Experimentally Determined Force Systems from Vertically Activated Orthodontic Loops

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Optimum control of tooth movement requires the application of specific orthodontic force systems. Therefore, a knowledge of the mechanics of orthodontic appliances is essential to achieve desirable and predictable treatment results. Considerable research has already been done both analytically and experimentally to describe the specific resulting force systems that are delivered by various orthodontic appliances.[1-11] The goal of this study is to define the mechanical behavior for three designs of vertically activated orthodontic loops to further extend this growing field of knowledge. Experimental force systems were obtained from T-loops, L-loops, and rectangular loops (Burstone) while parametrically varying gingival-horizontal lengths and vertical displacement. The resulting qualitative and quantitative data will aid in effective appliance selection and design.

MATERIALS AND METHODS

All of the loops (Fig. 1) were fabricated from 0.25 x 0.53 mm (0.010 x 0.021 in), 18-8 stainless steel wire. The parametric variations of gingival-horizontal length were 6, 10, 14 and 18 mm for the T-loop, and 6, 8, 10, and 12 mm for the L-loop and rectangular loop. Loop height was standardized at 6 mm in all cases. After fabrication all loops were stress relieved at 400°C for three minutes.[12] Four specimens of each configuration were tested in a specially designed apparatus to measure both forces and moments.[13] Uniplanar fixed end moments were obtained from angular displacement transducers and vertical force was measured with a linear variable differential transformer (LVDT). Horizontal force was not measured, but can be computed from the equation of static equilibrium. Another LVDT was used to measure vertical displacement, and its output was plotted against moments and vertical force on an analog X-Y plotter. The system sensitivity is greater than 1 gm in force and 5 gm-mm in moment measurements with a reproducibility error of less than 1%.

Each loop was centered and its ends rigidly fixed at an interbracket distance of 7 mm. Then it was vertically activated 3 mm gingivally and 3 mm occlusally.

The resulting analog plots of spring tester output were read at ±1, ±2, and ±3 mm vertical activation. Finally, mean values and standard deviations of the moments and forces were computed.

RESULTS

The mean values (with their corresponding standard deviations) of all forces and moments acting on the teeth (transducer chucks) are listed in Table I for T-loops, Table II for L-loops, and Table III for rectangular loops. The sign convention used in these tables is defined such that a clockwise moment is positive (as indicated by the arrows). The vertical forces are equal and oppositely directed at each fixed end and therefore listed only once, without sign, in the tables. Table I gives values for

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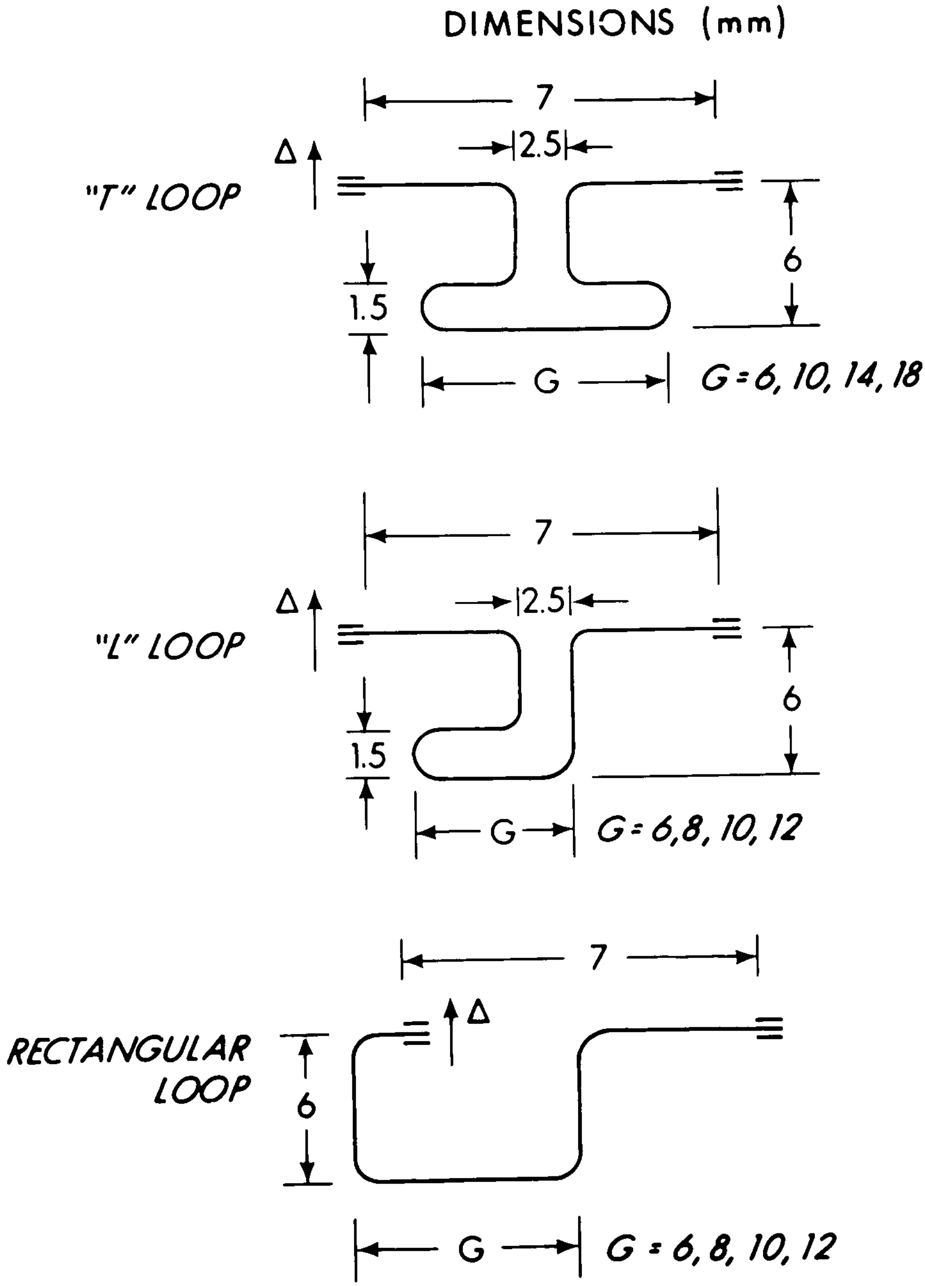
DIMENSIONS (mm)
"T" LOOP
7
2.5
Δ
6
1.5
G
G = 6, 10, 14, 18
"L" LOOP
7
2.5
Δ
6
1.5
G
G = 6, 8, 10, 12
RECTANGULAR LOOP
7
Δ
6
G
G = 6, 8, 10, 12

Fig. 1

TABLE I

Force system on "T" loop.

Δ (mm)	Loading on Wire	G = 6mm	G = 10mm	G = 14mm	G = 18mm
	M_A (gm-mm)		354 ± 20 *	84 ± 13	— 20 ± 8
3	F (gm)		151 ± 2	60 ± 5	40 ± 2
	M_p (gm-mm)		681 ± 12	335 ± 10	230 ± 4
	M_A (gm-mm)		252 ± 13	75 ± 5	8 ± 5
2	F (gm)		93 ± 2	39 ± 2	24 ± 2
	M_p (gm-mm)		402 ± 8	195 ± 5	136 ± 2
	M_A (gm-mm)	341 ± 9	139 ± 7	49 ± 2	15 ± 3
1	F (gm)	102 ± 1	46 ± 1	18 ± 2	11 ± 1
	M_p (gm-mm)	378 ± 11	177 ± 5	84 ± 2	60 ± 2

* mean ± standard deviation

TABLE II

Force system on "L" loop.

Δ (mm)	Loading on Wire	G = 6mm	G = 8mm	G = 10mm	G = 12mm
	M_A (gm-mm)	663 ± 28 *	359 ± 40	187 ± 16	124 ± 14
3	F (gm)	179 ± 5	90 ± 13	51 ± 5	34 ± 2
	M_p (gm-mm)	902 ± 30	641 ± 58	429 ± 15	315 ± 18
	M_A (gm-mm)	487 ± 20	273 ± 27	148 ± 12	105 ± 11
2	F (gm)	126 ± 4	66 ± 9	38 ± 2	25 ± 2
	M_p (gm-mm)	585 ± 22	407 ± 35	260 ± 9	192 ± 12
	M_A (gm-mm)	271 ± 9	155 ± 13	88 ± 6	62 ± 5
1	F (gm)	65 ± 1	34 ± 5	20 ± 2	14 ± 0
	M_p (gm-mm)	279 ± 7	190 ± 18	116 ± 3	84 ± 6
	M_A (gm-mm)	—330 ± 20	—207 ± 17	—118 ± 7	— 84 ± 7
—1	F (gm)	71 ± 7	41 ± 2	26 ± 3	19 ± 3
	M_p (gm-mm)	—257 ± 19	—148 ± 12	—81 ± 8	— 52 ± 6
	M_A (gm-mm)	—745 ± 50	—477 ± 36	—276 ± 14	—193 ± 15
—2	F (gm)	175 ± 9	105 ± 6	64 ± 7	43 ± 2
	M_p (gm-mm)	—505 ± 19	—280 ± 24	—139 ± 10	— 74 ± 12
	M_A (gm-mm)	—1230 ± 76	—813 ± 56	—459 ± 27	
—3	F (gm)	294 ± 14	194 ± 11	120 ± 6	
	M_p (gm-mm)	—753 ± 36	—397 ± 36	—162 ± 18	

* mean ± standard deviation

positive activations only because of the symmetry inherent in the T-loop. In this case a negative activation causes a reversal of signs on the moments and a transposition of the absolute values of anterior and posterior moments.

Tables I, II, and III list standard deviations which are larger than the accuracy of the spring testing device utilized. This increase is primarily attributable to experimental variability in geometry of the fabricated loops and placement into the testing device.

The tabularized results can be better understood and better utilized by analyzing the qualitative changes in moment to force and moment to moment ratios. Figures 2 through 9 illustrate these ratio changes obtained by varying loop design and activation. A lower left canine and first premolar are sketched in each quadrant of the graphs to aid visualization of the resulting force systems. By convention, clockwise moments on the teeth (illustrated by these figures) are positive.

TABLE III

Force system on Burstone rectangular loop.

Δ (mm)	Loading on Wire	G = 6mm	G = 8mm	G = 10mm	G = 12mm
	M_A (gm-mm)	143 ± 12 *	— 52 ± 12	— 96 ± 12	—101 ± 14
3	F (gm)	148 ± 19	84 ± 5	56 ± 2	39 ± 2
	M_p (gm-mm)	910 ± 29	631 ± 27	461 ± 13	370 ± 17
	M_A (gm-mm)	114 ± 12	— 15 ± 6	— 58 ± 7	— 56 ± 4
2	F (gm)	94 ± 11	57 ± 4	37 ± 1	25 ± 1
	M_p (gm-mm)	592 ± 21	417 ± 17	295 ± 7	240 ± 12
	M_A (gm-mm)	65 ± 4	0 ± 1	— 24 ± 3	— 22 ± 2
1	F (gm)	51 ± 6	28 ± 2	18 ± 1	13 ± 0
	M_p (gm-mm)	218 ± 12	197 ± 7	143 ± 4	115 ± 5
	M_A (gm-mm)	—106 ± 21	— 19 ± 8	0 ± 0	12 ± 8
—1	F (gm)	39 ± 5	23 ± 1	14 ± 0	10 ± 1
	M_p (gm-mm)	—244 ± 3	—167 ± 3	—116 ± 4	— 97 ± 2
	M_A (gm-mm)	—242 ± 47	— 57 ± 12	0 ± 8	24 ± 5
—2	F (gm)	97 ± 7	46 ± 5	26 ± 4	16 ± 2
	M_p (gm-mm)	—472 ± 9	—326 ± 8	—227 ± 7	—192 ± 9
	M_A (gm-mm)	—399 ± 75	—108 ± 32	— 10 ± 16	36 ± 8
—3	F (gm)	156 ± 9	74 ± 6	41 ± 4	27 ± 1
	M_p (gm-mm)	—684 ± 16	—468 ± 14	—329 ± 7	—274 ± 15

* mean ± standard deviation

With only a +1 mm vertical activation the effect of parametrically varying gingival-horizontal length on the moment to force ratio is shown in Figure 2 for T-loops, Figure 3 for L-loops, and Figure 4 for rectangular loops. Figure 5 shows the same effect on moment to moment ratios. Considering only loops with a gingival-horizontal length of 10 mm, the effect of vertical activation on the moment to force ratio is shown in Figure 6 for the T-loop, Figure 7 for the L-loop, and Figure 8 for the rectangular loop. The same effect on moment to moment ratios is shown in Figure 9.

Since the geometry of the various loop designs is increasingly altered with larger activation, each of the designs was compared initially using a small vertical activation of 1 mm. All dimensions were kept constant except the gingival-horizontal length (G).

The T-loop produces forces that intrude the anterior tooth and extrude the posterior tooth. The positive moments are directed to displace the roots mesially for both teeth (Fig. 2). As the "G" dimension of a T-loop becomes small, the anterior moment approaches that of the posterior. In the limiting case where the T-loop becomes a vertical loop, the end moments would be very nearly equal. As the gingival-horizontal dimension increases, the moment displacing the root mesially on the anterior tooth decreases, and the posterior moment increases. In situations where the anterior moment is considered an undesirable side effect, a larger "G" dimension would limit the undesirable tooth movement.

Although for a given "G" dimension the L-loop incorporates similar amounts of wire as the T-loop, the vertical forces of the L-loop are smaller (Tables I and II). Increasing the "G" dimension anteriorly does not affect the M/F ratio at A and increases the ratio at P (Fig. 3). The difference between the end moments in the L-loop does not increase as rapidly with an increasing

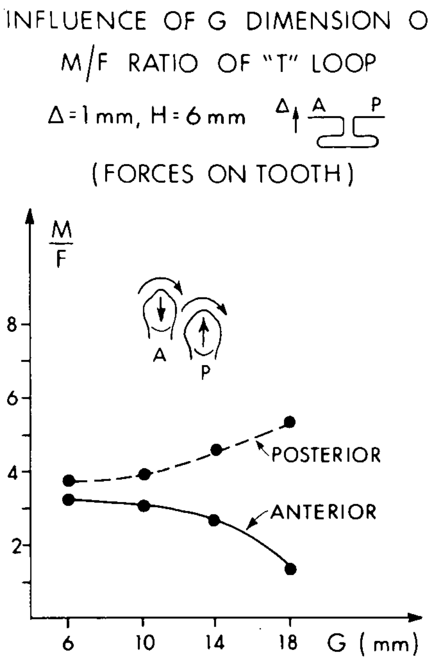

Fig. 2

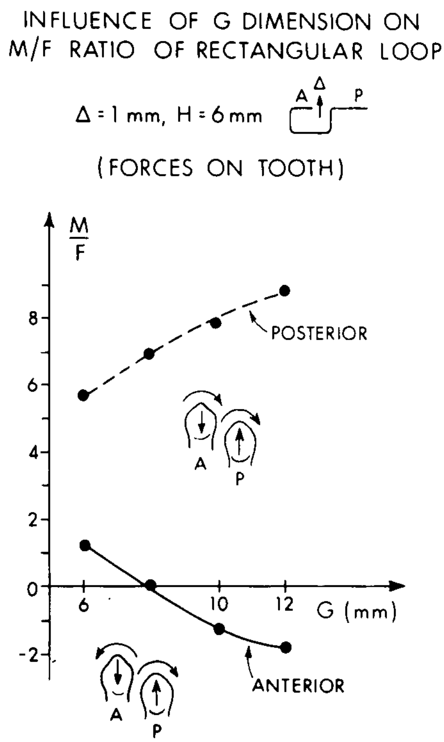

Fig. 4

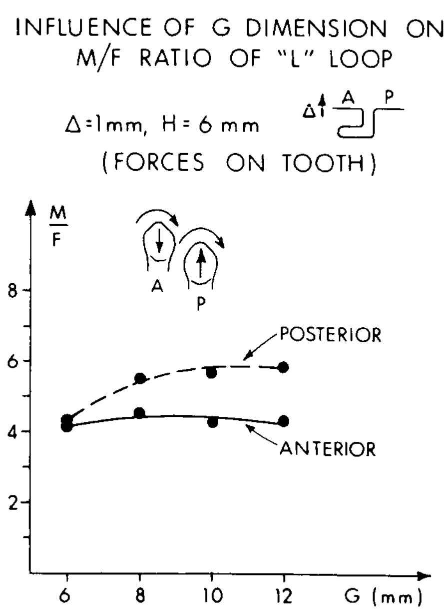

Fig. 3

"G" dimension as does the T-loop. As "G" becomes very small, both anterior and posterior moments approach the same value which is consistent since the limiting case for the L-loop is also a vertical loop.

The rectangular loop can be seen to possess a large moment difference at small "G" values (Fig. 4), unlike the other two designs. It is the loop most sensitive to "G" changes, with both anterior and posterior moment to force ratios strongly affected. The anterior moment is small and changes sign depending on the length of "G". A "G" dimension greater than 8 mm produces a moment tending to displace anterior root distally which is unlike other loops studied.

For a 1 mm activation, there is very little difference in moment to moment ratios between T-loops and L-loops of similar "G" dimension (Fig. 5). For

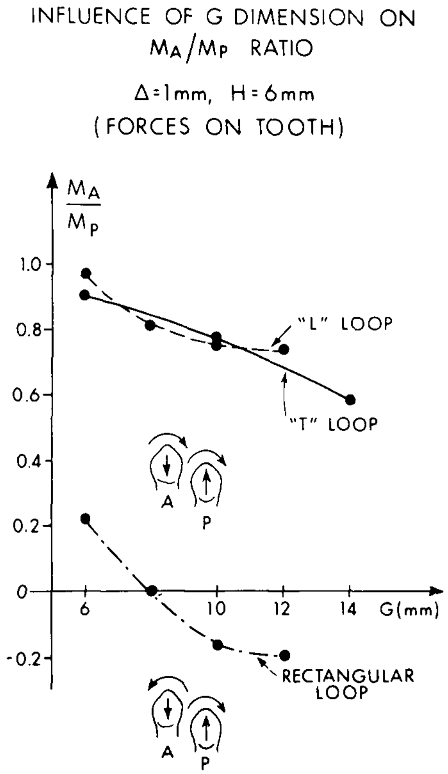

Fig. 5

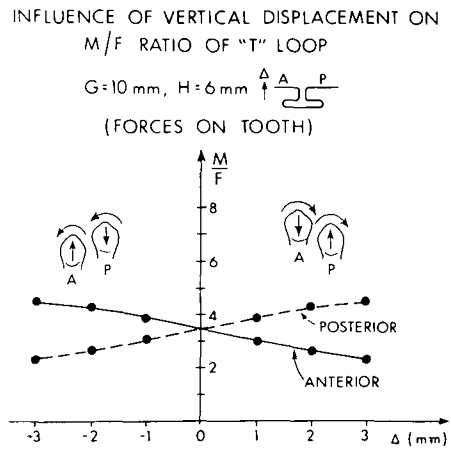

Fig. 6

larger activations, however, this is no longer true. Figure 5 also shows that the anterior moment direction in the rectangular loop can be easily controlled by the design length of "G". In the rectangular loops tested, an 8 mm "G" length produces zero moment at A.

As activation approaches zero in the T-loop, the value of the anterior moment approaches that of the posterior (Fig. 6). The symmetry of T-loop behavior is clearly shown by a comparison of positive and negative activations.

L-loops are dramatically nonlinear as vertical displacement is varied (Fig. 7). The values of the anterior and posterior moments begin equal but diverge quickly with activation and behave differently in the positive and negative directions.

A constant and predictable behavior of moment to force ratios is found in the rectangular loop with respect to activation (Fig. 8). The direction of the anterior moment is opposite to that of the posterior moment for positive activations, but is in the same direction as the posterior for negative activations.

Figure 9 shows the amount of geometric nonlinearity associated with each design. In all cases the ratio of anterior moment to posterior moment decreases with increasing activations. For a given loop design the more horizontal the graph of the moment to moment ratio versus displacement, the more predictable and constant is its force system. The superiority of the rectangular loop is evident.

Discussion

It is emphasized that this investigation considers only orthodontic loops with fixed ends and is therefore valid only for cases in which loop ends are rigid, either by design or by friction. Cases in which loop ends are free to slide horizontally through bracket attachments are not considered herein but are presently under investigation.

The magnitude of the standard deviations (Tables I, II, and III) indicates how sensitive these loops are to errors in fabrication and placement. In all

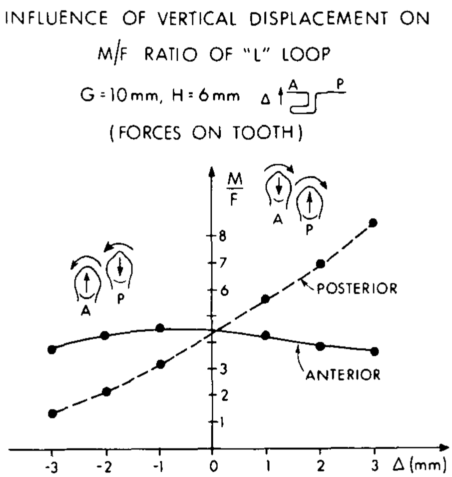

Fig. 7

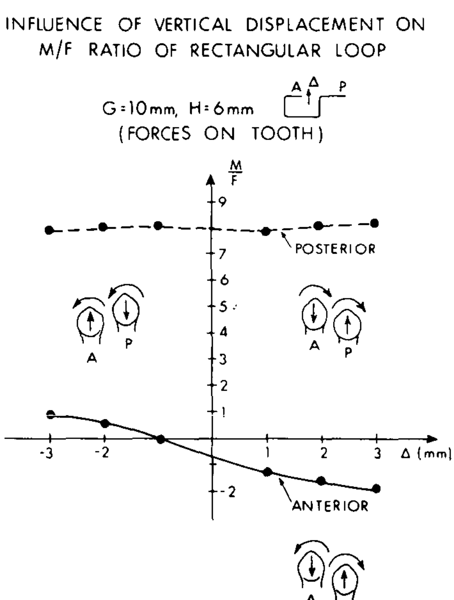

Fig. 8

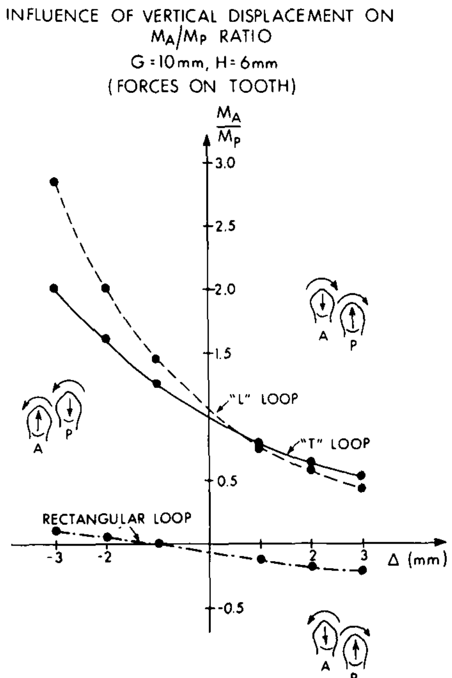

Fig. 9

cases considerably more care was taken than would be clinically practical or attainable. Even so, the standard deviations were at times surprisingly large. This points out a need to design and utilize orthodontic loops that are as forgiving as possible with respect to geometric variations in fabrication and placement to achieve a specific force system.

A most significant and surprising result of this study was the change in qualitative moment and force relations due to geometric nonlinearity. With only small differences in vertical activation the qualitative mechanical behavior of the loops can be significantly altered. Geometric nonlinearity causes differences in anterior and posterior moments, even with the symmetric T-loop. Also attributable to geometric nonlinearity is the differing mechanical behavior of L-loops and rectangular loops when comparing positive and negative vertical activations. An assumption of equal but oppositely directed forces and moments for positive and negative activation would clearly be erroneous.

The nonlinear behavior can be explained in part by careful observation of the activation. The horizontal distance between the brackets is held constant throughout activation, but the actual interbracket distance is increasing as the hypotenuse of the horizontal interbracket distance and the vertical activation. Thus, there are forces and moments associated with the interbracket lengthening which modify the forces and moments due to vertical displacement. This effect is most pronounced with the L-loop. A small amount of interbracket lengthening causes a relatively large anterior moment and a somewhat smaller oppositely directed posterior moment. The moment imbalance causes additional vertical forces. These additional forces and moments are directed such that, for a positive vertical activation, the vertical forces and the anterior moment are reduced, while the posterior moment is increased from the expected linear values. For a negative activation these effects are reversed.

The results have shown that the rectangular loop has the unique capability of being able to control the direction of the anterior moment by parametric changes in the gingival-horizontal dimension and the amount of activation, and that this loop gives the most constant Ma/Mp ratio.

Conclusions

1. Tables I, II, and III can be used as a design tool for fixed ended orthodontic loops. These tabularized results are based on 0.25 x 0.53 mm (0.010 x 0.021 in.) 18-8 stainless steel wire.

2. Geometric nonlinearity is a significant factor in loop mechanics with L-loops being the most affected and rectangular loops being the least affected.

3. Qualitative mechanical loop behavior is a function of the gingival-horizontal loop dimension. It can be advantageously used to control the force system in a rectangular loop.

4. All loops investigated herein are sensitive to fabrication and placement errors. Considerable precision is required to obtain a desired orthodontic force system.

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