Investigation into the effects of stainless steel ligature ties on the mechanical characteristics of conventional and self-ligated brackets subjected to torque

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Abstract (200 words or less)

Introduction: Torque is applied to brackets in order to alter the buccal-lingual angulation of a tooth. One factor that can affect torque is the ligation mode used to retain the archwire in the bracket slot. The objective this study was to investigate the effects of stainless steel ligation on torque expression and bracket deformation.

Methods: This study utilized 60 upper right central incisor Damon Q® brackets and 60 Ormco Orthos® Twin brackets. The brackets used in this study were subdivided into four groups: (1) Damon Q ® ligated with SS ligature; (2) Damon Q® with the sliding bracket door; (3) Orthos® Twin bracket ligated with SS wire and (4) Orthos® Twin ligated with elastic ties. All brackets were tested using an orthodontic torque simulating device that applied archwire rotation from 0° to 45°.

Results: All brackets ligated with stainless steel ties exhibited greater torque expression and less deformation than brackets without stainless steel ties. As well, Damon Q brackets exhibit less bracket deformation than Orthos Twin brackets.

Conclusions: Stainless steel ties can reduce the amount of plastic deformation for both types of brackets used in this study.

Key words: Orthodontic brackets, torque expression, bracket deformation, self-ligation, conventional ligation

Introduction

From a mechanical point of view, the definition of torque is used when a body experiences a net moment that causes rotation “about its axis of rotation” due to some external forces.[1,2] Within orthodontics, a torque is applied to alter the buccal-lingual root angulation of a tooth. This alteration is especially important to provide a proper inter-incisal angle (*i.e.*, the angle between the upper and lower incisors on the sagittal plane) that facilitates the incisal guidance for the anterior (protrusive) movement of the jaw. Anterior buccal-lingual root angulation also effects arch perimeter, alignment of anterior teeth, and hence smile esthetics. [3]

When a rectangular wire is twisted or axially rotated within a rectangular bracket slot, torque is generated in the bracket. The amount of torque is dependent upon the degree of axial rotation of the archwire relative to the bracket slot. Depending upon the size of the rectangular archwire, there is a range of possible twist angles that the wire can go through relative to the bracket slot without expressing any torque (torque play). The angle at which the wire engages the bracket slot and generates a torque is referred to as the engagement angle.[5, 6] The engagement angle may vary and is dependent upon the size of the rectangular archwire and of the bracket slot. For example a 0.019 × 0.025-in wire in a 0.022 × 0.028-in bracket could have between 10.8° to 11.9° of torque play.[6] Morina *et al.*[7] concluded that the amount of play between the wire and the slot is more important in determining torque than is the design of the bracket.

One of the factors that may affect torque expression, is the mode of bracket ligation. Gioka and Eliades[8] suggested that a stainless steel (SS) ligature tie would actually diminish the slot-wire play, which would therefore lead to an increased torque value. This would require the force of ligation to be sufficient to deform the bracket.

Elastic and plastic bracket deformation (increased slot dimensions) can occur with wire rotation resulting in reduced torque expression.[19] SS ligation has the potential to "re-enforce" the bracket walls and help resist bracket deformation associated with torque expression. A third possibility is that if the ligation presses the wire against the base of the bracket, rotation of the wire would be resisted by ligation and the base of the bracket, possibly even before the wire could sufficiently rotate to engage the wire edges against the side walls of the bracket.

Understanding the sources of the variations in torque is essential to provide predictable orthodontic treatment results, and the role of stainless steel ligature ties remains controversial. Huang *et al.*[9] reported that stainless steel ligation made no difference in terms of torque expression at 20° for a 0.019 × 0.025-in stainless steel archwire in a 0.022 × 0.028-in bracket. Contrary to the findings of Huang *et al.*[9], Hirai *et al.*[10] reported that with 0.019 × 0.025-in stainless steel wire in a 0.022 × 0.028-in bracket slot, the torque expression with steel ligation was 1.1–1.5 times larger than with elastic ligation. While recognizing the limitations of the available research due to the difficulties of controlling many variables (*e.g.*, bracket and wire deformation, and variations in slot dimensions) the real effects of steel ligation remains unclear.

The objective of the present study was to investigate the effects of stainless steel ligation on torque expression and bracket deformation with application of a torque.

Materials and methods

The present study utilized 60 upper right central incisor Damon Q® with 0.022 × 0.028-in (0.56 × 0.71 mm) SS slots, 15° torque and 5° tip prescription (Ormco Corporation, Orange, California, USA) and 60 upper right central incisor Ormco Orthos® Twin brackets with 0.022 × 0.028-in (0.56 × 0.71 mm) SS slots, 15° torque, and 5° tip prescription (Ormco Corporation, Division of Sybron, Orange, CA). The Damon Q® bracket group was subdivided into 30 brackets ligated tightly with SS ligature 0.010-in (0.25-mm) ties (DS group) and 30 ligated with the sliding bracket door (DC group). The Ormco Orthos® Ttwin bracket group was subdivided into 30 brackets tightly ligated with SS wire (TS group) and 30 ligated with elastic ties (TC group).

Brackets were torqued with a 0.019 × 0.025-in stainless steel archwire (Ormco Corporation, Orange, CA, USA). New wire was used for every test carried out on each bracket and the principle investigator ran all of the tests on the apparatus. Each bracket was numbered and tested in random order.

Sample size calculation used the following equation[11]:

$$n = \left(\sigma_1^2 + \sigma_2^2\right)\frac{\left(z_\beta + z_{\alpha/2}\right)}{\delta^2} \qquad (1)$$

where σ_1, σ_2 are the standard deviation of torque expression for stainless steel and elastic ligation and δ is the clinical minimum mean difference of torque expression between ligation type to be detected. In this study the significance level considered to be $\alpha = 0.05$, and the power of the study is 90% ($\beta = 0.1$) the *z*-statistics of α and β are: $z_\beta = 1.28$ and $z_{\alpha/2} = 1.96$ derived from the standard normal distribution. The clinical minimum difference of torque, δ, to be detected was chosen to be as 5 Nmm, which is the considered the minimum amount of torque needed to initiate movement in an upper incisor[12]. The standard deviations were taken from Hirai *et al.*[10] study. The sample size was calculated at 30 brackets for each bracket group.

Using the method previously described by Major *et al.*[5, 19, 24] the brackets were etched using the Ortho Technology TruEtch (50 micron aluminum oxide, item number 12300, The Arum Group, Spokane, WA, USA).[13] to reduce the surface reflectivity and then glued onto SS cylinders (bracket holders) with an epoxy adhesive (Loctite, E-60HP; Hysol, Henkel, Rocky Hill, CT, USA) using a mounting jig to squarely position each bracket at the centre of the bracket holder. The bracket holder was then placed into the torque testing apparatus (Figure 1).

Figure 1. Torquing apparatus (adapted from Major *et al.*[5]).

The test apparatus (Figure 1) used in the present study has been described elsewhere.[4,5,19,24] To summarize, the bracket holder was mounted onto a multi-axis force transducer (ATI Industrial Automation Nano 17 Multi-Axis force/torque transducer, Apex, NC, USA). An Ormco 0.019 × 0.025-in stainless-steel archwire (Ormco Corporation, Division of Sybron, Orange, CA, USA) is inserted and locked into the two beds that are mechanically connected to each other *via* a rigid arm (torquing arm) that is controlled through a stepper motor (Cool Muscle CM1- C-11L30, Myostat Motion Control Inc., Newmarket, ON, Canada). Using a gauging instrument (measuring 5 mm to approximately resemble the inter-bracket distance), the distance between the bracket and the mounting beds of the wire is measured. The bracket holder was tightened and the brackets ligated.

The imaging apparatus as previously described[13] has an overhead (over the bracket slot) charged coupled device camera (piA2400-12gm, 2448 × 2050 pixels, 8 bit, gray scale, Basler Vision Technologies, Exton, PA, USA) connected to a microscope (Edmund Optics, 55-908 MMS R4, Barrington, NJ, USA).

Custom computer software (LabWindows/CVI, National Instruments, Austin, TX, USA) was used to control the stepper motor and to collect data from the loading transducer as well as from the inclinometer (T2-7200-1N inclinometer, USDigital, Vancouver, WA, USA) and the overhead camera. The software also provided real-time feedback *via* an on-screen display of the loads and images of the bracket. The software was programmed to rotate the wire (clock-wise rotation relative to the bracket slot) from 0° to 45°, then reverse-rotate back to 0°, in order to gather torque measurements and overhead images of the slot every 3° of wire twist angle.

Overhead images of the orthodontic brackets were collected as the archwire was rotated within the bracket slot. For each image box regions of the overhead images representing the four bracket tie-wings were tracked through the data set. Displacement was measured optically be dividing each image into evenly spaced subsets and comparing the contrast between subsequent image subsets using a mathematical correlation algorithm[13]. As a result, a correlation map was recorded that corresponded to the average displacement of the observed image, and therefore the displacement of the tie-wings. Using a custom code (Matlab, The Mathworks Inc., Natick, MA, USA), the average displacements between the upper and lower tie-wings, or changes in the slot width (from an overhead perspective) were quantified[13]. Determination of the relative displacement between bracket tie-wings eliminates the effect of bulk motion of the bracket or load cell due to the applied archwire rotation.

The load cell measured three orthogonal components of force and their three corresponding moments at a location offset from the point that the arch wire applied load to the bracket. In order to report moments at the bracket slot instead of the load cell, a transformation method previously described by Major *et al.*[5] was used.

A statistical package SPSS 19.0 (Chicago, IL, USA) was used to carry out repeated measures ANOVA and MANOVA. Assumptions of normality and equality of variance were assessed by Boxplots, the Kolmogorov-Smirnov test, and Levene's test. The assumptions were all reasonably met for the torque data. A *post hoc* multiple comparisons to evaluate the effects of steel ties on torque expression for the brackets at each angle was undertaken, and because there were four comparisons (TS vs. TC, DS vs. DC, TS vs. DC and TS vs. DS) the statistical significance level for the multiple comparisons was set at Bonferroni corrected α, 0.05/4 = 0.012.

Assumption of normality was also met for bracket width data. The homogeneity of width variances among the bracket types was violated. Therefore, Brown-Forsythe and Welch test statistics were used to assess the statistical significance at all angles. *Post hoc* multiple comparisons between the groups using Tamhane tests were carried out at each angle. Because a four comparisons (TS vs. TC, DS vs. DC, TS vs. DC and TS vs. DS) were carried out, the statistical significance level was set at 0.05/4 = 0.012.

Results

Torque values for the 32 wire twist angles are provided in Table 1.

Table 1: Mean torque (Nmm) per angle of wire twist (°) according to bracket type and ligation method with their standard deviation in parenthesis**.** *TS: Orthos Twin with stainless steel ligation, TC: Orthos Twin with conventional elastic ligation, DC: Damon Q with conventional sliding door, DS: Damon Q with stainless steel ligation in addition to the sliding door.*

	Torque Angle °	TS Mean (SD)	TC Mean (SD)	DC Mean (SD)	DS Mean (SD)
Loading Angles (ascending)	0	1.33 (2.40)	0.52 (1.56)	0.01 (1.44)	0.22 (1.36)
	3	6.24 (2.35)	1.16 (1.50)	0.97 (2.02)	4.72 (1.53)
	6	8.91 (3.15)	1.81 (2.18)	2.27 (3.27)	7.17 (2.06)
	9	12.07 (4.31)	3.62 (4.01)	5.73 (3.80)	9.59 (2.70)
	12	17.62 (5.72)	9.19 (5.97)	12.15 (4.48)	13.85 (3.68)
	15	25.89 (7.23)	17.89 (6.91)	20.45 (5.07)	20.86 (4.53)
	18	35.53 (8.23)	27.63 (7.32)	29.89 (5.54)	29.80 (5.14)
	21	45.62 (8.55)	37.49 (7.47)	40.00 (5.70)	39.64 (5.48)
	24	55.51 (8.46)	47.05 (7.52)	50.19 (5.77)	49.71 (5.75)
	27	65.01 (8.20)	56.23 (7.48)	60.28 (5.78)	59.77 (5.93)
	30	74.06 (7.87)	65.01 (7.29)	70.05 (5.87)	69.70 (6.10)
	33	82.29 (7.43)	72.81 (7.11)	79.20 (5.79)	79.10 (6.19)
	36	89.47 (7.00)	79.44 (7.10)	87.55 (5.52)	87.17 (6.22)
	39	95.72 (6.58)	85.44 (6.94)	94.74 (5.32)	94.27 (6.27)
	42	101.05 (6.19)	90.55 (6.77)	100.86 (5.14)	100.20 (6.27)
	45	105.59 (5.88)	94.73 (6.62)	105.85 (4.99)	105.04 (6.19)
Unloading Angles (descending)	45	104.28 (5.79)	93.55 (6.55)	104.70 (4.95)	103.82 (6.07)
	42	88.98 (5.57)	78.96 (6.24)	90.30 (4.74)	88.94 (5.79)
	39	74.99 (5.39)	65.60 (5.95)	76.99 (4.52)	75.27 (5.52)
	36	61.90 (5.19)	53.18 (5.70)	64.65 (4.30)	62.56 (5.26)
	33	49.84 (5.07)	41.95 (5.27)	53.17 (4.09)	50.87 (5.02)
	30	38.22 (4.87)	30.66 (5.08)	42.39 (3.83)	39.66 (4.64)
	27	27.69 (4.55)	20.76 (4.76)	32.80 (3.59)	29.50 (4.26)
	24	18.30 (4.14)	12.32 (3.91)	23.93 (3.45)	20.48 (3.89)
	21	10.57 (3.58)	6.57 (2.60)	15.92 (3.24)	12.77 (3.43)
	18	5.06 (3.28)	2.88 (2.05)	9.70 (2.94)	6.68 (2.88)
	15	2.11 (2.71)	0.50 (1.51)	4.06 (2.53)	1.38 (2.20)
	12	1.34 (2.28)	0.09 (1.50)	1.16 (2.22)	-0.41 (1.56)
	9	0.70 (1.96)	-0.02 (1.43)	0.68 (1.99)	-0.68 (1.33)
	6	0.10 (1.63)	-0.21 (1.43)	0.53 (1.78)	-0.78 (1.22)
	3	-0.16 (1.62)	-0.30 (1.45)	0.43 (1.67)	-0.88 (1.19)
	0	-0.96 (1.81)	-0.58 (1.50)	0.43 (1.63)	-1.53 (1.45)

The repeated measures ANOVA showed a significant difference between groups over the range of the angles ($F(3,116) = 16.66$, $p < 0.001$). *Post-hoc* multiple comparisons of mean torque expressions between groups, with a 95% confidence interval, is shown in Tables 2 to 4.

Table 2. Comparison of torque (Nmm) between Damon Q bracket with stainless steel ligation (DS) and Damon Q bracket conventionally ligated (DC) at each collection angle (°)

	Torque Angle°	Mean Difference (DS-DC)	*p*-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0.21	>0.99	-1.00	1.41
	3	3.76	< 0.0001	2.45	5.06
	6	4.90	<0.0001	3.01	6.78
	9	3.86	<0.0001	1.26	6.46
	12	1.70	>0.99	-1.80	5.20
	15	0.42	>0.99	-3.78	4.61
	18	-0.08	>0.99	-4.71	4.55
	21	-0.36	>0.99	-5.15	4.44
	24	-0.48	>0.99	-5.31	4.35
	27	-0.51	>0.99	-5.31	4.29
	30	-0.35	>0.99	-5.08	4.39
	33	-0.10	>0.99	-4.72	4.52
	36	-0.38	>0.99	-4.88	4.12
	39	-0.47	>0.99	-4.84	3.90
	42	-0.65	>0.99	-4.90	3.59
	45	-0.81	>0.99	-4.93	3.31
Unloading Angles (descending)	45	-0.88	>0.99	-4.95	3.18
	42	-1.36	>0.99	-5.25	2.53
	39	-1.72	>0.99	-5.44	2.00
	36	-2.09	0.708	-5.65	1.47
	33	-2.30	0.428	-5.68	1.09
	30	-2.73	0.146	-5.94	0.48
	27	-3.30	0.022	-6.29	-0.31
	24	-3.45	0.005	-6.12	-0.77
	21	-3.15	0.002	-5.40	-0.91
	18	-3.02	<0.0001	-4.98	-1.06
	15	-2.68	<0.0001	-4.26	-1.10
	12	-1.57	0.012	-2.90	-0.23
	9	-1.36	0.014	-2.55	-0.18
	6	-1.31	0.007	-2.37	-0.25
	3	-1.32	0.005	-2.35	-0.28
	0	-1.96	<0.0001	-3.06	-0.85

Table 3: Comparison of torque (Nmm) between Orthos Twin bracket with steel ligation (TS) and elastic ligation (TC) at each collection angle (°)

	Torque Angle (Degrees)	Mean Difference (TS-TC)	*p*-value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0.80	0.455	-0.40	2.01
	3	5.08	< 0.0001	3.78	6.39
	6	7.11	< 0.0001	5.22	8.99
	9	8.45	< 0.0001	5.85	11.05
	12	8.44	< 0.0001	4.94	11.94
	15	8.00	< 0.0001	3.81	12.19
	18	7.91	< 0.0001	3.28	12.54
	21	8.14	< 0.0001	3.34	12.93
	24	8.46	< 0.0001	3.63	13.29
	27	8.79	< 0.0001	3.99	13.59
	30	9.05	< 0.0001	4.31	13.78
	33	9.48	< 0.0001	4.87	14.10
	36	10.03	< 0.0001	5.54	14.53
	39	10.28	< 0.0001	5.91	14.66
	42	10.50	< 0.0001	6.26	14.74
	45	10.86	< 0.0001	6.73	14.98
Unloading Angles (descending)	45	10.74	< 0.0001	6.67	14.80
	42	10.02	< 0.0001	6.13	13.91
	39	9.38	< 0.0001	5.66	13.11
	36	8.72	< 0.0001	5.16	12.28
	33	7.89	< 0.0001	4.51	11.28
	30	7.56	< 0.0001	4.35	10.77
	27	6.93	< 0.0001	3.94	9.92
	24	5.98	< 0.0001	3.30	8.65
	21	4.00	< 0.0001	1.76	6.24
	18	2.18	0.021	0.22	4.13
	15	1.61	0.044	0.03	3.19
	12	1.24	0.083	-0.09	2.58
	9	0.72	0.615	-0.46	1.90
	6	0.32	>0.99	-0.74	1.38
	3	0.13	>0.99	-0.90	1.17
	0	-0.37	>0.99	-1.48	0.73

Table 4: Comparison of torque (Nmm) between Orthos Twin bracket with elastic ties (TC) and Damon Q bracket conventionally ligated (DC) at each collection angle(°).

	Torque angle (Degree)	Mean Difference (TC-DC)	*p*-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0.51	>0.99	-0.692	1.719
	3	0.19	>0.99	-1.113	1.496
	6	-0.46	>0.99	-2.351	1.423
	9	-2.11	0.188	-4.715	0.491
	12	-2.96	0.150	-6.462	0.537
	15	-2.56	0.625	-6.748	1.634
	18	-2.26	>0.99	-6.891	2.367
	21	-2.51	0.978	-7.304	2.287
	24	-3.14	0.504	-7.970	1.694
	27	-4.05	0.152	-8.849	0.747
	30	-5.04	0.030	-9.778	-0.309
	33	-6.39	0.002	-11.011	-1.773
	36	-8.11	< 0.0001	-12.608	-3.612
	39	-9.30	< 0.0001	-13.675	-4.933
	42	-10.30	< 0.0001	-14.547	-6.061
	45	-11.12	< 0.0001	-15.241	-6.993
Unloading Angles (descending)	45	-11.16	< 0.0001	-15.225	-7.093
	42	-11.34	< 0.0001	-15.233	-7.452
	39	-11.39	< 0.0001	-15.107	-7.663
	36	-11.47	< 0.0001	-15.027	-7.905
	33	-11.22	< 0.0001	-14.601	-7.831
	30	-11.73	< 0.0001	-14.938	-8.521
	27	-12.04	< 0.0001	-15.028	-9.051
	24	-11.60	< 0.0001	-14.276	-8.929
	21	-9.36	< 0.0001	-11.599	-7.116
	18	-6.82	< 0.0001	-8.776	-4.862
	15	-3.56	< 0.0001	-5.143	-1.979
	12	-1.06	0.206	-2.398	0.270
	9	-0.71	0.667	-1.886	0.475
	6	-0.75	0.368	-1.808	0.314
	3	-0.73	0.376	-1.763	0.311
	0	-1.01	0.095	-2.121	0.098

Torque expression was significantly higher for the Damon Q ligated with SS ties compared to the Damon Q without SS ties for the first 3°-9° of wire rotation ($p<0.0001$). Torque expression was also significantly higher ($p<0.016$) for the Damon Q with SS ligation during the last 24° of unloading. Torque expression was higher ($p < 0.016$) for Orthos Twin brackets ligated with SS ties for all angles except the last 18° of the unloading.

There was no difference ($p>0.016$) between DC and TC upon loading from 0° to 30° twist angle. However, after loading angle of 30° DC had a significantly ($p < 0.016$) higher torque than TC until the unloading angle of 12°.

In Figure 2 the net opening of the brackets while under loading by the archwire for increasing and decreasing angles is graphically displayed. The figure compares the same bracket with different ligation methods. Overall, the amount of deformation for brackets that are conventionally tied is consistently higher than when the brackets are tied with stainless steel. The stainless steel ligated brackets in both groups experienced a decrease in slot width for the first 10° of wire twist. After 10°, in both groups, there is a continuous increase in the slot width as the degree of wire twist increases. Upon unloading, the slot width decreases as the angle of wire twist decreases, thus signifying some elastic and plastic deformations of the bracket slot up until the unloading angle of 13° at which point no further changes in slot width occur.

A

B

Figure 2 Average bracket width displacement (mm) per angle (°) of wire twist. A: Orthos Twin with steel ligation (TS) vs. Orthos Twin with elastic ties (TC); and B: Damon Q with stainless steel ties (DS) vs. conventional Damon Q (DC).

Repeated measures ANOVA demonstrated that the change in bracket slot width was significantly different ($p < 0.001$) between all four groups. The *post hoc* multiple comparisons identified that the Orthos Twin brackets having wire ligatures (TS) had significantly ($p < 0.012$) less deformation (increase in bracket width) than Orthos Twin brackets with elastic ligatures (TC) at all angles with the exception of 9° to 12° (Table 5). Similarly, the Damon Q having wire ligatures (DS) showed significantly ($p < 0.001$) less deformation than the DC-type brackets at all angles (Table 6).

TS brackets showed no significant deformation differences ($p>0.012$) in comparison to DS and significantly ($p< 0.012$) less deformation to DC brackets from 0° to 33° of the unloading, then TS had significantly ($p<0.012$) more deformation than DC and DS for the last (15° to 0°)and (27° to 0°) respectively of the unloading angles (Table 7 and 8).

Table 5. Comparison of bracket displacement (mm) between Orthos Twin with stainless steel ties and Orthos Twin with elastic ties.

	Torque Angle (°)	Mean Difference (TS − TC)	*p*-value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0	0	0.000	0.000
	3	-0.000	<0.0001	-0.001	-0.000
	6	-0.001	<0.0001	-0.001	-0.000
	9	-0.001	0.026	-0.002	-0.000
	12	-0.001	0.018	-0.003	-0.000
	15	-0.002	0.011	-0.004	-0.000
	18	-0.002	0.008	-0.004	-0.000
	21	-0.003	0.006	-0.005	-0.001
	24	-0.003	0.004	-0.006	-0.001
	27	-0.004	0.002	-0.007	-0.001
	30	-0.005	0.001	-0.008	-0.002
	33	-0.006	<0.0001	-0.010	-0.002
	36	-0.008	<0.0001	-0.013	-0.003
	39	-0.010	<0.0001	-0.016	-0.005
	42	-0.013	<0.0001	-0.020	-0.007
	45	-0.017	<0.0001	-0.025	-0.009
Unloading Angles (descending)	45	-0.017	<0.0001	-0.025	-0.009
	42	-0.016	<0.0001	-0.025	-0.008
	39	-0.016	<0.0001	-0.024	-0.008
	36	-0.015	<0.0001	-0.023	-0.007
	33	-0.014	<0.0001	-0.022	-0.007
	30	-0.013	<0.0001	-0.021	-0.006
	27	-0.013	<0.0001	-0.020	-0.005
	24	-0.012	<0.0001	-0.019	-0.005
	21	-0.011	0.001	-0.017	-0.004
	18	-0.010	0.002	-0.017	-0.003
	15	-0.010	0.001	-0.016	-0.003
	12	-0.010	<0.0001	-0.016	-0.004
	9	-0.010	<0.0001	-0.016	-0.004
	6	-0.010	<0.0001	-0.016	-0.004
	3	-0.010	<0.0001	-0.016	-0.004
	0	-0.010	<0.0001	-0.016	-0.004

Table 6. Comparison of bracket displacement (mm) between Damon Q bracket with stainless steel ligation (DS) and Damon Q bracket conventionally ligated (DC) at each collection angle.

	Torque Angle (°)	Mean Difference (DS − DC)	*p*-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0	0	0.000	0.000
	3	-0.001	<0.0001	-0.001	-0.000
	6	-0.001	<0.0001	-0.002	-0.001
	9	-0.002	<0.0001	-0.003	-0.001
	12	-0.004	<0.0001	-0.005	-0.002
	15	-0.005	<0.0001	-0.006	-0.003
	18	-0.005	<0.0001	-0.007	-0.004
	21	-0.006	<0.0001	-0.008	-0.004
	24	-0.007	<0.0001	-0.009	-0.005
	27	-0.007	<0.0001	-0.010	-0.005
	30	-0.008	<0.0001	-0.011	-0.006
	33	-0.009	<0.0001	-0.012	-0.007
	36	-0.010	<0.0001	-0.013	-0.008
	39	-0.011	<0.0001	-0.014	-0.008
	42	-0.012	<0.0001	-0.015	-0.009
	45	-0.013	<0.0001	-0.016	-0.010
Unloading Angles (descending)	45	-0.013	<0.0001	-0.016	-0.010
	42	-0.013	<0.0001	-0.016	-0.009
	39	-0.012	<0.0001	-0.015	-0.009
	36	-0.012	<0.0001	-0.015	-0.009
	33	-0.011	<0.0001	-0.014	-0.008
	30	-0.010	<0.0001	-0.013	-0.007
	27	-0.009	<0.0001	-0.012	-0.006
	24	-0.008	<0.0001	-0.010	-0.005
	21	-0.006	<0.0001	-0.009	-0.004
	18	-0.005	<0.0001	-0.008	-0.003
	15	-0.004	<0.0001	-0.006	-0.002
	12	-0.003	<0.0001	-0.004	-0.001
	9	-0.002	<0.0001	-0.004	-0.001
	6	-0.002	<0.0001	-0.004	-0.001
	3	-0.002	<0.0001	-0.004	-0.001
	0	-0.002	<0.0001	-0.004	-0.001

Table 7. Comparison of bracket displacement (mm) between Orthos Twin brackets ligated with steel ligation (TS) and Damon Q bracket conventionally ligated (DC) at each collection angle (°).

	Torque Angle (°)	Mean Difference (TS-DC)	*p*-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0	0	0.000	0.000
	3	0.000	0.002	0.000	0.000
	6	-0.001	<0.0001	-0.001	-0.000
	9	-0.002	<0.0001	-0.003	-0.001
	12	-0.004	<0.0001	-0.005	-0.002
	15	-0.005	<0.0001	-0.007	-0.003
	18	-0.007	<0.0001	-0.009	-0.004
	21	-0.008	<0.0001	-0.01	-0.005
	24	-0.009	<0.0001	-0.011	-0.006
	27	-0.010	<0.0001	-0.012	-0.007
	30	-0.011	<0.0001	-0.014	-0.007
	33	-0.011	<0.0001	-0.014	-0.007
	36	-0.012	<0.0001	-0.015	-0.007
	39	-0.011	<0.0001	-0.016	-0.007
	42	-0.011	<0.0001	-0.016	-0.006
	45	-0.010	<0.0001	-0.016	-0.004
Unloading Angles (descending)	45	-0.010	<0.0001	-0.015	-0.004
	42	-0.009	<0.0001	-0.015	-0.004
	39	-0.009	<0.0001	-0.014	-0.003
	36	-0.008	0.001	-0.013	-0.003
	33	-0.007	0.005	-0.012	-0.002
	30	-0.005	0.042	-0.010	-0.000
	27	-0.003	0.405	-0.008	0.001
	24	-0.001	0.999	-0.005	0.004
	21	0.002	0.653	-0.002	0.006
	18	0.004	0.049	0.000	0.008
	15	0.006	<0.0001	0.002	0.010
	12	0.009	<0.0001	0.005	0.012
	9	0.009	<0.0001	0.005	0.012
	6	0.009	<0.0001	0.006	0.012
	3	0.009	<0.0001	0.006	0.013
	0	0.009	<0.0001	0.006	0.013

Table 8. Comparison of bracket displacement (mm) between Orthos Twin ligated with stainless steel ligation (TS) and Damon Q bracket ligated with stainless steel ligation at each collection angle (°).

	Torque Angle (°)	Mean Difference (TS-DS)	*p*-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0	0	0.000	0.000
	3	0.000	0.883	-0.000	0.000
	6	0.000	0.774	-0.000	0.001
	9	0.000	0.992	-0.001	0.001
	12	0.000	1.000	-0.001	0.001
	15	-0.001	0.913	-0.002	0.001
	18	-0.001	0.385	-0.003	0.001
	21	-0.002	0.091	-0.004	0.000
	24	-0.002	0.045	-0.005	0.000
	27	-0.003	0.055	-0.005	0.000
	30	-0.002	0.133	-0.005	0.000
	33	-0.002	0.419	-0.005	0.001
	36	-0.001	0.883	-0.005	0.002
	39	0.000	1.000	-0.004	0.004
	42	0.001	0.973	-0.003	0.006
	45	0.003	0.516	-0.002	0.008
Unloading Angles (descending)	45	0.003	0.472	-0.002	0.008
	42	0.003	0.391	-0.002	0.009
	39	0.004	0.313	-0.002	0.009
	36	0.004	0.238	-0.001	0.009
	33	0.004	0.153	-0.001	0.009
	30	0.005	0.063	0.000	0.009
	27	0.006	0.009	0.001	0.010
	24	0.007	<0.0001	0.003	0.011
	21	0.009	<0.0001	0.004	0.013
	18	0.010	<0.0001	0.006	0.014
	15	0.011	<0.0001	0.007	0.014
	12	0.012	<0.0001	0.008	0.015
	9	0.011	<0.0001	0.008	0.015
	6	0.011	<0.0001	0.008	0.015
	3	0.011	<0.0001	0.008	0.015
	0	0.012	<0.0001	0.008	0.015

Discussion

Torque arises from the engagement of the torsion of rectangular wire in a rectangular bracket slot. The overall objective of this study was to evaluate if stainless steel ligatures would alter the torque expression. The secondary objective was to evaluate bracket deformation associated with ligation method and association with torque expression.

One of the major differences between the present experiment and the clinical setting is the fact that the wire was fixed to mounting dies on both sides of the bracket, with no possibility of any play or other movement.[9, 10, 14] The torque generated in our experiments would most probably be higher than those found in clinical cases where the root movement within the periodontal ligament space and the engagement angle of the wire at adjacent brackets will reduce the torque generated at the target bracket.

Steel ligation produced significantly ($p<0.0001$) higher moments for the first 3° to 9° of wire twist than the groups without steel ligation as shown in Figure 3. The range of clinically appropriate torque has been reported as 5-20 Nmm, though there is little evidence to support this estimate.[12, 16, 17] Both TS and DS achieved clinically relevant torque magnitude with 3° of wire rotation compared to 9° to 10° for self-ligation and elastic ligation. Clinically relevant torque can be reached considerably sooner with steel ligation.

Figure 3 First 15° of loading of averaged torque (Nmm) vs. wire twist angle (degrees) for all brackets groups.

In the present study the wire is inserted passively into the bracket slot, ligated, and then twisted. The stainless steel tie played a role in restricting the twisting movement of the wire inside the bracket by acting as the bracket's fourth wall. The tight stainless steel ligation presses the wire against the base of the bracket and pushes against the tie wings of the bracket to decrease the slot width. This concept is shown in Figure 4A. At this stage no torque should be exerted on the bracket. As the wire rotates inside the slot, it would be resisted by the ligature at one end and the base of the bracket at the other end (termed ligature engagement). This ligature, shown in Figure 4 B engagement occurs even before the wire can rotate sufficiently to engage the sidewalls of the bracket slot. The magnitude of the moment generated when a tight stainless steel ligation placed on a bracket with rotated archwire will depend upon the amount of force that the steel ligation delivers to resist the movement of the archwire. Khambay *et al.*[15] reported the force generated by stainless steel ligature ties to seat a 0.019 × 0.025-in stainless steel wire into a Orthos Twin bracket slot (0.022 × 0.028 in) to be ~ 3.5N. As the wire rotates and the ligature acts to resist wire rotation, the torque at the bracket will increase. Narrowing of the bracket slot by the steel ligature allows the wire to engage the bracket slot walls with less degrees of wire rotation. As the wire twists there will be additive effects of couple generated by the wire contacting with the ligature and the couple generated by the wire contacting the walls of the bracket.

As the wire rotation increases the bracket wall couple will become more dominate since the distance between the forces of this couple is larger than the distance of the couple generated by the ligature as shown in Figure 4 C.

Figure 4 Profile image of a bracket with the archwire and the stainless steel ligation. The arrows represent forces and couples exerted at each part (bracket, wire, and stainless steel ligation) separately as wire rotate: (A) wire is at 0° the stainless steel ligation exerting some forces on the wire and bracket, no motion is occurring, (B) wire rotated but not engaged yet with the slot walls, stainless steel ligation forces has resulted in a couple at the wire and the bracket, and (C) wire rotated and now engaged into the slot walls forming a second couple. The sum of the two couples is larger than the couple formed by the ligature. As the wire is rotated further the magnitude of the couple formed by the bracket walls becomes much larger than the couple formed by the stainless steel ligature.

The loading and unloading curves shown in Figure 2 for the experiment groups have similar shapes. Overall, the torque generated during unloading are considerably less than the torque upon loading, most likely as a result of some plastic (permanent) deformation of the wire and/or bracket.[6, 18] From a clinical point of view, the unloading curve is more important, than the loading curve. This is because when a twisted wire is inserted into a bracket the loading action occurs near instantly, while the unloading action is sustained during active tooth movement. When the unloading torque drops below the threshold (5 Nmm) to induce tooth movement, no further movement will take place.[3]

In this study, the unloading curve (for all brackets) commenced at 45°. Although there is no agreement in published literature regarding the maximum wire twist angle that would be clinically useful, it is unlikely that the twist angle would exceed 45°. In our experiment, the torque generated at the unloading angle of 27° for TC and at 24° for TS, DS, and DC are 18–23 Nmm, and in line with the previously recommended torque magnitude. All four experimental groups dropped below 5Nmm at the 15° unloading angle.

When compared between the groups TC and TS, during unloading from 27° to 0°, it is clear that steel ties only made a difference from 27° to 21°. For the final 18° (unloading 18° to 0°), no significant difference ($p > 0.016$) was identified, which is probably due to some bracket or wire plastic deformation[19], and most likely a deformation to the stainless steel ligature tie (possibly stretching) enough to diminish the seating force of this ligature and to eliminate the effects of stainless steel ties.

In order to explain some of the reasons behind the observed differences in torque between Orthos Twin steel-ligated brackets (TS) and Orthos Twin conventionally ligated brackets (TC), it is necessary to assess the bracket displacement data shown in Figure 2. Initial stainless steel ligation produced a slight decrease in slot width. As the wire was twisted the stainless steel ligature resisted the increase in slot width. After 10° of loading there is a continuous increase in the amount of deformation as the angle of twist increases for both types of brackets. The bracket deformation was considerably less for the SS ligature group at maximum wire rotation. Both groups showed recovery in slot width up to 15°. There was permanent (plastic) deformation in both groups, with the amount of deformation being less in the stainless steel ligation group.

A similar behavior occurs with Damon Q brackets with less plastic deformation.. The stainless steel ligature reduced the amount of plastic deformation for Orthos Twin brackets by 0.01mm (10 µm) and for Damon Q brackets by 0.00235mm (2.4 µm). At 45° wire torsion angle, steel ligation reduced maximum deformation (elastic and plastic) in amount of 0.0132mm (13.2 µm) and 0.016mm (16 µm) for Damon Q and Orthos Twin brackets respectively. These deformation effects should be considered in relation to the specific bracket/archwire used (in our case, 0.019 × 0.025-in stainless steel wire in a 0.022 × 0.028-in bracket).

In the literature, Brauchli *et al.*[20] did not find a difference between stainless steel ligated and elastic ligated brackets (moments were applied from -30° to +30° with 0.019 × 0.025-in stainless steel archwire and 0.022 × 0.028-in brackets). They measured torque every 100 millisecond in open (no ligation) first then in closed configuration (elastic or stainless steel ligation) while keeping the same bracket and wire in place. A possible explanation for not finding a difference would be the fact that they used the same bracket and wire which could have introduced some deformation to both the bracket and the wire, and this new variable (deformation) can compromise their findings. It is possible that the effects of steel ligation could not make up for the amount of lost torque due to the bracket/wire deformation from the first test done (no ligation).

It is important to note that all of our findings were specific to certain wire/bracket relationships (*i.e.*, 0.019 × 0.025-in stainless steel in 0.022 × 0.028-in bracket). Using different wire or bracket sizes may result in different findings. Although Hirai *et al.*[10] noticed an increase in torque in going from elastic ligated brackets to stainless steel ligated brackets using equivalent wire and bracket sizes to our experiment, they noticed no difference between these groups when using 0.021 × 0.028-in stainless steel in a 0.022-in slot. Looking into the effects of stainless steel ligation on different bracket/wire size combinations forms the basis of future investigations by our research group.

It is also important to understand that this study did not evaluate the role of wire deformation in torque during both loading and unloading. Upon wire torsion inside the bracket slot, there will be an increase in the stress that is located on the outside surface of the wire.[23] This increase in stress in the outer layer, at the corner or edges of the wire, combined with the relatively small cross-section of the wire used is enough to result in some wire deformation. This deformation can be significant to affect torque and can possible differ depending on the type and design of the brackets.[5] Clinically, wire deformation whether due to mechanical stresses applied by the clinician, or functional forces from a patient chewing, can also play an interesting role in the variation of torque expression. This interesting topic may lead to possible further investigation in the near future.

3.5 Conclusions

The following conclusions can be stated:

(1) SS ties increase torque for conventional Orthos Twin brackets . However, stainless steel ligation did not make a difference for self-ligated brackets (Damon Q).

(2) Stainless steel ligature ties resulted in a more immediate torque in Orthos Twin brackets than did the conventionally ligated self ligating (Damon Q) and Orthos Twin brackets.

(3) Torsion forces are sufficient to cause plastic deformation to all brackets.

(4) Damon Q brackets exhibit less bracket deformation than Orthos Twin brackets.

(5) Stainless steel ties can play an important role in reducing the amount of plastic deformation for both types of brackets; however, the clinical relevance of such a reduction is questionable.

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Figures

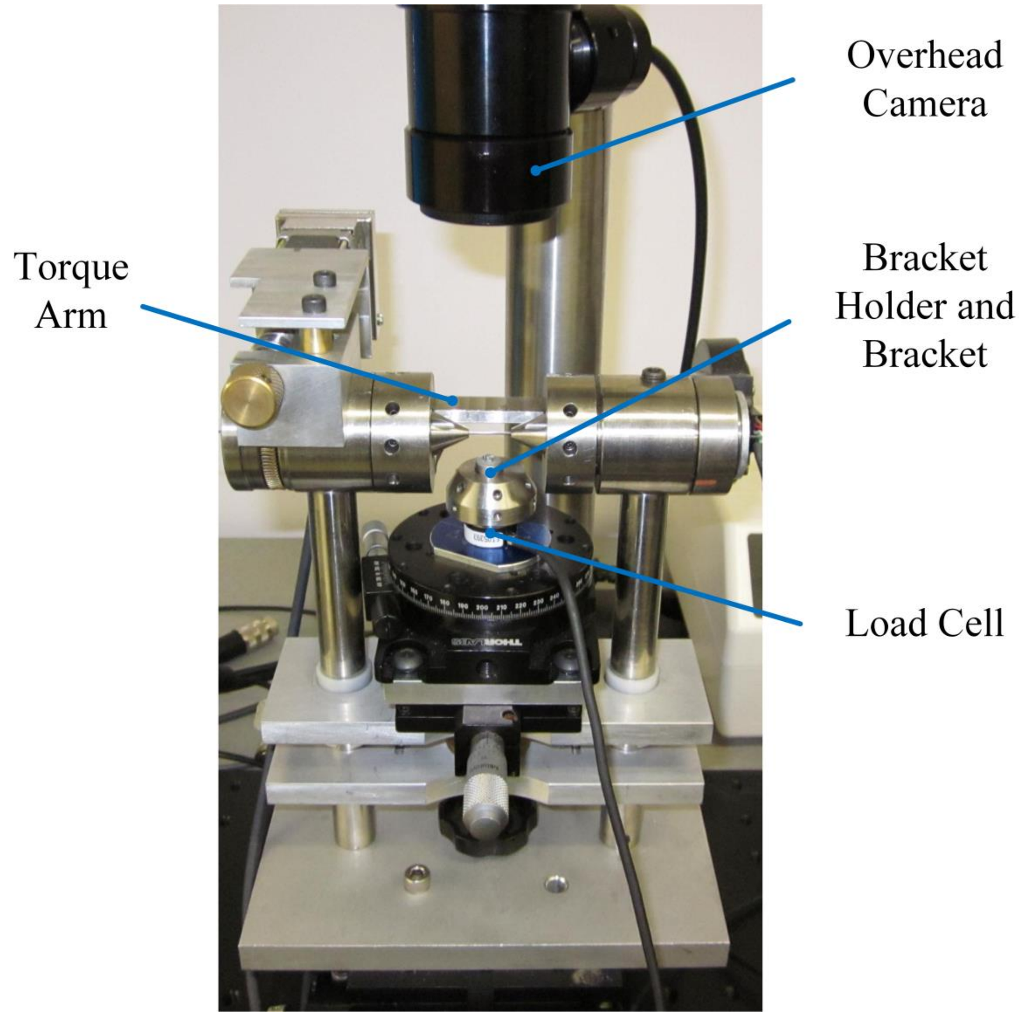


Figure 1. Torquing apparatus (adapted from Major *et al.*[5]).

Table 1: Mean torque (Nmm) per angle of wire twist (°) according to bracket type and ligation method with their standard deviation in parenthesis**.**

	Torque Angle °	TS Mean (SD)	TC Mean (SD)	DC Mean (SD)	DS Mean (SD)
Loading	0	1.33 (2.40)	0.52 (1.56)	0.01 (1.44)	0.22 (1.36)
	3	6.24 (2.35)	1.16 (1.50)	0.97 (2.02)	4.72 (1.53)
	6	8.91 (3.15)	1.81 (2.18)	2.27 (3.27)	7.17 (2.06)
	9	12.07 (4.31)	3.62 (4.01)	5.73 (3.80)	9.59 (2.70)
	12	17.62 (5.72)	9.19 (5.97)	12.15 (4.48)	13.85 (3.68)
	15	25.89 (7.23)	17.89 (6.91)	20.45 (5.07)	20.86 (4.53)
	18	35.53 (8.23)	27.63 (7.32)	29.89 (5.54)	29.80 (5.14)
	21	45.62 (8.55)	37.49 (7.47)	40.00 (5.70)	39.64 (5.48)
	24	55.51 (8.46)	47.05 (7.52)	50.19 (5.77)	49.71 (5.75)
	27	65.01 (8.20)	56.23 (7.48)	60.28 (5.78)	59.77 (5.93)
	30	74.06 (7.87)	65.01 (7.29)	70.05 (5.87)	69.70 (6.10)
	33	82.29 (7.43)	72.81 (7.11)	79.20 (5.79)	79.10 (6.19)
	36	89.47 (7.00)	79.44 (7.10)	87.55 (5.52)	87.17 (6.22)
	39	95.72 (6.58)	85.44 (6.94)	94.74 (5.32)	94.27 (6.27)
	42	101.05 (6.19)	90.55 (6.77)	100.86 (5.14)	100.20 (6.27)
	45	105.59 (5.88)	94.73 (6.62)	105.85 (4.99)	105.04 (6.19)
Unloading	45	104.28 (5.79)	93.55 (6.55)	104.70 (4.95)	103.82 (6.07)
	42	88.98 (5.57)	78.96 (6.24)	90.30 (4.74)	88.94 (5.79)
	39	74.99 (5.39)	65.60 (5.95)	76.99 (4.52)	75.27 (5.52)
	36	61.90 (5.19)	53.18 (5.70)	64.65 (4.30)	62.56 (5.26)
	33	49.84 (5.07)	41.95 (5.27)	53.17 (4.09)	50.87 (5.02)
	30	38.22 (4.87)	30.66 (5.08)	42.39 (3.83)	39.66 (4.64)
	27	27.69 (4.55)	20.76 (4.76)	32.80 (3.59)	29.50 (4.26)
	24	18.30 (4.14)	12.32 (3.91)	23.93 (3.45)	20.48 (3.89)
	21	10.57 (3.58)	6.57 (2.60)	15.92 (3.24)	12.77 (3.43)
	18	5.06 (3.28)	2.88 (2.05)	9.70 (2.94)	6.68 (2.88)
	15	2.11 (2.71)	0.50 (1.51)	4.06 (2.53)	1.38 (2.20)
	12	1.34 (2.28)	0.09 (1.50)	1.16 (2.22)	-0.41 (1.56)
	9	0.70 (1.96)	-0.02 (1.43)	0.68 (1.99)	-0.68 (1.33)
	6	0.10 (1.63)	-0.21 (1.43)	0.53 (1.78)	-0.78 (1.22)
	3	-0.16 (1.62)	-0.30 (1.45)	0.43 (1.67)	-0.88 (1.19)
	0	-0.96 (1.81)	-0.58 (1.50)	0.43 (1.63)	-1.53 (1.45)

TS: Orthos Twin with stainless steel ligation, TC: Orthos Twin with conventional elastic ligation, DC: Damon Q with conventional sliding door, DS: Damon Q with stainless steel ligation in addition to the sliding door.

Table 2. Comparison of torque (Nmm) between Damon Q bracket with stainless steel ligation (DS) and Damon Q bracket conventionally ligated (DC) at each collection angle (°).

	Torque Angle°	Mean Difference (DS-DC)	*p*-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0.21	>0.99	-1.00	1.41
	3	3.76	< 0.0001	2.45	5.06
	6	4.90	<0.0001	3.01	6.78
	9	3.86	<0.0001	1.26	6.46
	12	1.70	>0.99	-1.80	5.20
	15	0.42	>0.99	-3.78	4.61
	18	-0.08	>0.99	-4.71	4.55
	21	-0.36	>0.99	-5.15	4.44
	24	-0.48	>0.99	-5.31	4.35
	27	-0.51	>0.99	-5.31	4.29
	30	-0.35	>0.99	-5.08	4.39
	33	-0.10	>0.99	-4.72	4.52
	36	-0.38	>0.99	-4.88	4.12
	39	-0.47	>0.99	-4.84	3.90
	42	-0.65	>0.99	-4.90	3.59
	45	-0.81	>0.99	-4.93	3.31
Unloading Angles (descending)	45	-0.88	>0.99	-4.95	3.18
	42	-1.36	>0.99	-5.25	2.53
	39	-1.72	>0.99	-5.44	2.00
	36	-2.09	0.708	-5.65	1.47
	33	-2.30	0.428	-5.68	1.09
	30	-2.73	0.146	-5.94	0.48
	27	-3.30	0.022	-6.29	-0.31
	24	-3.45	0.005	-6.12	-0.77
	21	-3.15	0.002	-5.40	-0.91
	18	-3.02	<0.0001	-4.98	-1.06
	15	-2.68	<0.0001	-4.26	-1.10
	12	-1.57	0.012	-2.90	-0.23
	9	-1.36	0.014	-2.55	-0.18
	6	-1.31	0.007	-2.37	-0.25
	3	-1.32	0.005	-2.35	-0.28
	0	-1.96	<0.0001	-3.06	-0.85

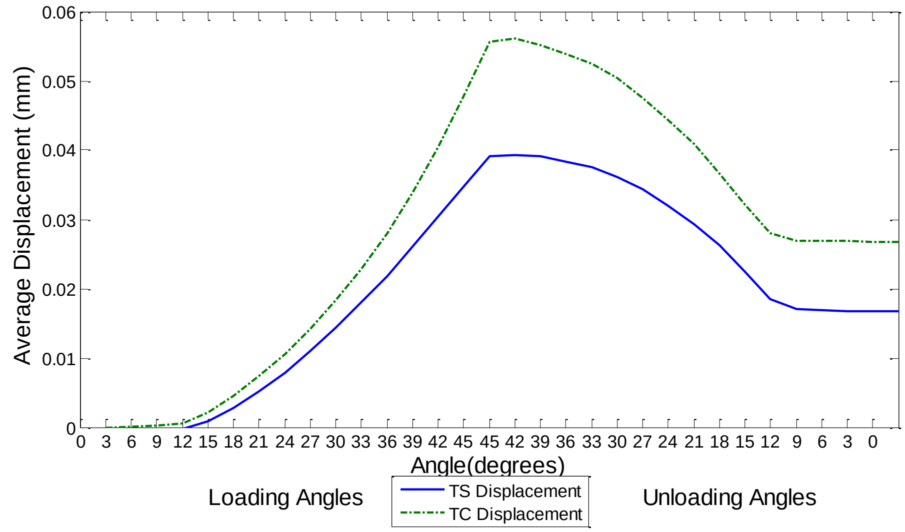
Table 3: Comparison of torque (Nmm) between Orthos Twin bracket with steel ligation (TS) and elastic ligation (TC) at each collection angle (°)

	Torque Angle	Mean Difference	*p*-value	95% Confidence Interval

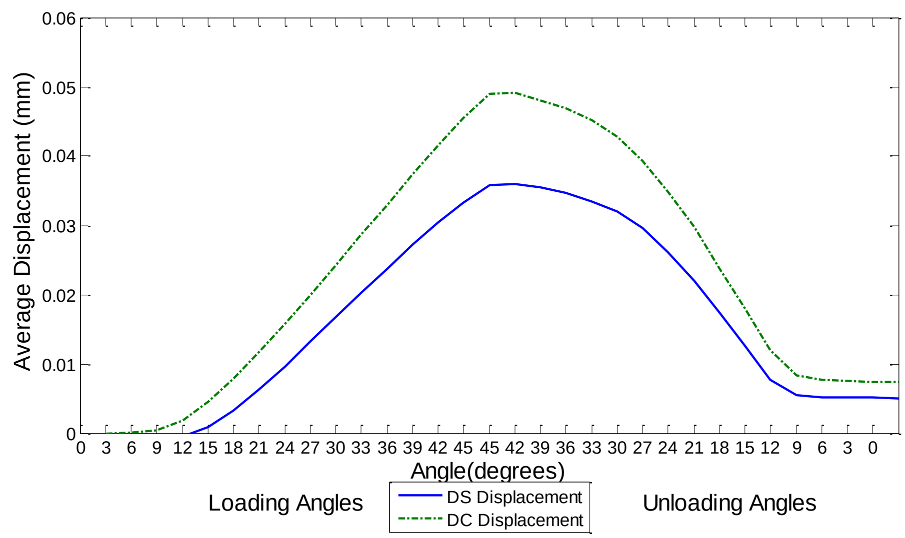
	(Degrees)	(TS-TC)		Lower Bound	Upper Bound
Loading Angles (ascending)	0	0.80	0.455	-0.40	2.01
	3	5.08	< 0.0001	3.78	6.39
	6	7.11	< 0.0001	5.22	8.99
	9	8.45	< 0.0001	5.85	11.05
	12	8.44	< 0.0001	4.94	11.94
	15	8.00	< 0.0001	3.81	12.19
	18	7.91	< 0.0001	3.28	12.54
	21	8.14	< 0.0001	3.34	12.93
	24	8.46	< 0.0001	3.63	13.29
	27	8.79	< 0.0001	3.99	13.59
	30	9.05	< 0.0001	4.31	13.78
	33	9.48	< 0.0001	4.87	14.10
	36	10.03	< 0.0001	5.54	14.53
	39	10.28	< 0.0001	5.91	14.66
	42	10.50	< 0.0001	6.26	14.74
	45	10.86	< 0.0001	6.73	14.98
Unloading Angles (descending)	45	10.74	< 0.0001	6.67	14.80
	42	10.02	< 0.0001	6.13	13.91
	39	9.38	< 0.0001	5.66	13.11
	36	8.72	< 0.0001	5.16	12.28
	33	7.89	< 0.0001	4.51	11.28
	30	7.56	< 0.0001	4.35	10.77
	27	6.93	< 0.0001	3.94	9.92
	24	5.98	< 0.0001	3.30	8.65
	21	4.00	< 0.0001	1.76	6.24
	18	2.18	0.021	0.22	4.13
	15	1.61	0.044	0.03	3.19
	12	1.24	0.083	-0.09	2.58
	9	0.72	0.615	-0.46	1.90
	6	0.32	>0.99	-0.74	1.38
	3	0.13	>0.99	-0.90	1.17
	0	-0.37	>0.99	-1.48	0.73

Table 4: Comparison of torque (Nmm) between Orthos Twin bracket with elastic ties (TC) and Damon Q bracket conventionally ligated (DC) at each collection angle(°).

	Torque angle (Degree)	Mean Difference (TC-DC)	*p*-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0.51	>0.99	-0.692	1.719
	3	0.19	>0.99	-1.113	1.496
	6	-0.46	>0.99	-2.351	1.423
	9	-2.11	0.188	-4.715	0.491
	12	-2.96	0.150	-6.462	0.537
	15	-2.56	0.625	-6.748	1.634
	18	-2.26	>0.99	-6.891	2.367
	21	-2.51	0.978	-7.304	2.287
	24	-3.14	0.504	-7.970	1.694
	27	-4.05	0.152	-8.849	0.747
	30	-5.04	0.030	-9.778	-0.309
	33	-6.39	0.002	-11.011	-1.773
	36	-8.11	< 0.0001	-12.608	-3.612
	39	-9.30	< 0.0001	-13.675	-4.933
	42	-10.30	< 0.0001	-14.547	-6.061
	45	-11.12	< 0.0001	-15.241	-6.993
Unloading Angles (descending)	45	-11.16	< 0.0001	-15.225	-7.093
	42	-11.34	< 0.0001	-15.233	-7.452
	39	-11.39	< 0.0001	-15.107	-7.663
	36	-11.47	< 0.0001	-15.027	-7.905
	33	-11.22	< 0.0001	-14.601	-7.831
	30	-11.73	< 0.0001	-14.938	-8.521
	27	-12.04	< 0.0001	-15.028	-9.051
	24	-11.60	< 0.0001	-14.276	-8.929
	21	-9.36	< 0.0001	-11.599	-7.116
	18	-6.82	< 0.0001	-8.776	-4.862
	15	-3.56	< 0.0001	-5.143	-1.979
	12	-1.06	0.206	-2.398	0.270
	9	-0.71	0.667	-1.886	0.475
	6	-0.75	0.368	-1.808	0.314
	3	-0.73	0.376	-1.763	0.311
	0	-1.01	0.095	-2.121	0.098



A



B

Figure 2 Average bracket width displacement (mm) per angle (°) of wire twist. A: Orthos Twin with stainless steel ligation (TS) vs. Orthos Twin with elastic ties (TC); and B: Damon Q with stainless steel ties (DS) vs. conventional Damon Q (DC).

Table 5. Comparison of bracket displacement (mm) between Orthos Twin with stainless steel ties and Orthos Twin with elastic ties.

	Torque Angle (°)	Mean Difference (TS − TC)	*p*-value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0	0	0.000	0.000
	3	-0.000	<0.0001	-0.001	-0.000
	6	-0.001	<0.0001	-0.001	-0.000
	9	-0.001	0.026	-0.002	-0.000
	12	-0.001	0.018	-0.003	-0.000
	15	-0.002	0.011	-0.004	-0.000
	18	-0.002	0.008	-0.004	-0.000
	21	-0.003	0.006	-0.005	-0.001
	24	-0.003	0.004	-0.006	-0.001
	27	-0.004	0.002	-0.007	-0.001
	30	-0.005	0.001	-0.008	-0.002
	33	-0.006	<0.0001	-0.010	-0.002
	36	-0.008	<0.0001	-0.013	-0.003
	39	-0.010	<0.0001	-0.016	-0.005
	42	-0.013	<0.0001	-0.020	-0.007
	45	-0.017	<0.0001	-0.025	-0.009
Unloading Angles (descending)	45	-0.017	<0.0001	-0.025	-0.009
	42	-0.016	<0.0001	-0.025	-0.008
	39	-0.016	<0.0001	-0.024	-0.008
	36	-0.015	<0.0001	-0.023	-0.007
	33	-0.014	<0.0001	-0.022	-0.007
	30	-0.013	<0.0001	-0.021	-0.006
	27	-0.013	<0.0001	-0.020	-0.005
	24	-0.012	<0.0001	-0.019	-0.005
	21	-0.011	0.001	-0.017	-0.004
	18	-0.010	0.002	-0.017	-0.003
	15	-0.010	0.001	-0.016	-0.003
	12	-0.010	<0.0001	-0.016	-0.004
	9	-0.010	<0.0001	-0.016	-0.004
	6	-0.010	<0.0001	-0.016	-0.004
	3	-0.010	<0.0001	-0.016	-0.004
	0	-0.010	<0.0001	-0.016	-0.004

Table 6. Comparison of bracket displacement (mm) between Damon Q bracket with stainless steel ligation (DS) and Damon Q bracket conventionally ligated (DC) at each collection angle.

	Torque Angle (°)	Mean Difference (DS − DC)	*p*-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0	0	0.000	0.000
	3	-0.001	<0.0001	-0.001	-0.000
	6	-0.001	<0.0001	-0.002	-0.001
	9	-0.002	<0.0001	-0.003	-0.001
	12	-0.004	<0.0001	-0.005	-0.002
	15	-0.005	<0.0001	-0.006	-0.003
	18	-0.005	<0.0001	-0.007	-0.004
	21	-0.006	<0.0001	-0.008	-0.004
	24	-0.007	<0.0001	-0.009	-0.005
	27	-0.007	<0.0001	-0.010	-0.005
	30	-0.008	<0.0001	-0.011	-0.006
	33	-0.009	<0.0001	-0.012	-0.007
	36	-0.010	<0.0001	-0.013	-0.008
	39	-0.011	<0.0001	-0.014	-0.008
	42	-0.012	<0.0001	-0.015	-0.009
	45	-0.013	<0.0001	-0.016	-0.010
Unloading Angles (descending)	45	-0.013	<0.0001	-0.016	-0.010
	42	-0.013	<0.0001	-0.016	-0.009
	39	-0.012	<0.0001	-0.015	-0.009
	36	-0.012	<0.0001	-0.015	-0.009
	33	-0.011	<0.0001	-0.014	-0.008
	30	-0.010	<0.0001	-0.013	-0.007
	27	-0.009	<0.0001	-0.012	-0.006
	24	-0.008	<0.0001	-0.010	-0.005
	21	-0.006	<0.0001	-0.009	-0.004
	18	-0.005	<0.0001	-0.008	-0.003
	15	-0.004	<0.0001	-0.006	-0.002
	12	-0.003	<0.0001	-0.004	-0.001
	9	-0.002	<0.0001	-0.004	-0.001
	6	-0.002	<0.0001	-0.004	-0.001
	3	-0.002	<0.0001	-0.004	-0.001
	0	-0.002	<0.0001	-0.004	-0.001

Table 7. Comparison of bracket displacement (mm) between Orthos Twin brackets ligated with steel ligation (TS) and Damon Q bracket conventionally ligated (DC) at each collection angle (°).

	Torque Angle (°)	Mean Difference (TS-DC)	*p*-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0	0	0.000	0.000
	3	0.000	0.002	0.000	0.000
	6	-0.001	<0.0001	-0.001	-0.000
	9	-0.002	<0.0001	-0.003	-0.001
	12	-0.004	<0.0001	-0.005	-0.002
	15	-0.005	<0.0001	-0.007	-0.003
	18	-0.007	<0.0001	-0.009	-0.004
	21	-0.008	<0.0001	-0.01	-0.005
	24	-0.009	<0.0001	-0.011	-0.006
	27	-0.010	<0.0001	-0.012	-0.007
	30	-0.011	<0.0001	-0.014	-0.007
	33	-0.011	<0.0001	-0.014	-0.007
	36	-0.012	<0.0001	-0.015	-0.007
	39	-0.011	<0.0001	-0.016	-0.007
	42	-0.011	<0.0001	-0.016	-0.006
	45	-0.010	<0.0001	-0.016	-0.004
Unloading Angles (descending)	45	-0.010	<0.0001	-0.015	-0.004
	42	-0.009	<0.0001	-0.015	-0.004
	39	-0.009	<0.0001	-0.014	-0.003
	36	-0.008	0.001	-0.013	-0.003
	33	-0.007	0.005	-0.012	-0.002
	30	-0.005	0.042	-0.010	-0.000
	27	-0.003	0.405	-0.008	0.001
	24	-0.001	0.999	-0.005	0.004
	21	0.002	0.653	-0.002	0.006
	18	0.004	0.049	0.000	0.008
	15	0.006	<0.0001	0.002	0.010
	12	0.009	<0.0001	0.005	0.012
	9	0.009	<0.0001	0.005	0.012
	6	0.009	<0.0001	0.006	0.012
	3	0.009	<0.0001	0.006	0.013
	0	0.009	<0.0001	0.006	0.013

Table 8. Comparison of bracket displacement (mm) between Orthos Twin ligated with stainless steel ligation (TS) and Damon Q bracket ligated with stainless steel ligation at each collection angle (°).

	Torque Angle (°)	Mean Difference (TS-DS)	*p*-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0	0	0.000	0.000
	3	0.000	0.883	-0.000	0.000
	6	0.000	0.774	-0.000	0.001
	9	0.000	0.992	-0.001	0.001
	12	0.000	1.000	-0.001	0.001
	15	-0.001	0.913	-0.002	0.001
	18	-0.001	0.385	-0.003	0.001
	21	-0.002	0.091	-0.004	0.000
	24	-0.002	0.045	-0.005	0.000
	27	-0.003	0.055	-0.005	0.000
	30	-0.002	0.133	-0.005	0.000
	33	-0.002	0.419	-0.005	0.001
	36	-0.001	0.883	-0.005	0.002
	39	0.000	1.000	-0.004	0.004
	42	0.001	0.973	-0.003	0.006
	45	0.003	0.516	-0.002	0.008
Unloading Angles (descending)	45	0.003	0.472	-0.002	0.008
	42	0.003	0.391	-0.002	0.009
	39	0.004	0.313	-0.002	0.009
	36	0.004	0.238	-0.001	0.009
	33	0.004	0.153	-0.001	0.009
	30	0.005	0.063	0.000	0.009
	27	0.006	0.009	0.001	0.010
	24	0.007	<0.0001	0.003	0.011
	21	0.009	<0.0001	0.004	0.013
	18	0.010	<0.0001	0.006	0.014
	15	0.011	<0.0001	0.007	0.014
	12	0.012	<0.0001	0.008	0.015
	9	0.011	<0.0001	0.008	0.015
	6	0.011	<0.0001	0.008	0.015
	3	0.011	<0.0001	0.008	0.015
	0	0.012	<0.0001	0.008	0.015

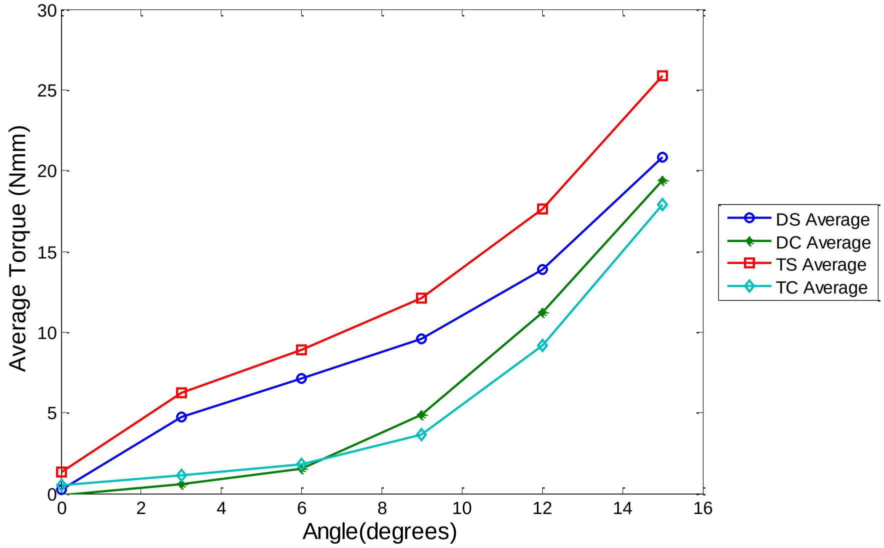


Figure 3 First 15° of loading of averaged torque (Nmm) vs. wire twist angle (degrees) for all brackets groups.

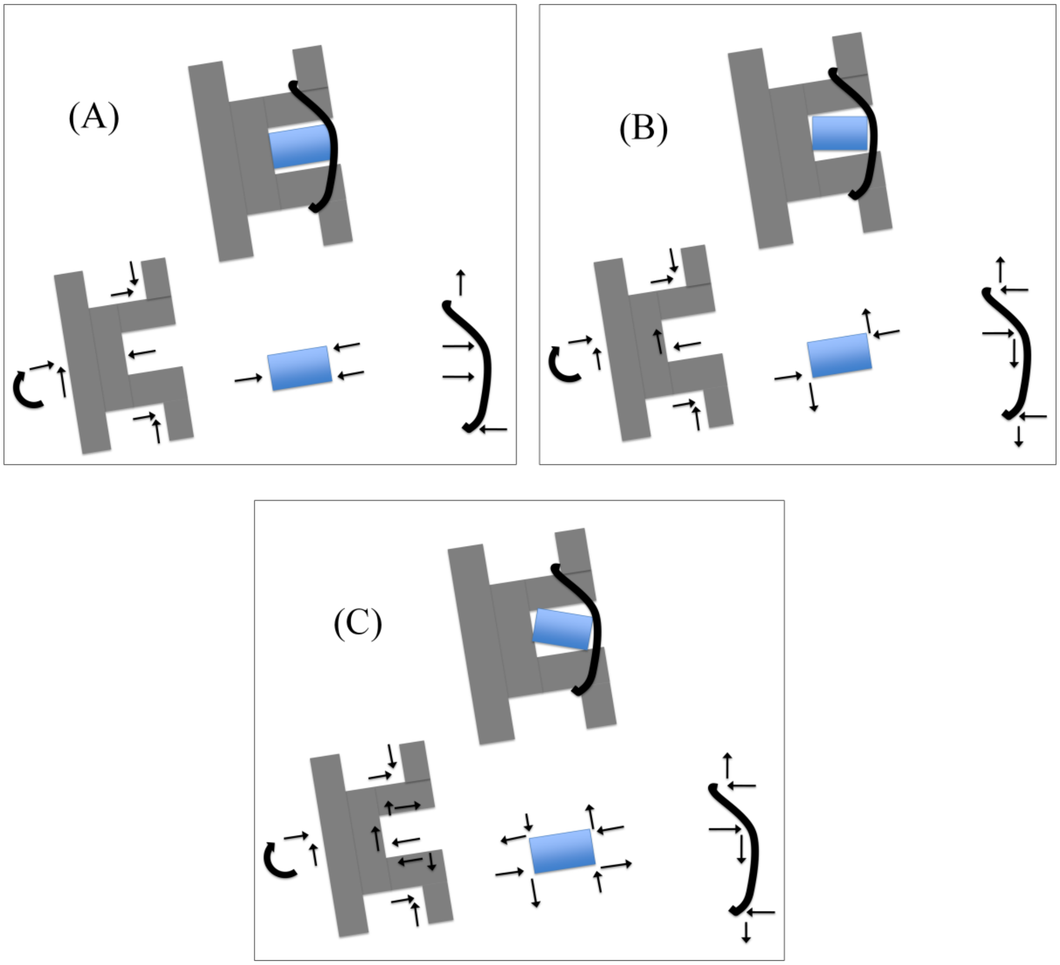


Figure 4 Profile image of a bracket with the archwire and the steel ligation. The arrows represent forces and couples exerted at each part (bracket, wire, and steel ligation) separately as wire rotate: (A) wire is at 0° the steel ligation exerting some forces on the wire and bracket, no motion is occurring, (B) wire rotated but not engaged yet with the slot walls, steel ligation forces has resulted in a couple at the wire and the bracket, and (C) wire rotated and now engaged into the slot walls forming a second couple. The sum of the two couples is larger than the couple formed by the ligature. As the wire is rotated further the magnitude of the couple formed by the bracket walls becomes much larger than the couple formed by the steel ligature.