Original Article

Evaluation of the Frictional Resistance of Conventional and Self-ligating Bracket Designs Using Standardized Archwires and Dental Typodonts

Sandra P. Henao, BS[a]; Robert P. Kusy, BS, MS, PhD[ab]

Abstract: The frictional behavior of four conventional and four self-ligating brackets were simulated using a mechanical testing machine. Analyses of the two-bracket types were completed by drawing samples of three standardized archwires through quadrants of typodont models in the dry/wet states. Pretreatment typodonts of an oral cavity featured progressively malocclused quadrants. As nominal dimensions of the archwires were increased, the drawing forces of all brackets increased at different rates. When coupled with a small wire, the self-ligating brackets performed better than the conventional brackets. For the 0.014-inch wires in the upper right quadrant, the maximum drawing forces averaged 125 and 810 cN for self-ligating and conventional brackets, respectively. When coupled with larger wires, various designs interchangeably displayed superior performance. For the 0.019- $\times$ 0.025-inch wires in the upper left quadrant, the maximum drawing forces averaged 1635 and 2080 cN for self-ligating and conventional brackets, respectively. As the malocclusion increased, the drawing forces increased. For example, in the least malocclused quadrant and with the smallest wire, maximum drawing forces for self-ligating and conventional brackets averaged 80 and 810 cN, respectively, whereas in the most malocclused quadrant tested with the same wire size, maximum drawing forces for self-ligating and conventional brackets averaged 870 and 1345 cN, respectively. For maximum values between the dry and wet states, significant differences between ambient states existed only for the In-Ovation brackets in the lower left quadrant. These test outcomes illustrated how bracket design, wire size, malocclusion, and ambient state influenced drawing forces. (*Angle Orthod* 2004;74:202–211.)

Key Words: Frictional resistance; Conventional brackets; Self-ligating brackets; Typodonts; Archwires

INTRODUCTION

During tooth movement, many factors exist that influence frictional forces. Comparative studies have found these factors to be vital when practitioners are choosing orthodontic materials.[1–4] Pizzoni et al[5] found that understanding archwire alloy, dimension, and angulation is crucial in frictional analysis. Frank and Nikolai[4] reported that increases in wire dimension, wire material, angulation, and ligation forces increased frictional resistance (FR). These four parameters, along with interbracket distance (IBD), accounted for a significant percentage of the variance in the FRs measured. Kusy and Whitley[6] incorporated a combination of parameters such as wire size (SIZE), bracket width (WIDTH), and dimension of the bracket slot (SLOT) to determine an equation for the critical contact angle (θ_c) for any archwire-bracket couple. Later, in a three-bracket study, Kusy and Whitley[7] emphasized the importance of sliding at or below θ_c. An engagement index (SIZE/SLOT) and a bracket index (WIDTH/SLOT) were defined, and an inverse correlation was found between the resistance to sliding (RS) and IBD for all alloys tested.

The aforementioned factors are critically important when considering the clinical application of sliding mechanics. After comparing in vivo and in vitro test values, Jost-Brinkmann and Miethke[8] concluded that frictional forces of immobile brackets in a laboratory setting were similar to forces exerted in a clinical setting. This conclusion validates the contention that laboratory results can predict clinical outcomes.

Regarding design, self-ligating brackets have been modified from the conventional brackets to increase efficiency

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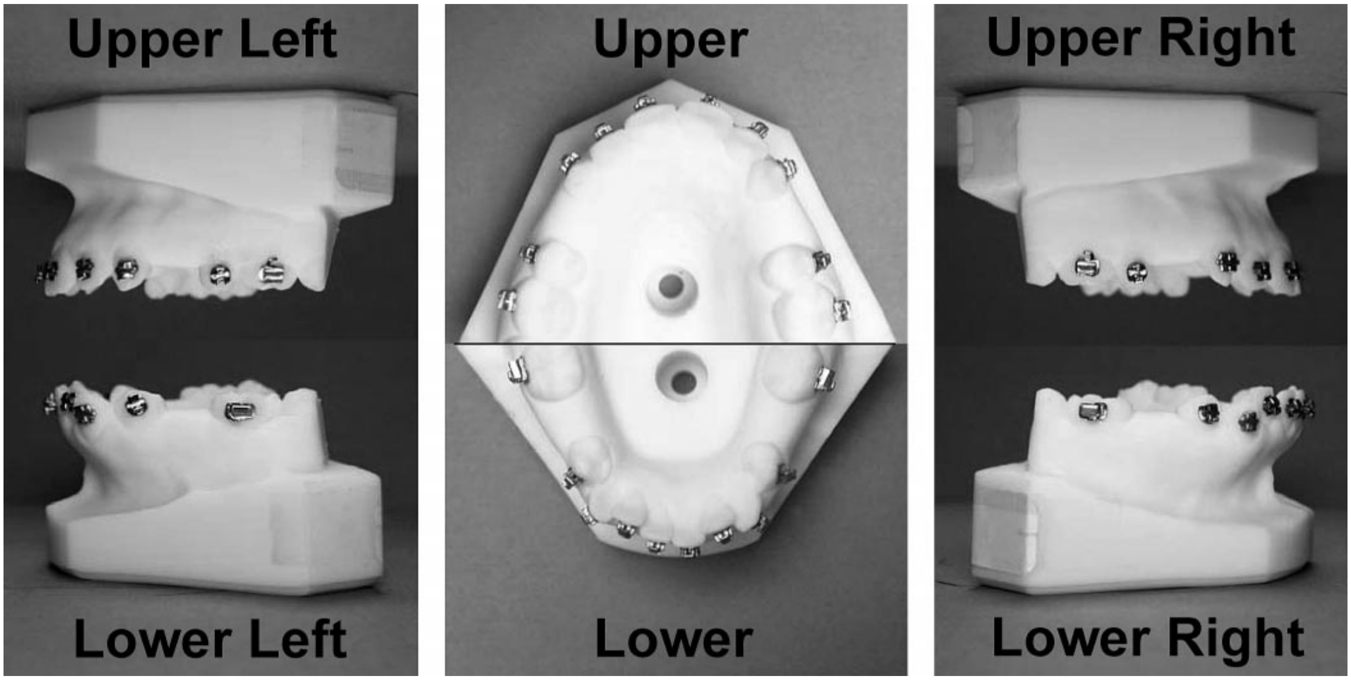


FIGURE 1. Photographs of the typical typodont model featuring the bracket placement of the TE design from six positions. Top row: UL, upper aerial view, and UR; bottom row: LL, lower aerial view, and LR.

and reproducibility and reduce RS. Their unique, ligatureless design decreased FR.[9,10] When comparing self-ligating brackets with conventional brackets, the wire size and material,[2,5,11] the mode of self-ligation,[10,12,13] and the angulation[11,14,15] have influenced FR. Pizzoni et al[5] reported that the Damon SL has no normal force at 0° angulation when coupled with rectangular wires. Moreover, Damon[12] emphasized that proper rotational control was possible when the correct wire sizes were used, which resulted in the low friction and force loads that are expected with this passive mode of self-ligation. The manufacturer claimed that the In-Ovation design was the only twin bracket that featured an active clip, which enhanced hygiene and reduced friction.[16] The SPEED brackets have been purported to experience lower friction at wire dimensions of up to 0.016 × 0.022-inch.[5,15,17] Likewise, Time brackets have reportedly shown near-frictionless movement in the initial stages of treatment with wire dimensions up to 0.018-inch.[18] When compared with conventional brackets, self-ligating brackets exhibited superior performance with respect to lower friction values, reduced treatment times, and increased patient comfort.[3,10,12,13,18,19]

In this investigation, drawing forces were measured when the same three sizes of nickel-titanium wires were passed through typodont models mounted with conventional and self-ligating brackets. In the past, dry- and wet-state studies have reported on self-ligating brackets and their behavioral characteristics: efficiency and reproducibility. The aim of this investigation is to confirm these behavioral characteristics in the multibracket testing situation. Furthermore, this investigation will determine how comparable conventional and self-ligating brackets are when clearances and IBDs decrease. In the wet state, test results will confirm whether self-ligating brackets maintain their superior characteristics compared with self-ligating tests in the dry state and conventional bracket tests in the wet state.

MATERIALS AND METHODS

Materials

Twenty-four typodont models (Allesee Orthodontic Appliances, Sturtevant, Wis) were replicated from a patient's oral cavity that displayed the misalignment of teeth before treatment in both the upper and the lower arches (Figure 1). Four participating manufacturers (Sybron Dental Specialties Ormco, Orange, Calif; GAC International Inc., Islandia, NY; Strite Industries Limited, Cambridge, Ontario, Canada; and American Orthodontics, Sheboygan, Wis) had clinicians mount their respective self-ligating brackets (Damon 2, In-Ovation, SPEED, and Time) onto five typodont models (Table 1). All brackets were mounted in the clinically appropriate position using a cyanoacrylate adhesive (Loctite 416, Loctite Corp. Rocky Hill, Conn). Each typodont was inspected for general anatomical appropriateness before one of the five models from each manufacturer was selected for frictional evaluations. Additionally, each participating manufacturer had conventional brackets mounted on a sixth typodont model. Three standard austenitic nickel-titanium (NiTi-A) archwires (Table 1), which were a representation of the wires used in various stages of orthodon-

TABLE 1. List of Self-Ligating Brackets, Participating Manufacturers, Archwires, and Conventional Brackets

Self-Ligating Bracket[a]	Participating Manufacturer[b]	NiTi-A[c] Archwire[d], Nominal Dimension (mil)	Conventional[e] Bracket[a]
Damon 2	Sybron Dental Specialties Ormco	14[f]	MD-SDS[g]
		16 × 22[h]	
		19 × 25[i]	
In-Ovation	GAC International	14[f]	MD-GAC[g]
		16 × 22[h]	
		19 × 25[i]	
SPEED	Strite Industries	14[f]	TE[j]
		16 × 22[h]	
		19 × 25[i]	
Time	American Orthodontics	14[f]	MMHT[k]
		16 × 22[h]	
		19 × 25[i]	

[a] Bracket slots had nominal slot dimensions of 22 mil.
[b] Participating manufacturers mounted their respective self-ligating brackets onto a typodont model.
[c] Nickel-titanium in the austenitic phase.
[d] Investigators obtained archwires directly from the manufacturers.
[e] Participating manufacturers selected, obtained, and mounted conventional brackets onto typodonts.
[f] Highland Metals, San Jose, Calif.
[g] Mini Diamond, Sybron Dental Specialties Ormco, Orange, Calif.
[h] RMO, Denver, Colo.
[i] Dentaurum, Pforzheim, Germany.
[j] Tip-Edge, TP Orthodontics, LaPorte, Ind.
[k] Mini Mono High Tech, Forestadent, Pforzheim, Germany.

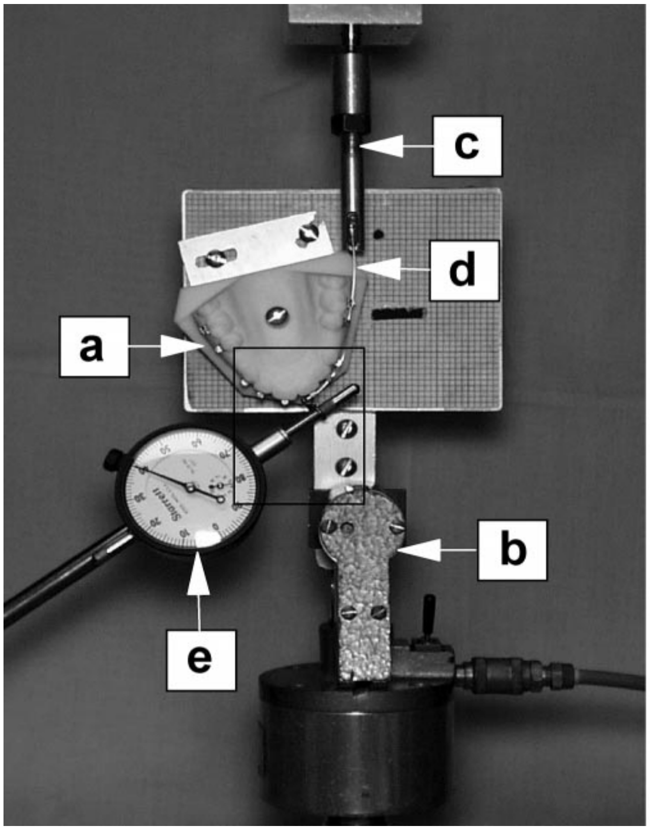
tic treatment, were selected and coupled with the self-ligating and conventional brackets.

Methods

The drawing force (P) values were evaluated in four quadrants: upper left (UL), upper right (UR), lower left (LL), and lower right (LR). A ranking of quadrants relative to the degree of malocclusion was determined by subjectively examining each quadrant and objectively applying a variant of Little's Irregularity Index[20] that incorporated three dimensions. Further supported by experimental results that are presented in the next section, the following order is the rank from the least malocclused quadrant to the most malocclused quadrant: UL, UR, LL, and LR. For all self-ligating and conventional brackets, tests were run in the dry state at an oral ambient temperature of 34°C. The self-ligating In-Ovation brackets and the conventional Mini Diamond SDS (MD-SDS) brackets were also tested in the wet (saliva) state at 34°C using only the 0.014-inch NiTi-A archwire (AW). Conventional brackets were ligated with elastic modules (Ligature Ringlet, RMO, Denver, Colo).

For frictional evaluations, each typodont model (Figure 2a) was attached to the crosshead of a mechanical testing machine (Instron Model TTCM, Instron Corp., Canton, Mass) through a pneumatic grip (Figure 2b). Using a custom-designed adaptor (Figure 2c), the AWs (Figure 2d) were gripped by crimping brass fittings onto the distal ends. In the standard testing sequence, each run began with a 0.014-inch AW, followed by a 0.016- × 0.022-inch AW, and then a 0.019- × 0.025-inch AW. This sequence was then repeated using a new wire for two samples per wire size per quadrant. For the conventional brackets, one minute was allotted for ligation of elastic modules, followed by a three-minute waiting period to allow a reproducible amount of stress relaxation to occur. Wet-state tests followed the same testing sequence. Here, the whole saliva of the primary investigator was used and found to be within normal viscosity limits.[21] A dial indicator (L.S. Starrett Co. Athol, Mass) (Figure 2e) that was fitted with an arm extension (Figure 2f) was positioned at the mesial end of the AW to ensure that movement occurred through all five brackets with a crosshead speed of 0.5 mm/min. From the time (t) vs P curves, nine data points (t, P) were recorded for AW movements in 0.25-mm increments. Once AW movement began, each run was approximately five minutes (2.00 mm). Load values were applied to a power regression equation $P = Xt^Z$, where P is in centi-Newtons (cN) (where 1 cN ≈ 1 g), t is cumulative time in minutes, and X and Z are constants. Unless otherwise stated, the lines represented the combined regression of two samples.

Intravariance was evaluated between various samples of the same AW size for In-Ovation and MD-SDS brackets. As separate experiments, three different sequences of testing were used: standard (previous paragraph), consecutive, and alternating. In the standard testing sequence (A1 and A2), two AWs for each design were run. In the consecutive testing sequence (B1, B2, and B3), three AWs for each design were run. In the alternating testing sequence (C1,



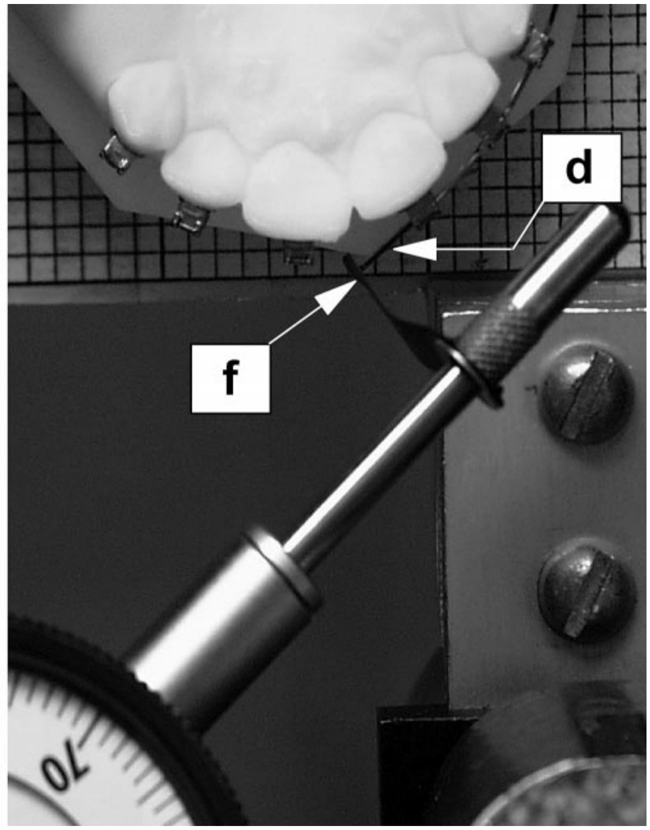


FIGURE 2. Representative photographs of the Damon 2 typodont (a) held in place through a pneumatic grip (b) that is mounted onto the crosshead (below but not shown) of the Instron machine. The custom-designed adaptor (c) is suspended by a 50-kg load cell (above but not shown), and a 0.016- × 0.022-inch NiTi-A AW (d) is ligated to the UR quadrant. A dial indicator (e) is positioned at the mesial end of the AW, where contact is monitored using an arm extension (f) of the dial.

C2, and C3), each AW was tested by alternating between a conventional and a self-ligating typodont model for each run.

For statistical analyses, Student's *t*-tests[22] were used to determine significance for bracket placement among models and between dry and wet states. Multivariate analysis of variance (MANOVA) (Systat Version 10.2, Systat Software Inc, Richmond, Calif) was used to determine significance and interactions among bracket type (conventional and self-ligating), bracket design (MD-SDS, Mini Diamond GAC [MD-GAC], Mini Mono High Tech [MMHT], Tip-Edge [TE], In-Ovation, Time, Damon 2, and SPEED), archwire sizes (0.014 inch, 0.016 × 0.022-inch, and 0.019 × 0.025-inch), and quadrants (UL, UR, LL, and LR). Nonsignificant (NS) values were defined as $P > .05$.

RESULTS

Typical intravariance of self-ligating and conventional brackets

The variations of the power regression curves could be seen for eight 0.014-inch AWs that were drawn through the most malocclused LR quadrant (Figure 3). Both In-Ovation and MD-SDS bracket designs showed a similar amount of scatter in P values (Figure 3, top row), the estimated differences between minimum and maximum data sets being approximately 400 cN. From this series of experiments, the average power regression curve through 72 data points (Figure 3, bottom row) showed that the P values for In-Ovation (875 cN at five minutes) were slightly lower than those for MD-SDS (1075 cN at five minutes). This difference was attributed to the presence of data sets A1 and A2 in the MD-SDS conventional brackets (Figure 3, lower right).

Overview of conventional brackets

For the conventional designs, the P values predictably increased as AW size increased (Table 2). Moreover, the P values tended to increase as malocclusion increased, thereby making AW engagement more problematic. Specifically comparing MD-SDS with MD-GAC, these conventional brackets showed that the MD-SDS design gave lower frictional results than the MD-GAC design, more often in the upper quadrants than in the lower quadrants. This outcome could be attributed to some variability in bracket manufacturing or to subtle differences in the positioning of the brackets on the teeth. However, statistical analysis indicated

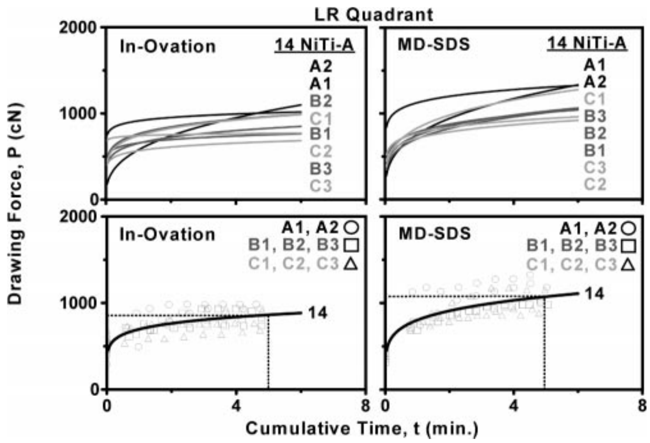


FIGURE 3. Variability of the drawing forces (P) against the cumulative times (t) for eight AWs of 0.014-inch NiTi-A. The individual power regression lines (top row) and the average power regression line through 72 data points (bottom row) were tested in three different experiments: A (○), B (□), and C (△). Wires were drawn through the LR quadrant of the In-Ovation bracket design (left column) and the MD-SDS–type bracket design (right column).

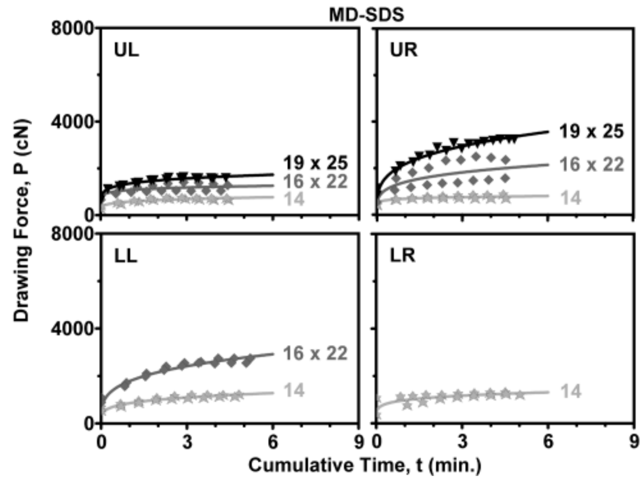


FIGURE 4. For a conventional bracket MD-SDS, influence of the P values against t in four quadrants (UL, UR, LL, and LR) for three different AW sizes: 0.014 inch (✻), 0.016 × 0.022-inch (♦), and 0.019 × 0.025-inch (▼) NiTi-A. Note that approximately five minutes elapsed for every 2.00 mm distance traveled.

that there were NS differences between the values of the two models in every quadrant except the UL (where $P = .02$). For each AW size, the dispersion of the data points for the two samples was referred to as the domain of its P values. The domains seen in Figure 4 did not overlap, and the distances between regression curves in Figure 4 increased from quadrant to quadrant as tooth irregularity increased (see Figure 1), progressing from the UL to the UR,

TABLE 2. In the Dry State, Ranges of P Values for the Conventional Brackets in Four Quadrants

			P (cN)							
			At UL		At UR		At LL[b]		At LR[b]	
Bracket	Wire[a] Size (mil)	Wire Sample	Min	Max	Min	Max	Min	Max	Min	Max
MD-SDS	14	1	260	700	450	875	700	1225	1100	1325
		2	420	740	400	700	550	1125	375	1225
	16 × 22	1	650	1400	925	2500	1100	2750	—	—
		2	675	1050	550	1575	900	2550	—	—
	19 × 25	1	640	1630	1125	3250	—	—	—	—
		2	640	1590	850	3250	—	—	—	—
MD-GAC	14	1	590	900	550	1000	1150	1475	450	1350
		2	500	870	550	900	600	1075	550	1525
	16 × 22	1	630	1560	1825	3475	1325	3200	—	—
		2	870	1510	975	1775	1025	2500	—	—
	19 × 25	1	830	1810	775	4075	—	—	—	—
		2	860	1790	1175	3000	—	—	—	—
MMHT	14	1	540	920	550	925	425	725	—	—
		2	615	960	525	750	475	925	—	—
	16 × 22	1	775	2350	700	1575	—	—	—	—
		2	1050	2100	650	1725	—	—	—	—
	19 × 25	1	1800	3350	1075	1950	—	—	—	—
		2	1525	3100	1225	2150	—	—	—	—
TE	14	1	350	675	500	650	700	1275	275	1100
		2	340	680	325	650	425	1025	775	1525
	16 × 22	1	400	800	400	925	—	—	—	—
		2	450	1075	500	975	—	—	—	—
	19 × 25	1	700	1875	550	1425	—	—	—	—
		2	475	1475	450	1175	—	—	—	—

[a] Wires are all NiTi-A.
[b] Quadrants in which any or all of the wires could not engage into the bracket slot, as shown by the dash.

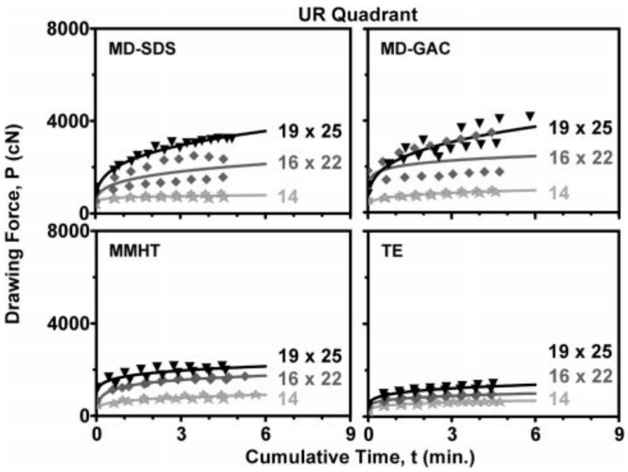


FIGURE 5. For all designs of the conventional bracket classification (MD-SDS, MD-GAC, MMHT, and TE), influence of the P values against t for 14 (✻), 0.016- × 0.022-inch (♦), and 0.019- × 0.025-inch (▼) NiTi-A AWs drawn through the UR quadrant.

to the LL, and then to the LR. Although Figure 4 only illustrates the results for the MD-SDS bracket design, the MD-GAC, MMHT, and TE results followed similar trends in domain from quadrant to quadrant. The UR quadrant showed the most variation among designs, and the 0.016- × 0.022-inch AW domain overlapped the 0.019-× 0.025-inch AW domain for the MD-GAC design (Figure 5). Among conventional designs, the TE bracket design always had average maximum P values that were the lowest in every run, except for those in the LL quadrant, where MMHT had average maximum P values that were lower than those of TE (Table 2). Statistically significant differences ($P < .01$) existed among the conventional designs.

Overview of self-ligating brackets

As expected, maximum P values (ie, the P_{max} values) increased as AW size increased. Values ranged from those that were nearly frictionless to those in excess of 7000 cN (Table 3). Moving across Table 3 from left to right showed increasing P_{max} values, with a few exceptions: for example, the UL quadrant gave higher maximum values than the UR quadrant for the two 0.019- × 0.025-inch AW samples coupled with In-Ovation brackets and for the first sample of the 0.014-inch AW coupled with SPEED brackets. For each quadrant, the domains of the three AW sizes did not overlap for the In-Ovation brackets (Figure 6). Although not shown, the Damon 2, SPEED, and Time brackets showed a similar trend of distinction in domains for different AWs. Variability in the performance of the individual archwire-brack-

TABLE 3. In the Dry State, Ranges of P Values for the Self-Ligating Brackets in Four Quadrants

			P (cN)							
			At UL		At UR		At LL[b]		At LR[b]	
Bracket	Wire[a] Size (mil)	Wire Sample	Min	Max	Min	Max	Min	Max	Min	Max
In-Ovation	14	1	40	65	90	120	250	450	300	1000
		2	30	45	50	110	350	450	400	1000
	16 × 22	1	540	840	910	1270	900	3580	—	—
		2	470	730	490	920	750	3500	—	—
	19 × 25	1	800	2010	900	1780	1250	5200	—	—
		2	810	1890	1040	1660	880	7060	—	—
Time	14	1	25	50	65	95	600	800	450	900
		2	25	50	50	55	600	800	625	950
	16 × 22	1	540	740	650	980	1250	3800	—	—
		2	540	690	490	1300	1300	3800	—	—
	19 × 25	1	900	2425	1650	2525	—	—	—	—
		2	500	2075	1425	2100	—	—	—	—
Damon 2	14	1	5	10	125	225	250	600	450	650
		2	5	10	150	175	250	350	250	675
	16 × 22	1	210	590	750	1700	650	4125	—	—
		2	170	500	375	1225	775	2700	—	—
	19 × 25	1	470	1020	110	2700	—	—	—	—
		2	540	1120	1000	2675	—	—	—	—
SPEED	14	1	225	305	100	100	250	550	600	875
		2	60	95	75	125	200	450	625	900
	16 × 22	1	540	1140	650	1225	1050	3450	—	—
		2	480	1140	625	1325	500	2000	—	—
	19 × 25	1	610	1160	1125	2000	1750	6350	—	—
		2	640	1370	1025	1925	1275	4475	—	—

[a] Wires are all NiTi-A.
[b] Quadrants in which any or all of the wires could not engage into the bracket slot, as shown by the dash.

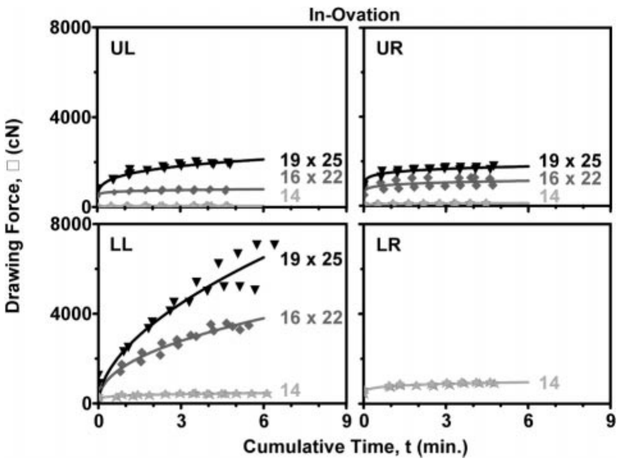


FIGURE 6. For a self-ligating bracket (In-Ovation), influence of the P values against t as detailed in Figure 4.

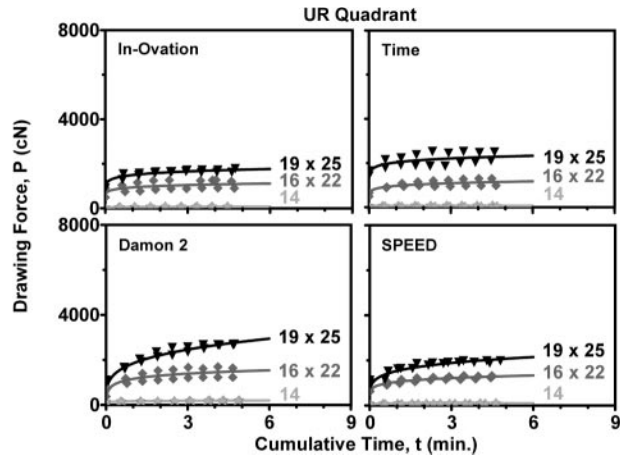


FIGURE 7. For all designs of the self-ligating classification (In-Ovation, Time, Damon 2, and SPEED), influence of the P values against t as detailed in Figure 5.

et couples and the size of the disparity between the curves from one design to another became apparent in the UR quadrant (Figure 7). Overall, no significant differences were observed among the self-ligating designs.

Comparison of conventional and self-ligating brackets

In general, the MANOVA indicated significant differences ($P < .01$) between the conventional and self-ligating brackets. However, when taking into account one wire size, the 0.014-inch AWs, statistically significant differences ($P < .001$) were observed between the two bracket types. When coupled with the 0.016- × 0.022-inch and the 0.019- × 0.025-inch AWs, NS differences existed between the two bracket types.

Outcomes in the wet state

In the least maloccluded quadrant (UL), the average P_{max} values were 50 cN for In-Ovation and 600 cN for MD-SDS. In the most maloccluded quadrant (LR), the average P_{max} values were 830 cN for In-Ovation and 980 cN for MD-SDS. The P_{max} values in the wet state increased with malocclusion from quadrant to quadrant, with one exception: For the MD-SDS brackets in the LL and the LR quadrants, the average P_{max} values were 1230 and 980 cN, respectively (Table 4). For either bracket type, initial statistical analyses indicated that there were NS differences between the dry and wet states, except for the In-Ovation brackets in the lower quadrants. The absence of a standard deviation in the P_{max} values caused a breakdown in the *t*-test's algorithm. A new *t*-test was performed that included all data points recorded for 0.014-inch AWs in the dry and wet states. The outcome of this test indicated significant differences ($P = .02$) between dry and wet states in the LL quadrant but NS differences in the LR quadrant.

DISCUSSION

Influence of repeated testing on the brackets

The rigid nature of the typodonts did not accommodate the physiological capabilities of in vivo teeth that would normally possess force-absorbing mechanisms. Nonetheless, the typodonts did represent some important testing variables, among which were maximal limitations and tooth irregularities. The lower quadrants exhibited more irregularity than the upper quadrants. Thus, the inherently smaller IBDs of the lower quadrants further increase the P values. Although three AW sizes were investigated, these same AW sizes were used for all runs to eliminate all other frictional variables except bracket design.

TABLE 4. In the Wet State, Ranges of P Values for a Conventional and a Self-Ligating Bracket Design in Four Quadrants

			P (cN)							
			At UL		At UR		At LL		At LR	
Bracket	Wire[a] Size (mil)	Wire Sample	Min	Max	Min	Max	Min	Max	Min	Max
MD-SDS	14	1	340	540	440	960	640	1230	540	910
		2	490	660	740	1050	710	1230	420	1050
In-Ovation	14	1	50	50	100	100	290	390	450	830
		2	50	50	70	100	270	390	690	830

[a] Wires are all NiTi-A.

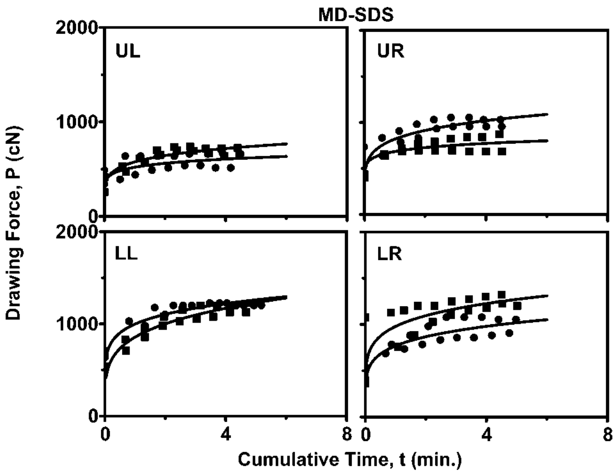


FIGURE 8. In the dry (■) and wet (●) states, influence of the P values against t for a conventional bracket (MD-SDS) coupled with 0.014-inch NiTi-A AWs in four quadrants (UL, UR, LL, and LR).

The scatter seen from such tests (Figure 3) was indicative of the least and greatest amount of difference in data sets that could be seen from repeatedly running 0.014-inch AWs through the same quadrants. When the results from experiment A (standard sequence) and experiment C (alternating sequence) were compared, a general trend of decreasing P values was seen (Figure 3, top row). Because the estimated differences between the highest and lowest data sets for MD-SDS and In-Ovation were similar, the uniform scatter permitted one to distinguish between the average power regression curves (Figure 3, bottom row). However, when considering how data sets A1 and A2 influenced the regression of the curve for the MD-SDS brackets, the results between the two bracket types appeared more comparable. Focusing on the dry state in Figures 8 (■) (MD-SDS) and 9 (In-Ovation), the two designs coupled with a 0.014-inch AW produced P values and levels of scatter that generally increased as the malocclussion of the quadrant increased. Therefore, the comparative behavior of the two averaged curves in Figure 3 (bottom row) may be explained by the high level of malocclusion that caused the P values and the amount of scatter to appear similar.

Influence of malocclusion

Similar trends were observed from quadrant to quadrant for either conventional brackets or self-ligating brackets (Tables 2 and 3). On the basis of these trends the least maloccluded quadrant was the UL and the most maloccluded quadrant, the LR. Statistical analysis showed the quadrants to be significantly different ($P < .001$). A least–mean squares plot also confirmed the ranking order of the quadrants that was previously established: UL, UR, LL, and LR. Because the lower arch is considerably smaller than the upper arch, the decrease in IBDs and an inherent presence of more rotation, angulation, and torque in the pretreatment typodont models enhanced the P values of the lower quadrants. The increasing friction that was caused, in part, by decreasing IBDs and increased angulations was consistent with the results of Read-Ward et al,[2] Frank and Nikolai,[4] Kusy and Whitley,[7] and Thorstenson and Kusy.[23] The number of wires that could not be engaged into the bracket slots further underscored the presence of more malocclusion in the lower arch—particularly as wire size increased.

Influence of wire size

Aside from the quadrant to quadrant variations, both conventional and self-ligating brackets displayed an increase in P values as AW size increased and AW clearance decreased (Figures 4–7). High frictional values from increased wire sizes and decreased amounts of clearance were consistent with previous studies.[2,4,6,7,11] Wire size also influenced the statistical significance between the conventional and self-ligating brackets. Performing a two-factor MANOVA for each wire size revealed significant differences ($P < .001$) among bracket types coupled with 0.014-inch AWs, whereas the two larger wires exhibited NS differences among the bracket types. Thus, the bracket types become more comparable with larger wire sizes. The absence of overlap in regression curves from a small AW to a larger AW was expected.

Influence of bracket design

These experiments did not test larger AWs to suggest that they should be considered for sliding. Instead, the experiments used the larger wires to identify more readily those limitations that exist for different brackets. Consequently, for each AW size tested against conventional brackets, the lowest P_{max} value within the four quadrants occurred for the TE design in six out of eight possible samples (Table 2). Its unique design accommodated more clearance than the other three designs, at the expense of controlling the continuity of AW engagement throughout the runs. Significant differences ($P < .01$) were found among the conventional designs. However, once the influence of the TE design was accounted for, a least–mean squares plot revealed more comparability among the MD-SDS, MD-GAC, and the MMHT designs. Hence, among these remaining conventional designs, the MD-SDS design had the lowest P_{max} value for six out of nine possible samples of each AW size within the four quadrants.

When the self-ligating brackets were added to the group, the P_{max} values of all self-ligating designs were lower than the P_{max} values of the conventional designs for each 0.014-inch AW sample in every quadrant (Tables 2 and 3). Concurrent with past studies, this confirmed that self-ligating brackets exhibited superior performance when coupled with smaller wires that are used in the early stages of orthodontic treatment.[2,3,5,9,11,12,15,17,18] However, when the larger 0.016- × 0.022-inch and 0.019- × 0.025-inch AWs were tested, the differences between the conventional and self-ligating brackets were not as evident. These results confirmed the ability of self-ligating brackets to maintain low frictional resistances only up to a certain size of AW.[5,12,15,17,18] This observation was consistent with past inconsistency between the extremely low friction associated with round wires and the extremely high friction associated with rectangular wires.[5,9] The multibracket nature of our experiment only accentuated this discrepancy. In the two quadrants that represented the extremes of malocclusion (UL and LR), the low frictional results of the Damon 2 suggested that the passive slide design may be the most accomodating of the bracket designs tested, albeit at the expense of some loss of control. This finding was consistent with other studies that compared the Damon SL bracket with the Time and SPEED brackets.[9,12]

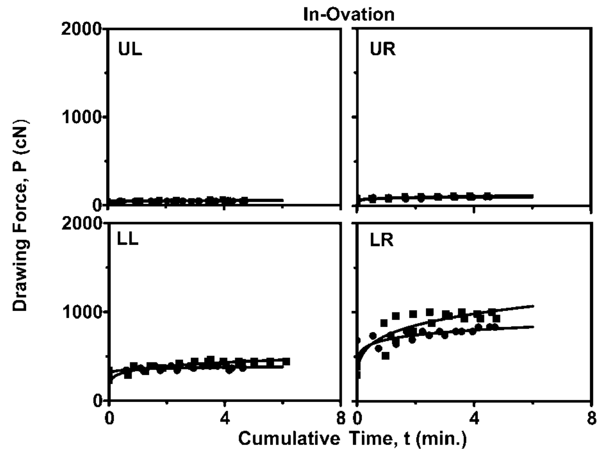


FIGURE 9. In the dry (■) and wet (●) states, influence of the P values against t for a self-ligating bracket (In-Ovation) as detailed in Figure 8.

Influence of bracket placement

The influence of bracket manufacturing and placement on the P_{max} values was readily noted when MD-SDS and MD-GAC were compared. The MD-SDS brackets consistently produced lower P_{max} values than the MD-GAC brackets in the UL quadrant, but no clear dominance in the UR, LL, or LR quadrants was observed (Table 2). Because NS differences between the values of the two models were observed in the UR, LL, and LR quadrants, the very small subtleties in bracket manufacturing and placement from model to model were not considered controlling factors. Note that in the early stages of orthodontic treatment, the proper bracket placement does not always imply lower P_{max} values—a complicating factor that was not considered in this investigation.

Influence of wet state on multibracket testing

When coupled with 0.014-inch AWs, the MD-SDS bracket design gave results in the wet state that were mixed compared with the results in the dry state (Figure 8). In the UL and LR quadrants, the MD-SDS brackets gave lower P_{max} values in the wet state than in the dry state; in the UR and LL quadrants the P_{max} values were higher in the wet state than in the dry state. When coupled with 0.014-inch AWs in the UL, UR, and LR quadrants, the In-Ovation bracket design gave P_{max} values in the wet state that were either similar to or lower than those in the dry state (Figure 9). For the LL quadrant, significant differences ($P = .02$) indicated by the Student's *t*-test were attributed to the small standard deviations present within the data sets for both ambient states. A closer look at the results of the *t*-test showed that the mean values for the dry (358 cN) and wet (398 cN) states differed by only 40 cN. Therefore, after taking into account the above-mentioned factors and the reproducibility of the self-ligating bracket, the results for the dry and wet states in the LL quadrant were considered similar. The overall variation in the effect of saliva confirmed the inconsistency seen between tests conducted in the dry and wet states.[2,14,24]

When comparing the two bracket designs, In-Ovation displayed much lower P values than MD-SDS when the malocclusion was mild. The scatter was also much less. When malocclusion was substantial, the results followed the same trend as in the dry state (see section Influence of Repeated Testing on the Brackets in Discussion). These results conveyed that efficiency and reproducibility, which are distinctive characteristics of self-ligating brackets, were maintained in the wet state until the malocclusion was substantial.

Future work

These frictional experiments strive to bridge the gap between single- or triple-bracket in vitro testing and in vivo evaluations. The use of the same typodont models, the same three AW sizes, and eight different bracket designs discriminated P values solely among various bracket designs in a multiple-bracket situation. A future study will investigate the best archwire-bracket couples, as selected by the participating manufacturers. Those conditions will be identical to those of this study with one exception: that different AW sizes may be selected for each bracket design by its manufacturer. Thereby, archwire-bracket systems will be tested. These frictional experiments will determine whether the perceived archwire-bracket systems truly produce the lowest P values.

CONCLUSIONS

This investigation simulated in vivo conditions by using the limitations associated with the in vitro testing of typodonts to simulate both low and high frictional possibilities. Multibracket testing of self-ligating brackets outperformed conventional brackets when coupled with small AWs, which emulated the early stages of orthodontic treatment. When coupled with larger AWs, which are used during the later stages of treatment, P values and the amount of scatter from conventional brackets were comparable with those of self-ligating brackets. This outcome emphasized the importance of alignment and leveling before using larger wires and sliding mechanics. When P values were plotted against time, results for different AW sizes were distinguishable, and the results showed a slight increase in values from quadrant to quadrant, which corresponded to an increase in malocclusion. This increase related directly to the combined effects of decreasing clearances and IBDs. Testing with small AWs in the wet state upheld the efficiency and reproducibility of the self-ligating brackets—a result that was not evident for the conventional brackets that were evaluated.

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