

Load system of segmental T-loops for canine retraction

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Introduction: The orthodontic load system, especially ideal moment-to-force ratios, is the commonly used design parameter of segmental T-loops for canine retraction. However, the load system, including moment-to-force ratios, can be affected by the changes in canine angulations and interbracket distances. We hypothesized that clinical changes in canine position and angulation during canine retraction will significantly affect the load system delivered to the tooth. **Methods:** The load systems of 2 T-loop groups, one for translation and the other for controlled tipping, from 9 bilateral canine retraction patients were made to the targeted values obtained from finite element analyses and validated. Each loop was tested on the corresponding maxillary dental cast obtained in the clinic. The casts were made before and after each treatment interval so that both initial and residual load systems could be obtained. The pretreatment and posttreatment interbracket distances were recorded for calculating interbracket distance changes. **Results:** As the interbracket distances decreased, the average retraction-force drop per interbracket distance reduction was 36 cN/mm, a 30% drop per 1 mm of interbracket distance decrease. The average antitipping-moment drops per interbracket distance reductions were 0.02 N-mm per millimeter for controlled tipping and 1.4 N-mm per millimeter for translation, about 0.6% and 17% drops per 1 mm of interbracket decrease, respectively. Consequently, the average moment-to-force ratio increases per 1 mm of interbracket distance reduction were 1.24 mm per millimeter for controlled tipping and 6.34 mm per millimeter for translation. There was a significant residual load, which could continue to move the tooth if the patient missed the next-scheduled appointment. **Conclusions:** Clinical changes in canine position and angulation during canine retraction significantly affect the load system. The initial planned moment-to-force ratio needs to be lower to reach the expected average ideal value. Patients should be required to follow the office visit schedule closely to prevent negative effects because of significant moment-to-force ratios increases with time. (Am J Orthod Dentofacial Orthop 2013;144:548-56)

Segmental T-loops are used in maxillary canine retraction. The resulting orthodontic load (force and moment) system on the canine is affected

by multiple factors, including changes in interbracket distance and tooth angulations.¹⁻³ However, the changes in the clinical load system that occur simultaneously with canine movement have not been quantified. Different load systems, especially small differences in moment-to-force ratios (M/F), result in different tooth movement patterns: tipping or translation.^{4,5} It is important to quantify the load changes for predicting the treatment effects and preventing potential side effects. We hypothesized that clinical changes in canine position and angulation during canine retraction will significantly affect the load system delivered to the tooth.

An orthodontic load system is 3 dimensional (3D) and consists of 3 force and 3 moment components. It is difficult to measure the entire 3D orthodontic load system clinically. Therefore, it has been investigated primarily in laboratory settings by using archwires placed on dental casts⁶⁻⁸; numeric estimations, such as the Loop simulation software (dHAL Software, Kifissia, Greece)⁹⁻¹²; or the finite element method.^{13,14} Vicilli¹² simulated

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All authors have completed and submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest, and none were reported.

Supported by the NIH/NIDCR under grant number 1R01DE018668.

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Submitted, January 2013; revised and accepted, May 2013.

0889-5406/\$36.00

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<http://dx.doi.org/10.1016/j.ajodo.2013.05.007>

the effect of changes of the canine position and angulation on the M/F. The study was 2-dimensional and based on ideal rotation. Despite the clinically applicable information acquired, these studies were mostly conducted on ideal dentures, and the changes of the load systems of individual patients during tooth movement have not been considered.

To better understand how the load system affects tooth movement clinically, the load components and their changes during clinical treatment need to be quantified. The objectives of this study were to monitor the clinical load systems on the canines undergoing retraction and to quantify the effects of the movement pattern on the load components.

MATERIAL AND METHODS

Customized segmental T-loops were designed and fabricated to retract the canines with tipping or translation. Measurements of force and moment components, and the M/F, were made by using models obtained from the patient at different times, with a custom-made orthodontic force tester. Interbracket distances and the initial and residual load components before and after canine retraction were quantified to investigate changes of the load system during canine retraction.

After approval by the institutional review board of Indiana University, 9 patients consented for this study. The inclusion criteria were (1) need for extraction of both maxillary first premolars and (2) a possible indication for maxillary canine retraction during treatment. The average age of these patients was about 21 years (range, 14–47 years). The maxillary first premolars were extracted, and the maxillary dental arch including the second molars was bracketed, leveled, and aligned with sequential archwires. Before canine retraction, a 0.019×0.025 -in stainless steel archwire was fully engaged in brackets with 0.022×0.028 -in slots. The maxillary second premolar, first molar, and second molar were coligated with a 0.010-in stainless steel wire, connected with a transpalatal arch to establish a posterior unit.

For each patient, the right and left canines were randomly assigned to receive controlled tipping or translation orthodontic tooth movements. To accomplish controlled tipping or translation, 2 segmental T-loops, made of 0.017×0.025 -in TMA wire (Ormco, Glendora, Calif), were designed and fabricated to deliver different M/F to retract the canines. The T-loops on both sides were designed to deliver 124 cN of retraction force.¹⁵ The desired M/F for controlled tipping and translation were calculated by using finite element models of the patients, constructed based on cone-beam computed tomography. The maxillary image was taken before the

canine retraction using an i-CAT device (Imaging Sciences International, Hatfield, Pa) at the resolution of 0.25-mm voxel size with a scanning time of 27 seconds. For each patient, the raw image data of the cone-beam computed tomography scan were processed using MIMICS software (Materialise, Leuven, Belgium) to create a reconstructed digital model of the teeth, periodontal ligament, and maxillary bone complex. A finite element model was created from the digital model and then imported into ANSYS software (Canonsburg, Pa) to compute the tooth displacement from an orthodontic load. The load consisted of the retraction force and a couple (moment), which were applied at the bracket (Fig 1). The resulting tooth displacement pattern was calculated. The moment was then incrementally increased. The moment and force pairs that create translation and controlled tipping were identified. The details of the modeling were reported previously.¹⁶ M_x/F_y was used to control the distal tipping. The average desired amounts of M_x/F_y of the 9 patients were 7.7 mm for controlled tipping and 10.4 mm for translation.

The interbracket distance was defined as the distance from the mesial aspect of the auxiliary tube of the first molar bracket to the distal aspect of the canine bracket. This was expected to decrease during canine retraction; with it, there would be more decrease in force than moment, resulting in an increase of the M/F. For this reason, measures for initial M/F adjustment needed to be conducted. The M/F increase in the retraction plane per 1 mm of interbracket distance reduction was estimated using the Loop simulation software. An approximately 50% increase in the M/F was estimated per 1 mm of interbracket distance reduction from this analysis. In this study, each treatment period was defined as when a canine was retracted more than 1 mm, measured during each office visit. The interbracket distance changes were expected to vary significantly because of variations in treatment time periods caused by scheduling-related issues. Thus, the total increase of M/F could only be estimated; it was set at 70%. To be consistent, the calculated M/F for translation was decreased by approximately 35% (half of the estimated total M/F increase) to ensure that the average M/F during the treatment period was close to the ideal value. The M/F for tipping was further discounted to enhance the tipping effects. In addition, to prevent mesial out rotation caused by the retraction force, the desired antirotation moment for translating the tooth was also calculated with the same finite element model. M_z/F_y was used to control the tooth rotation. To ensure that the average M_z/F_y was close to the desired value, the implemented initial M_z/F_y was reduced by approximately 35% on both canines to compensate for the effects of interbracket distance

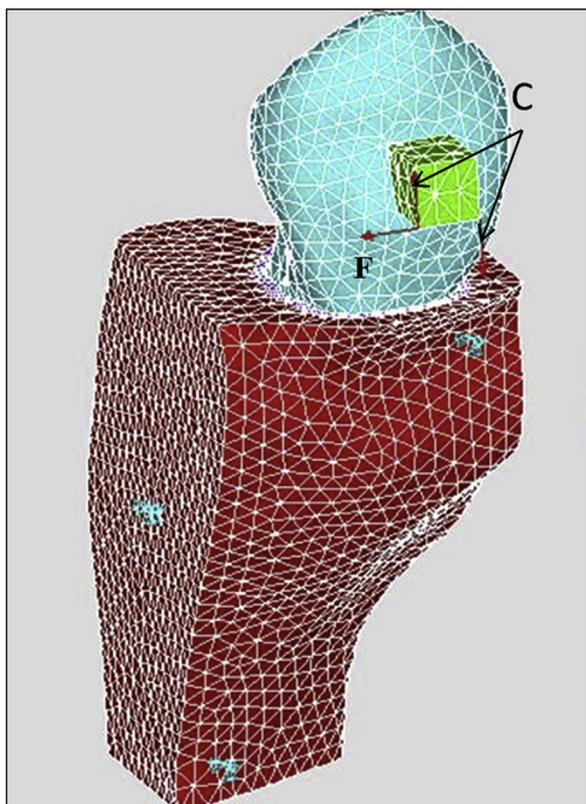


Fig 1. The finite element model of a canine-periodontal ligament-bone complex for estimating the M/F required to translate or tip the canine. A force, F , and a couple, C , were applied at the location of the tube on the bracket. The resulting tooth displacement was calculated. The F and C pairs that produced translation and controlled tipping were selected.

reduction. However, the target M_z/F_y was difficult to achieve because it was primarily realized by adjusting the first-order gable angles. Large gable angles were required in many patients; they caused the T-loop to interfere with the cheek or gum. To prevent interference, only smaller gable angles could be used; they caused M_z to be lower than the target value. The main focus of this study was on translation and tipping. Control of M_z was considered secondary and thus was allowed to be compromised in some subjects. Other load components were kept minimal when the T-loops were produced.

According to the desired load system, the T-loops were bent to express the desired force and moment components. These components were calibrated experimentally on the corresponding dental casts. The casts were prepared using the following protocol. Over the period of canine retraction, the patients were seen every 5 to 6 weeks. A decision was made on whether a treatment interval was completed. A treatment interval was defined

when 1 canine moved more than 1 mm. Thus, multiple intervals might occur for each patient because all patients in this study had more than 3 mm of space between the canine and the second premolar. However, the number of intervals varied among the patients because of the differences in tooth movement rates and durations between office visits. When an interval was completed, an impression was made, the T-loop was retrieved, and a new T-loop was designed and applied. Then the next treatment interval began. The casts were made before and after each interval. At the beginning of each treatment interval, each T-loop was adjusted on the corresponding duplicate acrylic model attached to a custom-made orthodontic force tester to ensure delivering accurate loads.⁶ An impression of the maxillary dental arch was made by injecting light and medium polyvinylsiloxane material (Examix NDS; GC, Tokyo, Japan) over the brackets, followed by an alginate impression. Duplicate canine and first molar brackets with tubes (Burstone; Ormco) were placed in the polyvinylsiloxane, and autopolymerizing acrylics (Repair Material; Dentsply, York, Pa) were packed into the impression and allowed to cure. The acrylic model was attached to the orthodontic force tester with 2 screws. The target teeth (canines) were attached to the load cells with epoxy adhesive (Loctite E-120HP Hysol; Henkel, Rocky Hill, Conn) and then were completely separated from the acrylic model, thus maintaining their original positions and orientations (Fig 2).

After we measured the initial interbracket distances between the canine and molar tubes of the acrylic model, we made a T-loop with the geometry shown in Figure 3. The size, shape, leg length, and dimensions of the T-loops were determined by considering their effects on the load system, as well as preventing interferences with the cheek and gum.² The first-order and second-order gable bends were added symmetrically to the T-loops to bring the load components to the targets (Fig 4). The loop bending and adjustment process was iterated until the desired force and moments were accurately expressed. The horizontal leg was bent on each end of the T-loop to allow easy insertion into the tube. The method also ensured that the interbracket distance was identical when transferred the orthodontic force tester validated T-loop to the patient (Fig 5). The validation was performed on the orthodontic force tester. T-loops were installed on the duplicate acrylic model attached to the orthodontic force tester for testing force and moment components. The orthodontic force tester was designed to measure the orthodontic load system at the canine bracket (Fig 2, A). Two load cells (Multiaxis force/torque Nano17; ATI Industrial Automation, Apex, NC) were used to measure the 6 force and moment

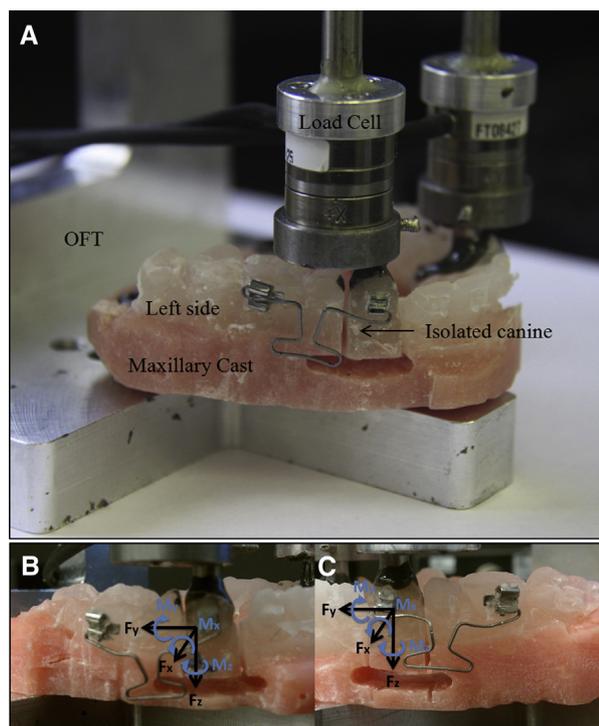


Fig 2. A, The laboratory setting for measuring the orthodontic load system on the canines. The setting includes an orthodontic force tester, a dental cast with brackets, and the T-loops. The coordinate systems on B, the left side and C, the right side were defined at the centers of the canine brackets.

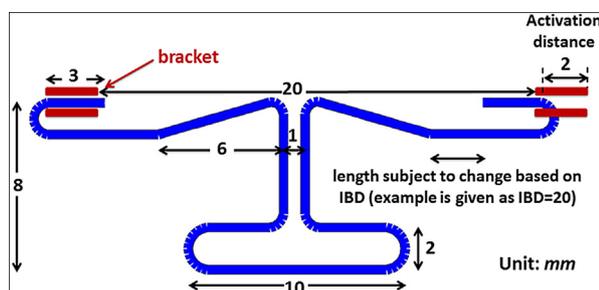


Fig 3. The geometry and dimensions of the loops before the first- and second-order bends were added.

components applied at the canine brackets. The force range of each load cell was 0 to 20 N, with a 0.025-N resolution, and the moment range was 0 to 100 N-mm with a 0.003 N-mm resolution. A local coordinate system was established on each left canine with the retraction direction aligned with the load cell's positive y-axis, the buccal direction with the positive x-axis, and the gingival direction with the positive z-axis (Fig 2, B). The local coordinate system on the right canine was



Fig 4. The fabricated T-loops.



Fig 5. A canine retraction patient with the T-loop on the left side.

different from that of the left canine (Fig 2, A and B). In this study, the clinically expressed load systems were of interest, and the side was not a controlled parameter because tipping or translation was randomly assigned to each side. Thus, the clinically used coordinate system on the left side was used to describe the results.

For each treatment interval, an acrylic model was fabricated after each treatment period, and a new T-loop was bent for each canine and adjusted using the orthodontic force tester. The posttreatment inter-bracket distances were also recorded. The T-loops used in the previous treatment were retrieved and installed on the posttreatment acrylic model to measure the residual load system with the orthodontic force tester. The T-loops retrieved were examined visually for signs of permanent deformation or other damage from removal. Damaged T-loops were excluded from this study. Consequently, both initial and residual load systems were recorded.

Statistical analysis

Linear regressions were performed on the retraction force, F_y , drop, antitipping moment, M_x , drop, and $M_x/$

F_y increase with respect to interbracket distance changes. The initial and residual load systems were compared using paired t tests. The force and moment drops between the controlled tipping and translation groups were compared using a t test. Significance was tested at the 95% confidence level.

To assess the errors from wire installation and instrument, a cast and a T-loop were used for a repeatability test. The same T-loop was installed on the same cast 10 times. The resulting load system corresponding to each installation was measured. The means and standard deviations were calculated.

RESULTS

The installation and instrument errors of the 6 load components are shown in Table I. The maximum standard deviations for the key load components, F_y , M_x , and M_z , were only 1%, 1%, and 3%, respectively, meaning that the measurements were consistent.

Only 9 T-loops on the controlled tipping side and 11 on the translation side passed the visual inspections. The initial interbracket distances in this study ranged from 16.4 to 24.4 mm because of interpersonal difference or variations in incremental tooth displacement. The interbracket distance decrease in each treatment interval ranged from 0.3 to 1.9 mm (average, 1.23 mm). Despite the 1-mm canine movement criterion for the treatment interval, there were intervals with greater canine movements, causing larger interbracket distance decreases. The larger decrease was primarily due to prolonged treatment intervals caused by missed appointments. The initial and residual load systems were measured (Table II). The load systems on both sides were expressed using the same convention. The positive y-axis corresponded to the retraction (distal) direction, the positive x-axis represented the buccal direction, and the positive z-axis corresponded to the gingival direction. The positive M_x tips the crown distally, the positive M_y tips the crown lingually, and the positive M_z rotates the crown distal in. Thus, negative M_x is the antitipping moment. The initial retraction force, F_y , was 124.4 ± 3.3 cN. On the retraction plane, the initial antitipping moments, M_x , were -780 ± 0.8 cN-mm for translation and -340 ± 1.1 cN-mm for controlled tipping. Consequently, the initial M_x/F_y amounts were -6.3 ± 0.8 mm for translation and -2.8 ± 0.9 mm for controlled tipping after we implemented the M/F discounts described previously. The M_z/F_y was not reported because M_z was compromised to prevent interference with the cheek and gum.

The load systems between the 2 groups were compared first. Statistically, there was no significant

Table I. Results from the 10 tests to estimate errors from T-loop installation and instrument

Test	F_x (N)	F_y (N)	F_z (N)	T_x (N-mm)	T_y (N-mm)	T_z (N-mm)
1	-0.28	1.16	0.21	-6.95	-3.32	-5.10
2	-0.29	1.18	0.23	-6.93	-3.29	-4.88
3	-0.29	1.19	0.25	-6.81	-3.22	-4.77
4	-0.30	1.17	0.26	-6.70	-3.54	-4.63
5	-0.29	1.17	0.25	-6.80	-3.49	-4.67
6	-0.30	1.14	0.23	-6.92	-3.56	-4.64
7	-0.28	1.17	0.23	-6.86	-3.23	-4.90
8	-0.28	1.17	0.25	-6.70	-3.47	-4.70
9	-0.29	1.15	0.25	-6.78	-3.47	-4.71
10	-0.28	1.17	0.26	-6.66	-3.41	-4.74
Mean	-0.29	1.17	0.24	-6.81	-3.40	-4.77
SD	0.01	0.01	0.02	0.10	0.12	0.15

T, Moment component.

difference in the force drops ($P = 0.4046$), but there was a significant difference ($P = 0.02037$) in moment drops between the controlled tipping and translation groups. The retraction forces dropped to 58.5 ± 20.6 cN (residual force) on the controlled tipping side and 55.6 ± 26.6 cN on the translation side at the end of each treatment interval. The average initial antitipping moment, M_x , drop on the controlled tipping side was 140 ± 130 cN-mm, which decreased to -200 cN-mm (residual moment); on the translation side, it was 250 ± 150 cN-mm, which dropped to -530 cN-mm. Consequently, the average M_x/F_y drop on the controlled tipping side was 1.1 ± 2.3 mm; on the translation side, it was 4.0 ± 3.6 mm. In the other directions, like the retraction force, the initial load components were the same; thus, the data of the 2 groups were combined. The buccolingual force, F_x , changed from -5.6 ± 17.5 cN (lingual) to 9 ± 24.9 cN (buccal); the occlusogingival force, F_z , changed from 4.7 ± 11.9 cN to 3.4 ± 17.9 cN (intrusion); the antitipping moment, M_y , in the buccolingual direction, changed from 60 ± 180 N-mm to 50 ± 180 cN-mm (lingual tipping); and the antirotation moment, M_z , changed from -580 ± 190 cN-mm to -520 ± 240 cN-mm (crown mesial in).

The retraction forces, F_y , were decreased as the interbracket distance was reduced because of canine retraction. Figure 6 shows the interbracket distance reduction vs force drop of each loop. The linear regressions of force drop vs the interbracket distance change for the 2 groups were estimated as F_y drop (cN) = $35.3 + 26.7 \times$ interbracket distance reduction (mm) for controlled tipping, and F_y drop (cN) = $14.9 + 44.9 \times$ interbracket distance reduction (mm) for translation.

The average amounts of retraction force drop per interbracket distance reduction were 26.7 cN/mm on the controlled tipping side and 44.9 cN/mm on the

Table II. Means and standard deviations of the load components on the controlled tipping (CT) side, the translation (TR) side, and both sides combined

	Status	F_x (cN)	F_y (cN)	F_z (cN)	M_x (cN-mm)	M_y (cN-mm)	M_z (cN-mm)	M_x/F_y (mm)
CT	Initial							
	Mean	-1.22	123.00	2.67	-340	81	-519	-2.74
	SD	15.64	2.35	16.12	110	112	202	0.91
	Residual							
	Mean	9.11	57.33	6.22	-203	-3	-490	-3.81
	SD	31.70	22.56	19.80	120	157	211	2.62
TR	Initial							
	Mean	-9.09	125.55	6.36	-779	043	-629	-6.22
	SD	18.90	3.67	7.34	81	218	166	0.78
	Residual							
	Mean	8.91	52.09	1.00	-522	86	-551	-11.11
	SD	19.31	24.68	16.80	157	195	274	3.61
Combined	Initial							
	Mean	-5.55	124.40	4.70	-582	60	-580	-4.66
	SD	17.53	3.33	11.89	242	175	187	1.95
	Residual							
	Mean	9.00	54.45	3.35	-379	46	-524	-7.83
	SD	24.89	23.28	17.91	213	180	243	4.86

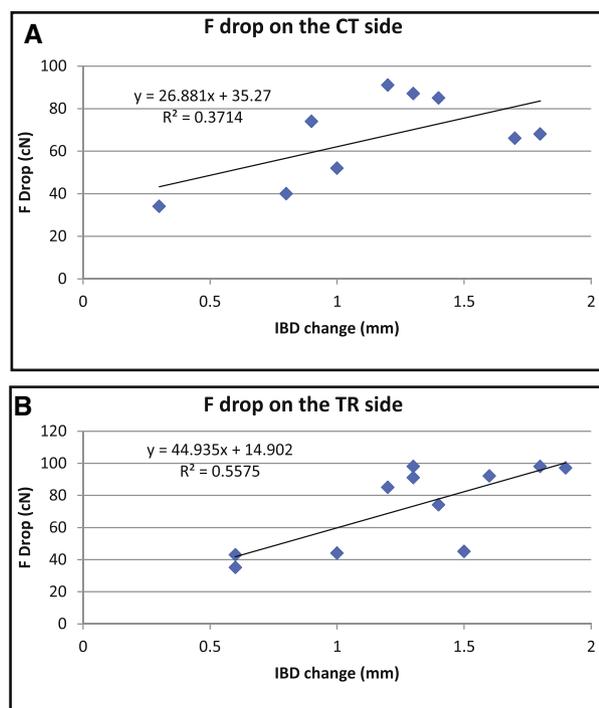


Fig 6. Interbracket distance decrease vs force drop of each loop: **A**, on the controlled tipping (CT) side; **B**, on the translation (TR) side.

translation side, meaning that after 1 mm of interbracket distance decrease, the retraction force has dropped by 20% on the tipping side and by 36% on the translation side from the initial values ($P < 0.0001$). The coefficients

of determination (R^2) were 0.3714 and 0.5575. This coefficient is between 0 and 1; the higher the value, the stronger the correlation.

Similarly, the antitipping moment, M_x , was also reduced with decreasing interbracket distances (Fig 7). The linear regressions of antimoment drops vs interbracket distance reductions were expressed as M_x drop (cN-mm) = $134 + 2.1 \times$ interbracket distance reduction (mm) for controlled tipping, and M_x drop (cN-mm) = $72 + 144 \times$ interbracket distance reduction (mm) for translation.

The coefficients of determination were $R^2 = 0$ for controlled tipping and 0.1899 for translation. The average antitipping moment drops per 1 mm of interbracket distance decrease were about 2 cN-mm per millimeter for controlled tipping and 144 cN-mm per millimeter for translation, an 18% drop per 1 mm of interbracket distance decrease.

In contrast, the M_x/F_y ratio increased with the reduction in interbracket distance (Fig 8). The linear regressions of antimoment drop vs interbracket distance reduction were expressed as M_x/F_y increase (mm) = $-0.35 + 1.25 \times$ interbracket distance reduction (mm) for controlled tipping, and M_x/F_y increase (mm) = $-3.33 + 6.34 \times$ interbracket distance reduction (mm) for translation.

The coefficients of determination were $R^2 = 0.063$ and 0.4836, respectively. The average M/F increases per interbracket distance decrease were 1.25 mm per millimeter for controlled tipping and 6.34 mm per millimeter for translation.

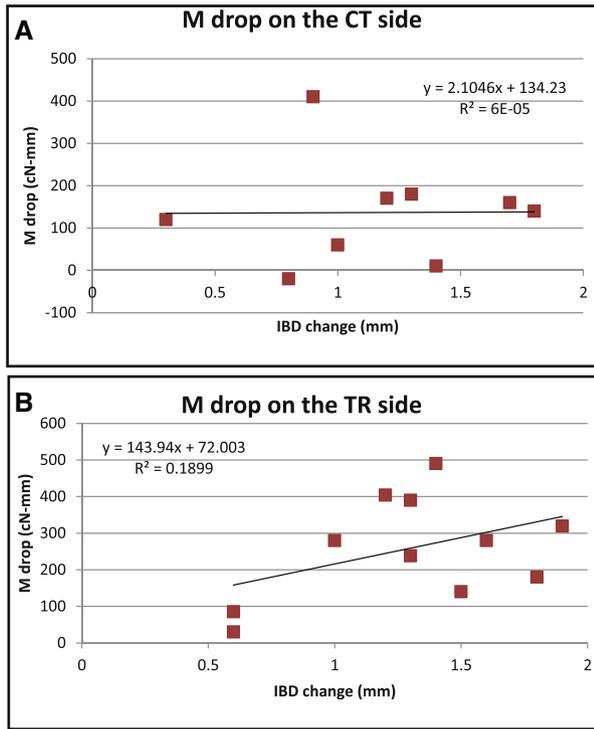


Fig 7. Interbracket distance decrease vs moment drop of each loop: **A**, on the controlled tipping (CT) side; **B**, on the translation (TR) side.

DISCUSSION

In this clinical study, we quantified the orthodontic load system of a T-loop segmental wire for canine retraction and its residual load system as a function of interbracket distance reduction from canine movement. Our in-vitro “transfer” method, simulating the clinical condition, provides the best estimates at present on the clinical load systems because it preserves the boundary conditions that occur in the clinic; these are the dominating factors affecting accuracy.⁶ The effects of a bracket’s translation and rotation in all 3 directions were considered; this has never been done before. Although these results are limited to this type of T-loop, they have a broader implication because they express changes that could occur with loops with dimensions and activations calibrated to deliver similar load systems.¹⁷

The load systems on the canines were controlled and quantified, with the same retraction force and different antitipping moments in the retraction plane for either controlled tipping or translation. There were no significant differences in retraction force, F_y , drop vs interbracket distance decrease between the controlled tipping and the translation groups. Thus, the F_y data

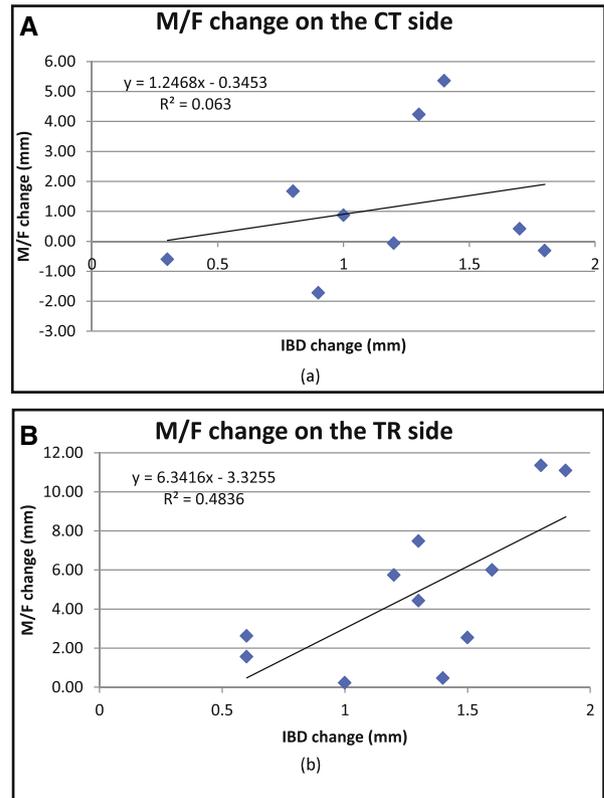


Fig 8. Interbracket decrease vs M/F increase of each loop: **A**, on the controlled tipping (CT) side; **B**, on the translation (TR) side.

were combined for further analyses. The average retraction force drop per interbracket distance decrease was 36 cN/mm, a 30% drop per 1 mm of interbracket distance decrease ($P < 0.0001$). The antitipping moment, M_x , drop vs the interbracket distance decrease was significantly different between the 2 groups, most likely because the initial moments were different. The rate of M_x drop per interbracket distance change was higher for translation than for controlled tipping. Translation requires a higher moment, which indicates that the M_x drop depends on the initial moment level. The higher the initial moment, the faster it drops. When the initial moment is low, there is a negligible moment drop (Fig 7).

Canine retraction causes both retraction force, F_y , and antitipping moment, M_x , to drop (Figs 6 and 7). Interbracket distance is directly related to canine retraction but is not the only dominant factor affecting the force and moment drops. The coefficient of determination of regression analysis on interbracket distance reduction vs force drop indicated some relationship between interbracket distance and force drop. The coefficient of determination indicated the amount of variability in force drop explained by the interbracket distance decrease.

The coefficient of determination for moment drop vs interbracket distance decrease on the translation side was only 0.1899, meaning that interbracket distance decrease explains only 18% of the variability in moment drop. Theoretically, if the displacement only occurs in the retraction plane and there is no bracket angulation change due to tipping, the M/F change should have little variation, and the coefficient of determination should be high. However, in the clinic, the canine moves in 3 dimensions; this causes the bracket to rotate about all 3 axes. Consequently, other factors, such as bracket angulation, also contribute to the moment change, which creates the significant scattering of the data shown in Figure 7.

In this clinical study, there were large initial and residual out-of-retraction-plane load components, such as F_x , M_y , and M_z , shown in Table 1; these might initiate out-of-retraction-plane displacements and affect final tooth positions, including bracket angulations. These initial out-of-retraction-plane load components are difficult to eliminate for T-loop designs. The values are not trivial and thus need to be considered. To understand their effects on the load component drops, the 6 components of clinical displacement should be further studied.

Ideally, the load drops are expressed with the 3D tooth displacement, which includes angulation changes measured from the tooth's tipping and rotation. This ensures that coupling effects of angulation changes in 3 directions are considered; this reflects the clinical reality. Previous studies measured 2-dimensional distal tipping angles from radiography and input the angles into computer models to calculate the residual load.^{18,19} The residual load was under ideal boundary conditions, and the effects of angulations in the other 2 directions were not included. Although the results were more consistent, they might not accurately represent reality and did not reflect interpersonal variations. Thus, the results can be used only qualitatively. These issues were addressed in this study. However, the 3D displacement components are hard to measure clinically and difficult to present. Only interbracket distance is directly measurable clinically; thus, it was used in this study.

Our results showed that as the canine retracted, both retraction force and antitipping moment decreased at different rates. The load drop was significant (30% reduction per 1 mm of interbracket distance loss) and faster than the antitipping moment (0.6% and 18% reductions per 1 mm of interbracket distance loss for controlled tipping and translation, respectively). These differential drops between load and antitipping moment increase the M/F. Our results

support previous findings that the antitipping moment, M_x , is less affected by the interbracket distance change than the retraction force, although the increasing rate is different because of different T-loop designs.¹⁷ The tooth displacement pattern relies on the M/F. When a T-loop designed for translation is used, prolonged treatment caused by missed appointments will continue to increase the M/F, meaning that a relatively stronger antitipping moment than is needed for translation is applied. If this reaches a critical level, it can cause canine crown tipping in the mesial direction. Unless this is a desired tooth movement, the patient should be strongly advised to keep the scheduled office visits and have the T-loop adjusted close to the scheduled time. On the other hand, if a higher antitipping moment is needed but is not achievable clinically, having longer intervals between visits might achieve the desired M/F for translation as long as the residual retraction force is still effective.

Current theory requires that certain M/F to be maintained to either translate or tip the canine, depending on the treatment strategy. This is difficult to achieve for a segmental T-loop because the M/F changes as the tooth moves. Our results show the level of changes, which are significant enough to make a clinical impact. To ensure that the average M/F is close to the desired value, the initial M/F should be reduced depending on the expected tooth displacement in each treatment period. If the expected tooth displacement is 1 mm, then the initial M/F for translation should be about 3 mm less than the expected value because the M/F drop is about 6 mm per 1 mm of interbracket distance reduction. The greater the expected tooth movement, the greater the M/F reduction that is needed.

The initial retraction force should not be too low. It is commonly accepted that there is an effective force level for moving a tooth, although there is no consensus on the actual level. An initial force less than 36 cN would drop below zero when the canine retracts more than 1 mm; this would have no retraction effect. On the other hand, if the initial load is as high as 124 cN, as in our case, the retraction force would still be greater than the effective force level after the predetermined treatment period; thus, the tooth would still move if the patient misses appointments. This force combined with the slower dropped antitipping moment would cause M/F to increase and exceed the value for translation, causing tipping in the protraction direction, a side effect to avoid. Therefore, clinicians might want to consider this when determining the initial force level and scheduling the office visits.

CONCLUSIONS

A 3D approach to calibration of customized segmental T-loops with desired loadings and measurements of the change of loadings was developed and validated in a canine retraction clinical study. The following conclusions were made.

1. Clinical changes in canine position during canine retraction can significantly affect the load system delivered to the tooth.
2. In canine retraction, the retraction force decreases faster than the antitipping moment; this results in an M/F increase.
3. Out-of-retraction-plane load components exist and change, and they will affect out-of-retraction-plane movement.
4. The initial M/F needs to be lower than the targeted value to reach the expected effect. The reduction can be approximately half of the expected M/F increase during the treatment interval.
5. The initial force needs to be higher to ensure that the residual force is effective during the treatment period. The value depends on the force drop corresponding to the level of expected tooth movement.

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