis difficult. Thus, much of orthodontics depends on experience-based clinical judgment. Clearly, rigorous engineering approaches are needed to study the generated forces and moments and to identify the dominant design factors that can be used to control spring behavior.

Instruments have been built to measure orthodontic loads.[1–9] Analytical and computational analyses have been performed to calculate load components.[1,2,4,7,8,10,11] Based on linear theory and small deformation assumptions, or on nonlinear large deformation theory, these investigations typically used beam theory or the finite element method to calculate wire deflections or reactions. Specific examples include the studies of off-centered T-loops,[9] and the effects of height changes in gabled T-loops.[4] Other factors, such as the interactions of T-Loop size and heat-treated gable bends, need to be investigated.

Thus, the objectives of this study were to experimentally measure the load components produced by T-loop springs, and to ascertain the effects of design variations. Design parameters (dimensions) and gable bend preactivation with heat-treatment (GPH) were altered within clinically acceptable ranges and their effects were assessed.

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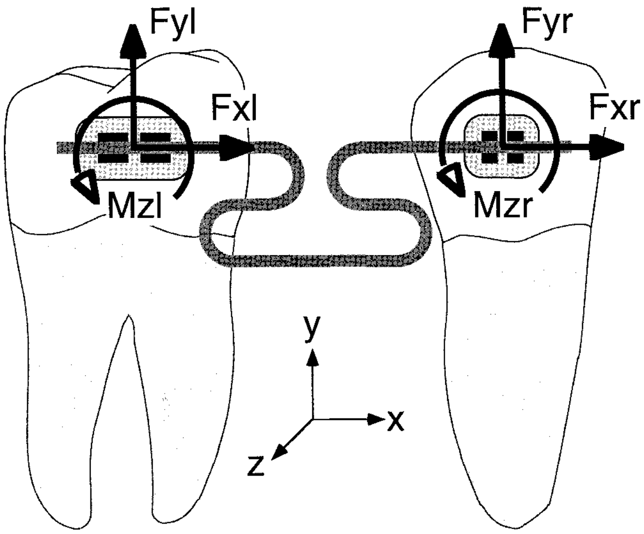

FIGURE 1. In the general 2-dimensional x-y plane model, Fx, Fy, and Mz are nontrivial. ("l" and "r" refer to the left and right sides, respectively. The forces and moments are shown acting on the brackets.) With specified horizontal activations of the right bracket, the load components on the left bracket were experimentally measured.

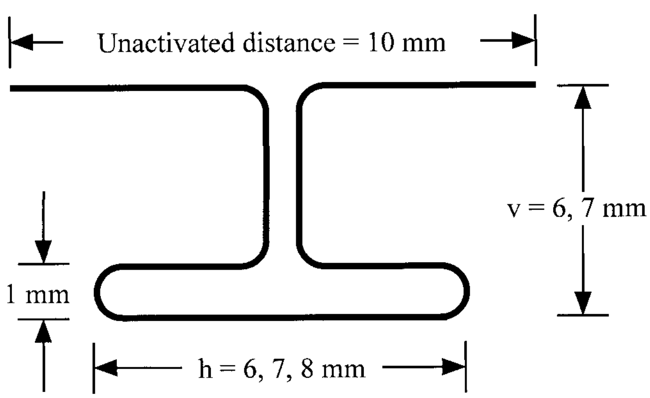

FIGURE 2. Schematic showing the shape (not to scale) and dimensions of the springs. (The first subscript of "Tvh" refers to the spring's vertical dimension, the second is its horizontal dimension.)

MATERIALS AND METHODS

An orthodontist, using 0.016 inch × 0.022–inch 18-8 stainless steel wire, bent the T-loop springs on a template jig (Figure 2). The vertical (v) and horizontal (h) dimensions were 6 or 7 millimeters and 6, 7, or 8 millimeters, respectively. The nomenclature used to identify these clinic suitable springs is Tvh. Thus, the 6 spring geometries are identified as T66, T67, T68, T76, T77, and T78. For statistical reasons, 10 specimens of each design (60 total) were fabricated. The same springs were also tested with 30° gable preactivation and stress-relieving heat treatment (GPH) at 700°F for 11 minutes followed by bench cooling.[12] In this way, a parametric study was performed to investigate the effects of spring dimensions and GPH.

An instrument (Figure 3) was built and calibrated to measure orthodontic load components. The device consisted of a modified microscope stage, 6 strain gauges that formed 3 half-bridges, and a fixed (left-side) and a moving (right-side) fixture "bracket". Spring activation was achieved by displacing the moving frame along the x-direction. The moment (Mz) and forces (Fx and Fy) on the left side were recorded from the transducer outputs that had <0.1 N resolution. [Editor's note: N, or Newton, is a technically correct unit for the measurement of force. Grams are a measure of mass. A force, measured in Newtons, is equal to mass times the acceleration of gravity.]

The springs with no GPH were tested first. Since the deformations were below the elastic limit of the stainless steel, GPH was done on the same spring and the test was repeated. In the testing instrument (Figure 3), spring ends were fixed in chucks, thus avoiding variability introduced by ligation methods. For activation, 3 displacement increments (1.0, 2.0, and 3.0 mm) to the right were imposed on the right side. The resulting reactions (Fx, Fy, and Mz) on the left side were measured and recorded. Means and standard deviations of 6 repeated measurements ($N = 10$) on each of the 60 springs were determined at each increment.

The effects of vertical and horizontal dimensions and activation distance on Fx, Mz, and Mz/Fx were compared for the T-loop using repeated measures analysis of variance models. The analyses were performed separately for the groups with and without GPH. Multiple comparisons were made using Fisher's projected least significant differences at an overall confidence level of 95%. Linear and quadratic trends in distance activation and horizontal dimensions were also examined when appropriate. This study did not involve comparisons across spring designs.

RESULTS

According to theory, with geometric and load symmetries, we should have measured negligible Fy. However, due to slight unavoidable asymmetries, nonzero Fy results were obtained.[13–15] Since these Fy were about 5% of Fx, these results are not presented. The differences discussed are all significant ($P < .0001 \sim .05$).

T-loop without GPH

With activation, the average horizontal force, Fx, increased from 1.4 N to 3.8 N (Table 1). At 2 and 3 mm of activation, increasing the vertical dimension from 6 to 7 mm reduced Fx by about 10%. At all activation levels, increasing the horizontal dimension from 6 mm produced 20% higher Fx. Horizontal dimensions of 7 and 8 mm were different from each other only at 2 and 3 mm activations. The load-deflection rate (ie, the slopes of the Fx versus activation curves) was approximately 1.2 N/mm (Figure 3).

The moment, Mz, was affected by most design changes (Table 1). With activation, its average value increased from

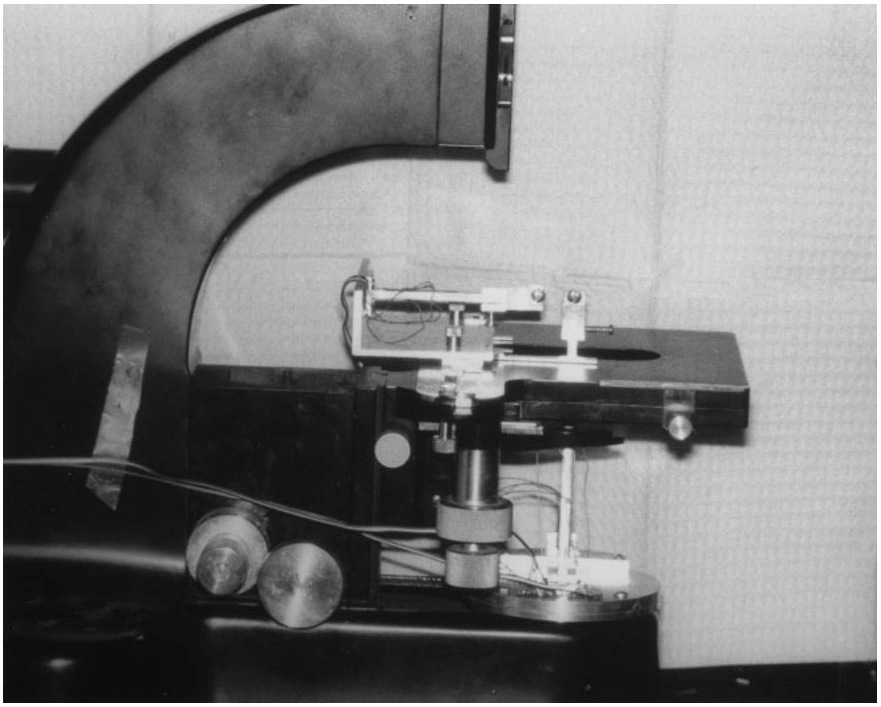

FIGURE 3. Instrument designed and built to measure the reaction loads (Fx, Fy, and Mz) on the left bracket with horizontal activation of the right bracket.

TABLE 1. Spring Characteristics of T-loop Springs without 30° Gable Preactivation and Heat Treatment at Different Horizontal Activation Levels

Dimensional Variations	Fx, N			Mz, N-mm			Mz/Fx, mm		
	1 mm	2 mm	3 mm	1 mm	2 mm	3 mm	1 mm	2 mm	3 mm
T66	1.65	3.15	4.3	8.39	16.16	22.12	5.08	5.13	5.2
T67	1.48	2.85	4.02	7.53	13.5	18.03	5.09	4.75	4.51
T68	1.38	2.63	3.62	6.29	11.99	16.42	4.56	4.56	4.56
T76	1.62	2.84	4.09	7.91	14.06	20.24	5.02	5.01	5.07
T77	1.37	2.56	3.67	6.75	12.42	16.78	4.91	4.84	4.57
T78	1.18	2.24	3.29	5.54	10.08	14.16	4.79	4.55	4.33
Average	1.45	2.71	3.83	7.07	13.04	17.96	4.91	4.81	4.71

approximately 7 to 18 N-mm. Increasing the vertical dimension from 6 to 7 mm lowered Mz by approximately 20% at 2 and 3 mm of activation. Increased horizontal dimension resulted in about a 38% decrease in Mz at all activations. The bending stiffness increased with activation at a rate of approximately 5.5 N-mm/mm.

Activation and vertical dimension had insignificant effects on the Mz/Fx ratio (Table 1). The ratio did not change from about 4.8 mm. However, the shortest springs (T66 and T76) generated approximately 10% higher Mz/Fx.

T-loop with GPH

With activation, the average horizontal force, Fx, increased from approximately 1.5 to 4.3 N (Table 2). Increasing the vertical dimension from 6 to 7 mm lowered Fx by about 20% with 2 and 3 mm of activation. The 6-mm horizontal dimension produced about 25% higher Fx than the 8 mm at all activations. Stiffness was about 1.4 N/mm.

The Mz generated by all springs increased with activation (Table 2). Its average magnitude more than doubled from about 9 to 22 N-mm. Increasing the height from 6 to 7 mm lowered Mz by about 14% at all activation levels. Increased horizontal dimension produced a larger (45%) effect. Mz increased with activation at about 6.5 N-mm/mm.

The highest Mz/Fx ratios were at 1 mm activation. The loops with the largest horizontal dimension (8 mm) exhibited 17% lower ratios (Table 2). There were no differences at the other activations. With 6 mm horizontal dimension, the vertical dimension had no effect on Mz/Fx at any activation. The average Mz/Fx ratio was about 5.8 mm. The range for all springs was 5.0–6.8 mm.

TABLE 2. Spring Characteristics of T-loop Springs with 30° Gable Preactivation and Heat Treatment at Different Horizontal Activation Levels

Dimensional Variations	Fx, N			Mz, N-mm			Mz/Fx, mm		
	1 mm	2 mm	3 mm	1 mm	2 mm	3 mm	1 mm	2 mm	3 mm
T66	1.78	3.39	5.06	11.76	20.27	27.25	6.61	5.98	5.39
T67	1.52	3.09	5.36	10.11	16.56	24.04	6.67	5.37	5.52
T68	1.43	2.84	3.91	7.29	14.04	19.16	5.15	4.96	4.92
T76	1.64	3.03	4.43	10.22	17.1	25.36	6.26	5.65	5.73
T77	1.47	2.54	3.67	8.97	15.15	22.04	6.09	6.01	6.04
T78	1.28	2.47	3.56	6.39	12.25	17.71	5.18	4.96	4.98
Average	1.52	2.89	4.33	9.12	15.90	22.59	5.99	5.49	5.43

DISCUSSION

Orthodontic tooth movement is typically characterized as pure translation, pure rotation, or combinations thereof. The ability of a spring to produce a particular displacement depends on the moment-to-force ratio that it can deliver. In addition, the load magnitude must be sufficiently high to effect tooth movement without causing injury.[16–23] For these criteria, the critical spring attributes include a low load-deflection rate and a high moment-to-force ratio.[24] This study demonstrates how spring design (GPH and changes in dimensions) influences these T-loop characteristics.

Increasing the vertical or horizontal dimension increases the length of wire incorporated into the spring. As previously demonstrated, this lowers the load-deflection rate. Unfortunately, due to the relatively larger reduction in Mz, Mz/Fx decreases approximately 12% as the horizontal dimension is increased from 6 to 8 mm. This is in qualitative agreement with Faulkner et al,[4] but direct comparison is impossible because of differences in wire size and spring design. The relative insensitivity of Mz/Fx to activation distance was also previously reported.[2]

Our results show that GPH may be clinically useful as a means of increasing Mz/Fx; however, the consensus appears to be that even our highest achieved value, 5.7 mm, is insufficient for bodily translation.

In summary, the results demonstrate that the moments and forces generated by a T-loop spring are functions of its geometry and gable angle combined with heat treatment. In general, increasing its vertical or horizontal dimension reduces the load-deflection rate and the moment-to-force ratio. Gable preactivation and stress relieving heat treatment has the opposite effect.

REFERENCES

1. Yang TY, Baldwin JJ. Analysis of space closing springs in orthodontics. *J Biomech.* 1974;7:21–28.
2. Burstone CJ, Koenig HA. Optimizing anterior and canine retraction. *Am J Orthod.* 1976;70:1–19.
3. Vanderby RJr, Burstone CJ, Solonche DJ, Ratches JA. Experimentally determined force systems from vertically activated orthodontic loops. *Angle Orthod.* 1977;47:272–279.
4. Faulkner MG, Fuchshuber P, Haberstock D, and Mioduchowski A. A parametric study of the force/moment systems produced by T-Loop retraction springs. *J Biomech.* 1989;22:637–647.
5. Demange C. Equilibrium situations in bend force systems. *Am J Orthod Dentofacial Orthop.* 1990;98:333–339.
6. Gjessing P. Controlled retraction of maxillary incisors. *Am J Orthod Dentofacial Orthop.* 1992;101:120–131.
7. Eden JD, Waters NE. An investigation into the characteristics of the PG canine retraction spring. *Am J Orthod Dentofacial Orthop.* 1994;105:49–60.
8. Chen J, Chen K, Katona TR, Baldwin JJ, Arbuckle GR. Nonlinear large deformation FE analysis of orthodontic springs. *Biomed Mater Eng.* 1997;7:99–110.
9. Kuhlberg AJ, Burstone CJ. T-Loop position and anchorage control. *Am J Orthod Dentofacial Orthop.* 1997;112:12–18.
10. Fotos PG, Spyrakos CC, Bernard DO. Orthodontic forces generated by a simulated archwire appliance evaluated by the Finite Element Method. *Angle Orthod.* 1987;60:277–282.
11. Siatkowski RE. Continuous arch wire closing loop design, optimization, and verification. Part I. *Am J Orthod Dentofacial Orthop.* 1997;112:393–402.
12. Marcotte MR. Optimal time and temperature for maximum moment and springback and residual stress relief of stainless steel wire [thesis]. Indiana University School of Dentistry; 1970.
13. Mulligan TF. Common sense mechanics. 1. *J Clin Orthod.* 1979; 13:588–594.
14. Burstone CJ, Koenig HA. Creative wire bending: the force system from step and V bends. *Am J Orthod Dentofacial Orthop.* 1988; 93:59–67.
15. Ronay F, Kleinert W, Melsen B, Burstone CJ. Force system developed by V bends in an elastic orthodontic wire. *Am J Orthod Dentofacial Orthop.* 1989;96:295–301.
16. Storey E, Smith R. Design of cuspid retraction springs. *Aus J Dent.* 1952;56:292–304.
17. Lee BW. Relationship between tooth-movement rate and estimated pressure applied. *J Dent Res.* 1965;44:1053.
18. Hixon EH, Aasen TO, Clark RA, Klosterman R, Miller SS, Odom WM. On force and tooth movement. *Am J Orthod.* 1970;57:476–489.
19. Fortin JM. Translation of premolars in the dog by controlling the moment-to-force ratio on the crown. *Am J Orthod.* 1971;59:541–551.
20. Boester CH, Johnston LE. A clinical investigation of the concepts of differential and optimal force in canine retraction. *Angle Orthod.* 1974;44:113–119.
21. Andreasen GF, Zwanziger D. A clinical evaluation of the differential force concept as applied to the edgewise bracket. *Am J Orthod.* 1980;78:25–40.
22. Quinn RS, Yoshikawa DK. A reassessment of force magnitude in orthodontics. *Am J Orthod.* 1985;88:252–260.
23. Proffit WR, ed. *Contemporary Orthodontics. 2nd ed.* St. Louis, Mo: Mosby-Year Book Inc; 1993:–307.
24. Burstone CJ, Baldwin JJ, Lawless DT. The application of continuous forces to orthodontics. *Angle Orthod.* 1961;31:1–14.