3-D experimental identification of force systems from orthodontic loops activated for first order corrections

Chiara Menghi, DDS, MS; Jens Planert, Dr Dr; Birte Melsen, DDS, PhD, Dr.Odont.

Abstract: Intra-arch irregularities can be corrected using wire of low stiffness, wires of increasing stiffnesses, or by the activation of loops built into the appliance. While the orthodontist controls only the magnitude of force when leveling with continuous arches, the configuration and positioning of loops offer the possibility of controlling the type and direction of force. In the present study, force systems developed by the L-loop, the T-loop, and the rectangular (R-) loop were analyzed with respect to the force systems acting for first order irregularities, buccolingual movement, and rotation along the long axis of the tooth. An interbracket distance of 21 mm was chosen, and the loops were analyzed in a testing machine that made it possible to register forces and moments simultaneously in three planes of space. The activations included a symmetrical translation of 1 mm made in steps of .2 mm, corresponding to a buccolingual movement, and 10-degree rotations clockwise and counterclockwise in steps of one degree. Force systems were recorded during activation and deactivation. Loops made of TMA wire delivered 40% of the force delivered by the same loops made of stainless steel wire. The T-loop generated a force system that deviated qualitatively only slightly from that delivered by a straight wire. The L-loop generated a force system that was dependent on orientation; constancy was better corresponding to the anterior part of the loop. It was evident that the rectangular loop was capable of generating any desired moment-to-force ratio, and the R-loop demonstrated a high degree of constancy of the force system. Rectangular loops should, therefore, be preferred for making first order corrections.

Key Words: Wires, Loops, First order correction, Force system

Intra-arch tooth alignment is an important part of most orthodontic treatment. In the so-called straight-wire approach, potential alignment in first, second, and third order is built into the bracket slot.[1-2] As a result, the teeth can be displaced to their ideal positions if a full-size wire is inserted. The introduction of superelastic wires has facilitated the rapid replacement of undersized wires with full-size wires during the course of treatment, thereby taking advantage of the bracket design.[3-7]

Despite these qualities, it is well known that preadjusted brackets do not solve all problems. It is often forgotten that straight-wire leveling occurs as a consequence of a force system that is outside the orthodontist's control. This system is a consequence of the mutual positions of individual teeth and is influenced by friction as the wires slide through the brackets. The teeth may thus end up aligned, but with a plane of occlusion not in agreement with the treatment goal.

The force system developed in relation to different types of tooth positioning was described in the classic paper by Burstone and Koenig[8] on forces from an ideal arch. Burstone[9] also demonstrated the side effects of the straight-wire approach and showed how straight-wire leveling is dangerous if no differentiation is made between the active and passive units. One way of generating a predefined force system is by using loops as part of free-end mechanics, i.e., not bent into a continuous arch but either part of a cantilever or added to a bypass.

Loops are also useful for final detailing. Marked biological variation within the same type of teeth[10-11] and difficulties in perfect seating of the brackets[12] make some detailing necessary. By varying the design and position of minor bends, Burstone and Koenig[13] showed how the desired combination of moments and forces could be obtained for a specific tooth movement.

If the only discrepancies to be corrected are small ones, minor bends—such as steps and V bends—can theoretically be used to deliver any moment-to-force ratio on one side of the bend.[13-14] In the case of a small interbracket distance, the location of the V bend is so critical that the force

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system generated may be practically uncontrollable; insertion of loops makes it easier to produce the necessary activation for a special force system. Whenever a major correction in any plane of space is necessary, loops are needed for several reasons: to lower the load-deflection rate, to eliminate friction, to deliver a predictable force system with respect to the moment-to-force ratio, and to dissociate forces and moments.[15-16]

Loops introduced for leveling purposes are best used in free-end mechanics; a vast number of different configurations have been described, but the three prototypes described by Vanderby et al.[17] have attracted the most interest. These loops were studied analytically,[15,16,18] but experimental data are needed in order to establish clinical usefulness.

The force system developed by a multiple-loop archwire during horizontal (first order) and vertical (second order) displacements was analyzed by Waters.[19] The results were later checked experimentally by Brown.[20] Both investigators focused on the influence the relative size of the loop components had on the stiffness of the appliance, but without considering the moments developed at the extremities of the looped span; the papers focused on loops bent into a continuous arch.

The force-deflection characteristics of two unusual types of multiple-loop archwires, including modified vertical loops, were investigated by Waters and Ward,[21] using a theoretical approach based on simple beam theory with regard to radial (first order) and vertical (second order) displacement. This approach was also used by Cavino and Waters[22] in their analysis of the stiffness of multiple loops used for rotation (first order) and mesiodistal tipping (second order).

A complete description of the force systems developed by different loop configurations in first order corrections has not been published.

Table 1A
Method error related to determination of forces compared with a known load in the direction of the x-, z-, and y-axes

True load gm	Fx2 Measurement diff. %	Fz1 Measurement diff. %	Fz2 Measurement diff. %	Fy2 Measurement diff. %
10.12	-8.7	11.1	2.4	2.4
24.37	-3.7	8.7	-1.0	-1.0
35.67	-5.1	7.4	-2.6	-2.6
75.48	-6.2	6.5	-2.8	-2.8
134.07	-2.2	8.0	-1.0	-1.0
210.67	-3.7	7.9	-1.0	-1.0
248.55	-1.2	7.8	-2.9	-2.8

Table 1B
Method error related to determination of moments around the x- and y-axes calculated on the basis of a known distance and a known load

Calculated moment	Mx1 Measurement diff. %	Mx2 Measurement diff. %	My1 Measurement diff. %	My2 Measurement diff. %
202.4	3.5	6.5	-7.6	0.2
487.4	1.0	-0.5	-8.2	1.1
713.4	-0.1	-3.7	-5.2	-2.7
1509.6	-0.6	-8.3	-7.5	-2.1
2681.4	-0.8	-6.8	6.7	-2.8
4213.4	-0.7	-5.9	-7.3	-3.5
4971.0	-0.6	-6.6	-7.5	-6.0

Table 2
Load-deflection rate (gm/mm) of forces during buccolingual translation

Config.	Material	Fz - gm/mm x	sd	95%
L-loop	SS	61.7	0.41	60.8 - 62.4
	TMA	23.7	0.38	22.9 - 24.5
T-loop	SS	69.1	0.44	66.2 - 69.5
	TMA	23.4	0.22	23.0 - 23.8
R-loop	SS	36.7	0.26	38.2 - 39.2
	TMA	15.2	0.23	14.8 - 15.7

The aim of this investigation was to establish experimentally a three-dimensional description of the force systems delivered by three different loop configurations and two types of material when subjected to first-order activations.

An attempt was made to answer the following questions: How does material affect the force system? and How does configuration of the loops affect the force system?

Materials and methods

Three loop configurations were chosen: T-, L-, and R- (rectangular) loops. Two materials were also tested: stainless steel (SS) and beta titanium (TMA), both of nominal cross-section .017 x .025. All the loops of the same material originated from the same batch of wire.

Ten specimens of each configuration and material combination were fabricated with the aid of a loop-forming board.[23] Loop height and gingival-horizontal length were standardized in all cases at 6 mm and 8 mm, respectively.

All the loops were tested in an orthodontic testing machine (FSI system, Figure 1) equipped with special sensors.[24] The FMS (Force Moment System) is based on the transformation of forces and moments into electrical impulses by means of 16 strain gauges.[25,26] The FSI system uses six incremental motors that control the rotation or translation of two sensors in relation to each other within predetermined intervals. The precision of the testing machine in recording forces and moments was evaluated through calibration by means of known loadings in all three planes of space (Table 1).

In the present investigation, L- and T-loops were centered with the ends rigidly fixed with a screw mechanism at an interbracket distance of 21 mm (Figure 2). This distance was chosen to facilitate comparison with forces developed from straight wire, as described by Burstone and Koenig.[8] The distance is also similar to the average molar-canine distance.

In the case of the rectangular loops, the end facing the rectangle was fastened to a mandibular incisor bracket (.018 edgewise, 0° torque, 0° angulation) with a double metallic ligature (one for the mesial wing, one for the distal). The 21-mm distance was then measured to the center of the brackets, which also coincided with the middle of the free arm of the rectangular loop. The middle point was marked to check for sliding during the test.

Each loop was subjected to simulations of first-order corrections in randomly chosen order. The displacements were translation along the z-axis (in-out displacement) and rotation around the y-axis (Figure 2E-F). These two types of displacement occur clinically when a tooth is displaced buccally or lingually (z translation), or when a tooth is rotated mesially or distally around its

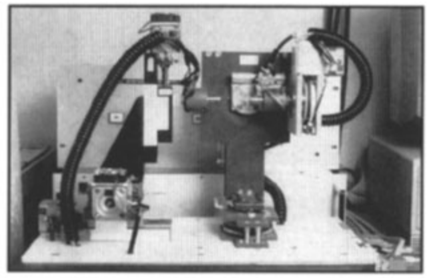


Figure 1
Testing machine for force system identification and measurements

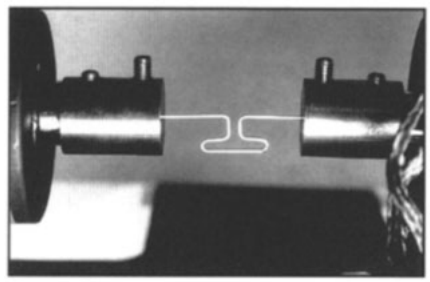


Figure 2A

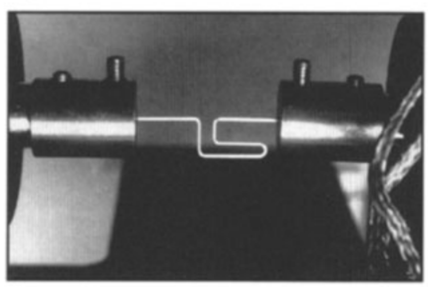


Figure 2B

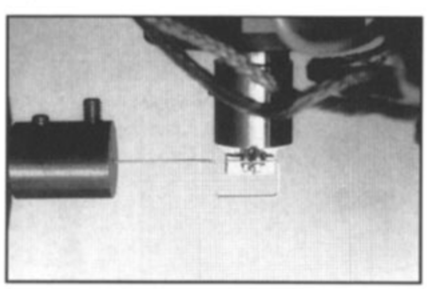


Figure 2C
A-C: Individual setups of three loops in the testing machine

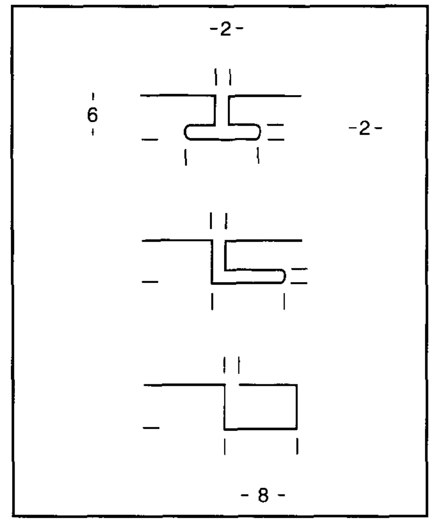


Figure 2D
Dimensions in millimeters of individual loops

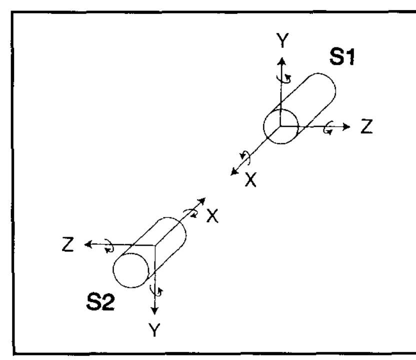


Figure 2E
Axis used in for T-loop and L-loop

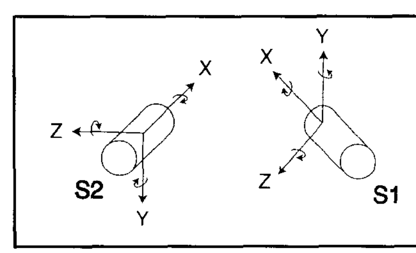


Figure 2F
Axis used for R-loop

long axis (y rotation).

Translation was performed in the interval between -1 and +1 mm, as follows: from 0 (start position) to -1 in five steps; from -1 to +1 in ten steps; and from +1 to 0 in five steps. A total of 20 readings was taken. Rotation was done in the interval between -10 and +10 degrees as follows: from 0 to -10 in five steps; from -10 to +10 in ten steps; and from +10 to 0 in five steps, for a total of 20 readings. Forces and moments were measured 5 seconds after each activation.

In each position the sensors measured forces and moments in three planes of space at both ends of the loop for a total of six forces (fx1, fx2, fy1, fy2, fz1, fz2) and six moments (mx1, mx2, my1, my2, mz1, mz2). All

Table 3
Change in moments (cNmm/degree) in relation to activation for first order buccolingual translation

			Mx / degree			My / degree		
			x	sd	95%	x	sd	95%
L-loop	SS	S1	243.71	4.30	235.19 - 252.24	635.04	7.34	620.50 - 649.59
		S2	-247.36	2.95	-253.21 - -241.51	-539.85	5.74	-551.22 - -526.48
	TMA	S1	91.41	12.34	66.96 - 115.84	255.67	11.97	231.96 - 279.38
		S2	- 91.68	4.73	-101.06 - - 82.30	-221.28	3.25	-227.73 - -214.84
T-loop	SS	S1	273.63	4.02	265.68 - 281.59	797.23	7.89	761.60 - 812.85
		S2	-261.92	2.52	-266.91 - -256.92	-499.34	3.90	-570.08 - -491.62
	TMA	S1	94.98	2.20	90.63 - 99.33	273.01	5.94	261.22 - 284.81
		S2	-88.95	2.47	- 93.85 - - 84.05	-174.27	3.36	-180.92 - -167.62
R-loop	SS	S1	123.12	5.65	111.92 - 134.33	-108.68	6.81	-122.18 - - 95.19
		S2	-137.74	3.31	-144.30 - -131.18	-527.96	6.24	-540.32 - -515.60
	TMA	S1	40.27	4.50	31.36 - 49.16	- 31.47	8.02	- 47.35 - - 15.60
		S2	- 52.80	2.63	- 58.01 - - 47.59	-202.60	3.33	-209.20 - -196.00

values were saved in a Statistical Analysis System (SAS) file. For each type of activation, six force-translation and six moment-rotation graphs were created. As mechanical equilibrium exists in the system, the selection of graphs was based on the following considerations: The forces along the same axis are equal and opposite, thus the intensity of the force was read only at one sensor. For each type of activation, the values of some parameters did not change significantly from zero during the deformation, e.g., force in y direction during z translation; these parameters were discarded.

The following parameters remained: fz1, mx1, mx2, my1, my2, mz1, mz2. For each displacement value of the selected parameters, the mean, standard deviation, the upper and lower 95% percentiles of the deflection were produced for each of the 20 readings on ten sets of measurements. A linear regression analysis was applied and the average force-deflection and moment-deflection rates were expressed. The values expressing the slope were compared with a Student's t-test.

Table 4
Load-deflection rate (gm) of forces during first order rotation

Config.	Mat.	Fz - gm/degree x	sd	95%
L-loop	SS	9.12	0.03	9.10 - 9.21
	TMA	3.46	0.02	3.42 - 3.50
T-loop	SS	12.05	0.05	11.95-12.15
	TMA	4.03	0.04	3.95 - 4.10
R-loop	SS	3.11	0.03	3.05- 3.17
	TMA	1.16	0.02	1.12- 1.20

Results

The method error related to the testing machine varied between 0% and 11% and was relatively higher in the case of the smallest loading (10.12 grams, Table 1). The method error related to registration of moments was of the same magnitude. None of the method errors could be considered of any consequence for the final results because interloop variations were considerably larger. Force- and moment-displacement curves from the stainless steel loops were 2.5 to 3 times steeper than those of the TMA loops. All the other features of the plots were the same across wire materials. In the following description of the force- and moment-displacement curves, only values from the stainless steel loops are discussed (Tables 2 to 5).

Translation along the z-axis (buccolingual movement): In this type of displacement the values of forces and moments were the same at activation, corresponding to -1 and +1 mm. The deflection was symmetrical with respect to the initial plane of the undeformed loop.

The fz1 load-deflection rates differed significantly among the three configurations (Table 2). The lowest stiffness was found in the case of the R-loop, with an fz1 value of 36.7 gm/mm at -1 mm of activation, followed by the L-loop, with 61.7 gm/mm, and by the T-loop, with 69.1 gm/mm (Figure 3).

The moments were largest around the y-axis when measured at sensors 1 (my1) and 2 (my2). They were opposite but different for the L-loop and equal and opposite for the T-loop, but when the R-loop was activated, the moments were different but had the same sense. In the test position for the R-loop, the y1- and y2-axes have the same orientation, Figure 3, Table 3. For all configurations there was a significant differ-

Table 5
Change in moments (gm-mm/degree) in relation to activation for first order rotation

			Mx / degree			My / degree		
			x	sd	95%	x	sd	95%
L-loop	SS	S1	-32.7	0.60	31.49 - 33.69	-135.97	1.12	133.76 - 138.19
		S2	35.56	0.35	34.98 - 36.25	38.69	0.45	38.00 - 39.79
	TMA	S1	-12.52	0.53	11.47 - 13.56	-52.41	0.54	-51.33 - -53.48
		S2	13.01	0.30	12.41 - 13.61	17.29	0.40	16.49 - 18.09
T-loop	SS	S1	-45.01	0.22	-45.45 - -44.56	-182.57	1.05	-184.65 - -180.49
		S2	45.01	0.41	44.22 - -45.85	-47.05	0.51	46.03 - 48.06
	TMA	S1	-15.28	0.31	-15.90 - -14.66	-60.66	0.62	-61.88 - -59.43
		S2	15.39	0.32	-14.76 - -16.03	16.76	0.36	16.07 - 17.49
R-loop	SS	S1	12.76	0.44	1.89 - -3.63`	-67.38	0.49	-68.36 - -66.40
		S2	-14.44	0.25	-14.93 - -13.95	8.67	0.34	8.01 - 9.34
	TMA	S1	0.90	0.41	0.08 - -1.71	-26.19	0.57	-27.33 - -25.06
		S2	-4.76	0.25	-5.27 - -4.25	3.44	0.56	2.32 - 4.55

ence between the absolute values of the moment-rotation rates registered at sensors 1 (my1) and 2 (my2). In the case of the L- and T-loops, my1 was larger than my2, whereas the opposite was observed in the case of the R-loop. Small moments around the x-axis were also observed, equal and opposite for all configurations (Figure 3).

Rotation around the y-axis was done to simulate the force system developed in relation to correction of a dental rotation. The forces developed were equal and opposite when activating -10 and +10 degrees. The load-deformation rates for fz1 were significantly different for the three configurations. The T-loop exhibited the highest stiffness and the R-loop exhibited the most constant force system (Table 4, Figures 4 to 6). The moments around the y-axis likewise differed significantly between sensors 1 and 2 and varied among the three configurations. The moment generated at sensor 1 (my1) was much larger than the moment registered at sensor 2 (my2). Change in moment per degree of activation is shown in Table 5. The moments around the y-axis at sensor 1 reached 1372 gram-mm for the L-loop, 1812 gram-mm for the T-loop, and 744 gram-mm for the R-loop.

Small moments around the x-axis were observed. These moments were equal and opposite in the case of the T-loop, but differed slightly in the case of the L-loop. For the R-loop, the moment at sensor 1 was smaller than the one measured at sensor 2 (Figure 6).

Discussion

Comments on the method

The calibration of the sensors revealed that sensitivity was highly related to the magnitude of the value measured, the relative error being significantly larger in the case of a small loading. From a clinical perspective, the errors were of a magnitude that was not relevant because intracon-figuration variation was significantly larger. The magnitudes of the standard deviations indicate how sensitive these loops were to variations in fabrication and placement. Considerably greater care was taken in the experiment than would be clinically practical or attainable. Even so, the standard deviations were, at times, surprisingly large. This outcome means that, in an actual clinical situation, which is never as controlled and standardized as the in vitro conditions, a wider range of variation must be expected, together with the possible occurrence of unpredicted forces and moments. The standard deviation was related to the type of loop configuration, being smallest in relation to the R-loop.

Comments on the alloy used

Loops can be produced only in wires of alloys characterized by a considerable plastic range, limiting the choices to stainless steel and beta titanium. The comparison of the stainless steel and TMA loops confirmed that TMA loops generated force- and moment-deformation curves with regression coefficients that were 2.5 to 3 times smaller than those of comparable stainless steel loops.[27,28] This finding was in agreement with the relative values of the modulus of elasticity for the two materials[27] and with the elastic-properties ratios of orthodontic archwires presented in the monograms by Kusy.[28]

The force- and moment-deflection curves for TMA loops had the same characteristics as the corresponding graphs from the stainless steel loops, but exhibited a relatively wider range of variation. The variation coefficient (SD/mean) of the regression coefficient for the slope of these curves was thus higher for the loops made of TMA.

Several factors related both to the thermomechanical processing of the wire and the larger elastic range, which required a different bending technique, could contribute to the explanation of this variation.[29] The TMA loops would, despite this variation, be preferable due to their larger range and more constant force delivery. This implies that the requirements for precision in bending and activations were lower for the TMA loops than for the corresponding loops in stainless steel.

The load-deflection curves

The activation for translation would, in the case of a straight wire, result in a force system corresponding to a geometry I that, according to Burstone and Koenig,[8] is characterized by two opposite and identical forces and two identical moments rotating the two teeth in the same direction. Any deviation from this force system is the result of the loop configuration. It was obvious that the deviation from the straight-wire force system was smallest in the case of the T-loop and largest in the case

Figures 3-6
Force-deflection and moment-deflection curves for individual tests. The following abbreviations are used: T, L, and R for the loop type; followed by ss (stainless steel) or tma (beta titanium) for the material type; followed by either T (translation) or R (rotation) for the displacement type. Abbreviations in the second row indicate whether the measurements are forces (f) or moments (m) and at which sensor the registrations are performed. Each test was repeated 10 times and the range is indicated on the graphs for each measurement position.

Figure 3A-J
Forces and moments developed during the first order translation of the L-, T-, and R-loops, all formed in .017" x.025" TMA wire.

Figure 4A-E
Forces and moments developed during first order rotations of stainless steel rectangular loops.

Figure 5A-E
Forces and moments developed during first order rotations of stainless steel T-loops.

Figure 6A-E
Forces and moments developed during first order rotations of stainless steel L-loops.

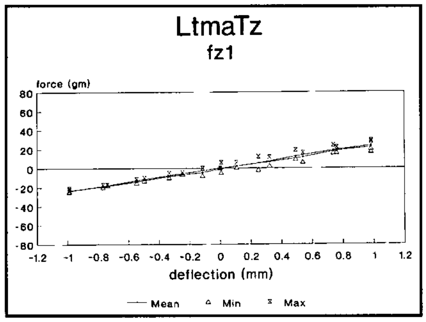


Figure 3A

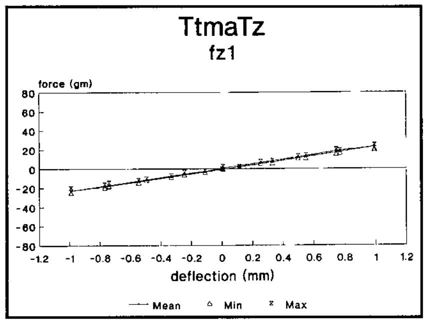


Figure 3B

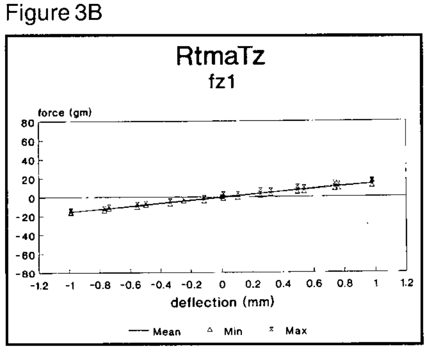


Figure 3C

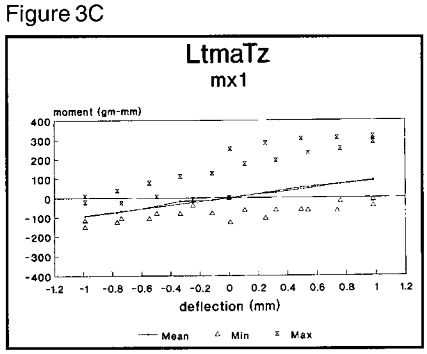


Figure 3D

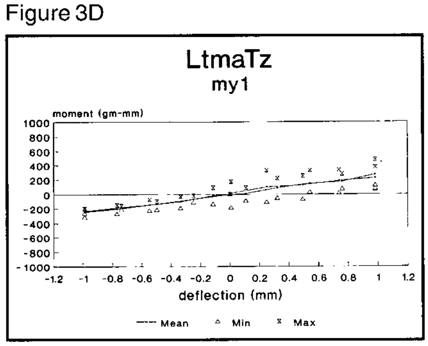


Figure 3E

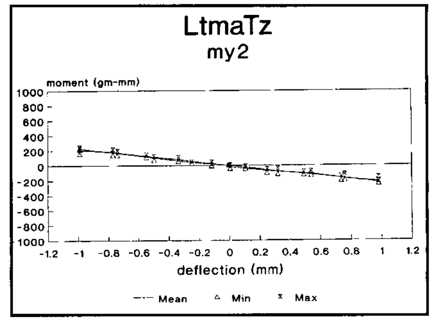


Figure 3F

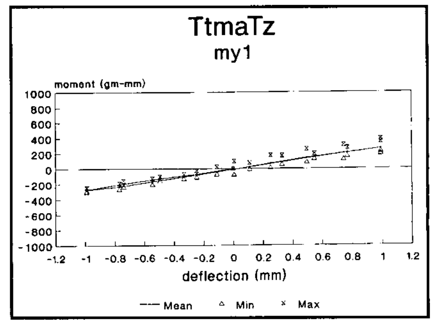


Figure 3G

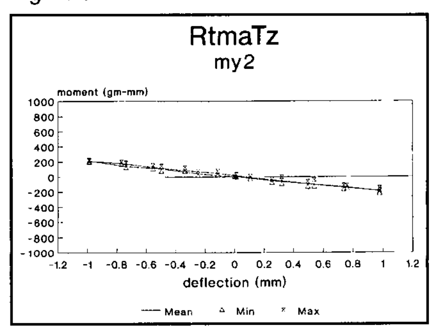


Figure 3H

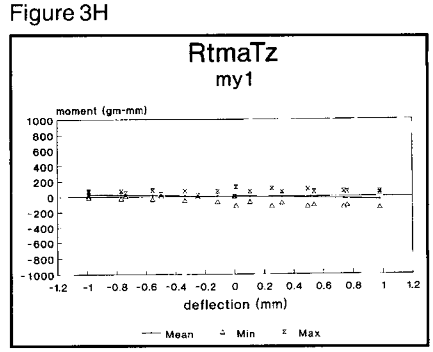


Figure 3I

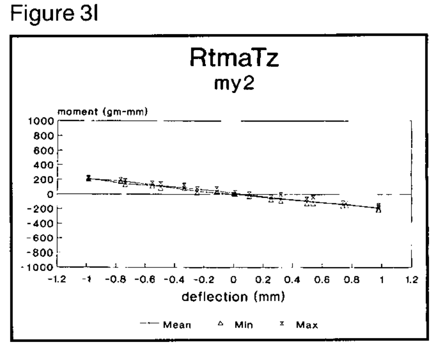


Figure 3J

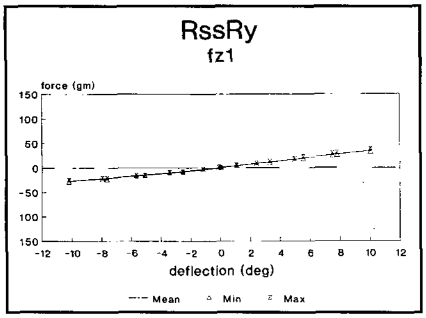


Figure 4A

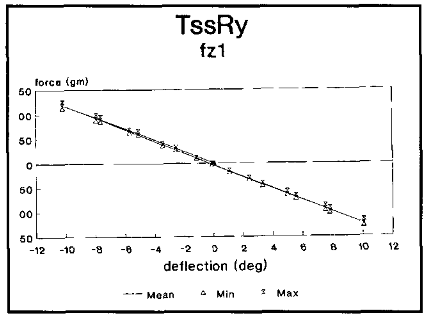


Figure 5A

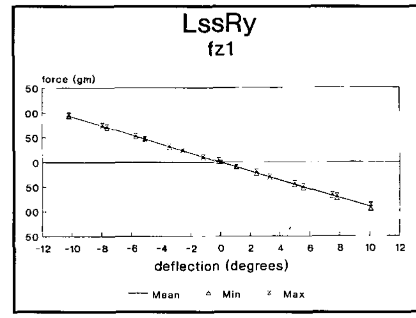


Figure 6A

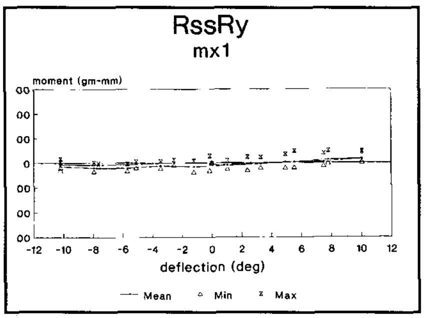


Figure 4B

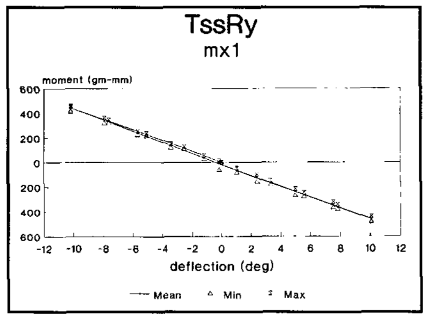
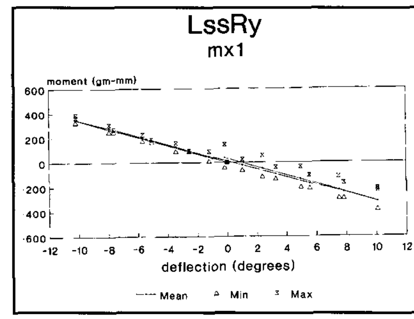


Figure 5B



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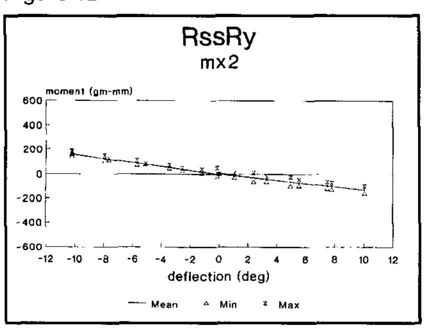
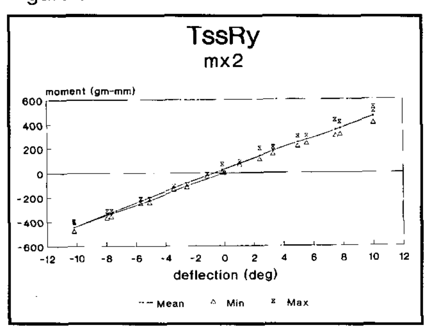


Figure 4C



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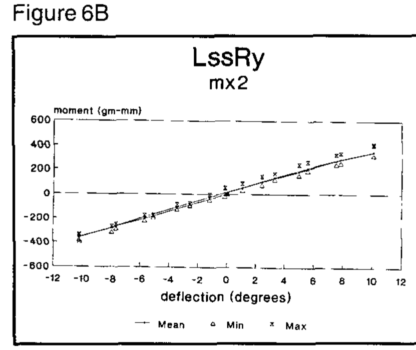

Figure 6C

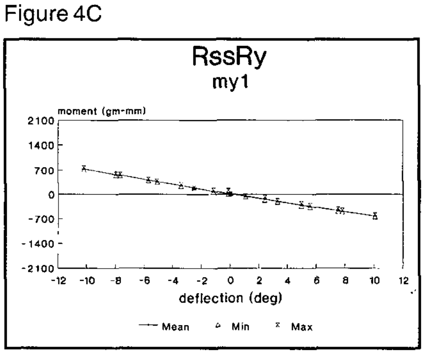

Figure 4D

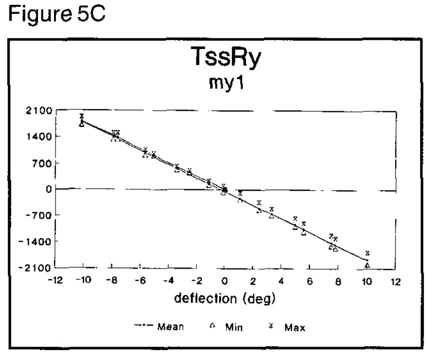

Figure 5D

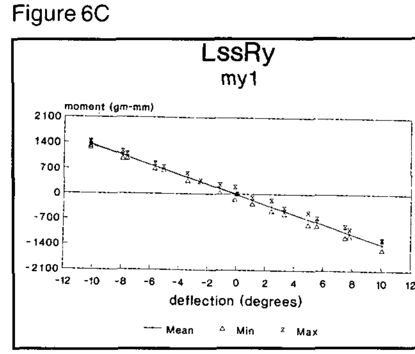

Figure 6D

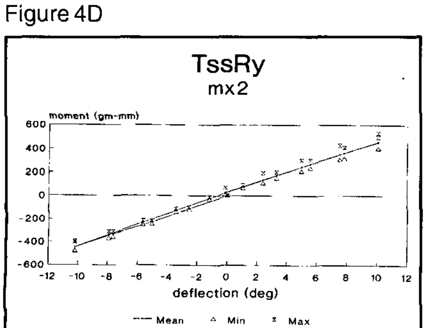

Figure 4E

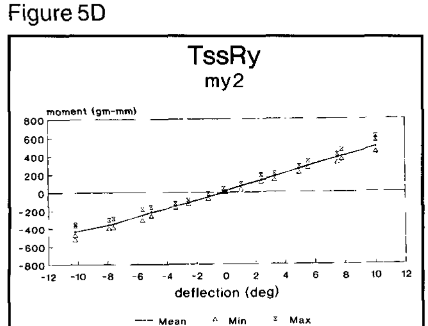

Figure 5E

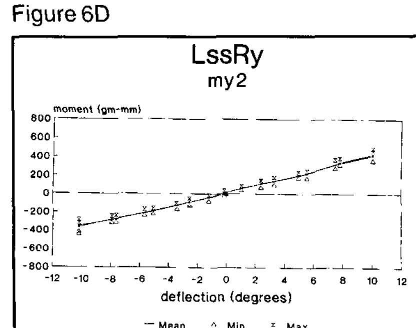

Figure 6E

of the R-loop. The insertion of a T-loop would primarily lower the load-deflection rate whereas the R-loop makes it possible to generate any moment-to-force combination to one of the two included units. The force system delivered to the other unit would be the one necessary to establish mechanical equilibrium.

In the case of activation for rotation, the force system developed by a straight wire would correspond to a geometry VI, i.e., two equal and opposite moments, and the deviation from this force system would reflect the loop configuration. Although insertion of loops leads to the development of a force system deviating significantly from that of a straight wire, this deviation was much more pronounced in the case of rotation of one of the units. As in the case of translation, the smallest deviation was found in the case of the T-loop, and the largest was developed by the rectangular loop. In the analysis of the rectangular loop the point of force application is also of crucial importance. De Franco et al.[16] described the possibility of disassociation between force and moment based on an analytical model. This facility makes it possible for the clinician to develop the exact force system desired for the active unit. In addition, it allows for a high degree of constancy of the force system, especially with respect to the active unit.[17] It should, however, be recognized that the price of the changes caused by undesirable force system is paid by the reactive unit, which therefore has to consist of a large, rigid anchorage assembly.

The force systems developed by loops reflect the wire distribution, and are thus also dependent on the interbracket distance and the relative positions of the loops. The point of disassociation of a loop is defined as the point to which the forces and moments developed relative to the loop are disassociated, i.e., a change in moment does not necessarily correspond to a change in force. This point also reflects that the stiffness of the wire is identical on both sides of the bracket.[16] This is the case if the interbracket distance corresponds to the horizontal length of the R-loop and at an interbracket distance corresponding to approximately one-half the horizontal dimension of the L-loop. The latter would, however, be nearly impossible as it would require a very small interbracket distance or a very large horizontal extension of the loop. The principle of disassociation is, therefore, best used in relation to the R-loop.[20,21] These possibilities have not been approached in the present study, where neither the interbracket distance nor the loop position varied. Clinically the experiment resembles that of an intrasegmental alignment in the case of a segmented-arch approach. Even under these test conditions it was obvious that the requirements for constancy of the force system were best met by the R-loop, as changes in the degree of activation resulted in only modest changes in the force system delivered.

Conclusions

The present study showed that the insertion of loops for correction of first order discrepancies are best done by the R-loop, followed by the L-loop. The orientation of the loops should be carefully considered before insertion, and the difference in force systems developed at the two ends should be taken into consideration.

Acknowledgments

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