Original Article

Frictional Evaluations of Dental Typodont Models Using Four Self-ligating Designs and a Conventional Design

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

Abstract: After a previous study using typodonts and three standardized archwire (AW) sizes, the frictional evaluations of four self-ligating brackets were directed toward the optimal AW-bracket system. Four participating manufacturers suggested three AWs, which were a representation of the three stages of orthodontic treatment, to be coupled with their respective self-ligating design. Four replicated typodont models were mounted with a self-ligating design, and a fifth model was mounted with a conventional design that served as a control. The first experiment evaluated the manufacturer-suggested AWs against the respective self-ligating design. Because no third-stage AWs could engage their respective designs, a second experiment was implemented to gain more detailed analyses of the designs. This experiment included any successful manufacturer-suggested AWs from the first experiment against the four self-ligating designs and the control design. All self-ligating designs performed with the efficiency and reproducibility associated with expectations. Specifically, self-ligation outperformed the conventional brackets when coupled with up to 0.020- × 0.020-inch wires. The clearance of the various AW sizes and alloys changed with malocclusion. Furthermore, the parameter that best correlated with drawing forces was the bending stiffness of the AW, which was directly associated with the nominal dimension of each wire. The best AW-bracket system can be selected, when taking into account the stiffness (elastic modulus and size of the AW) along with the amount of malocclusion present, once the treatment plan is determined. (*Angle Orthod* 2004;75:75–85.)

Key Words: Frictional resistance; Self-ligating brackets; Conventional brackets; Typodont models; Multiple brackets

INTRODUCTION

Earlier studies have emphasized the influences of the various mechanical properties that characterize orthodontic materials.[1–6] Frictional resistance (FR) has been attributed to many factors, such as bracket type, wire size and alloy, method of ligation, angulation, and slot size.[1] Bending stiffness and wire shape have been found to dictate frictional values at high angulations.[2] With respect to friction, round wires were reported to have a greater dependency on angulation than rectangular wires.[3] When clearance existed in the slot of a self-ligating bracket with slides, a negligible level of resistance to sliding (RS) was observed.[4] When wires reached a certain dimension and contacted the clip of a self-ligating bracket, the RS was dependent on the AW size, the bracket design, and the material of the couple.

Studies of individual brackets suggested that self-ligating brackets produced lower frictional values, better hygiene, and patient comfort.[3,7,8] A multiple-bracket study found that interbracket distance (IBD) inversely correlated with the RS.[5] Clinical studies have concluded that orthodontic treatment with self-ligating brackets reduced chairtime and shortened treatment time.[6,9–11]

A more recent study used typodont models, having different degrees of malocclusion, to simulate the low and high frictional possibilities associated with in vitro testing.[12] This comparative study evaluated four self-ligating designs and four conventional designs against three standardized archwires (AWs), which were representative of the three stages of orthodontic treatment. Self-ligating brackets outperformed conventional brackets when smaller AWs were engaged. When larger AWs were engaged, the two bracket types were more comparable. The combined effects of decreasing clearances and IBDs that were directly related to an increase in malocclusion resulted in a corresponding increase in drawing forces. This study affirmed that the characteristic behavior of self-ligating brackets was constant for both individual bracket and multiple-bracket studies.

---

[a] Graduate Student, Department of Biomedical Engineering, University of North Carolina, Chapel Hill, NC.

[b] Professor, Department of Biomedical Engineering and Department of Orthodontics, University of North Carolina, Chapel Hill, NC.

Corresponding author: Robert P. Kusy, BS, MS, PhD, Department of Orthodontics, University of North Carolina, Building 210-H, Room 313, Chapel Hill, NC 27599
(e-mail: rkusy@bme.unc.edu).

Accepted: January 2004. Submitted: December 2003.

TABLE 1. List of Self-ligating or Conventional-type Brackets, Participating Manufacturers, and Archwire Sizes and Alloys. Shaded Regions Denote the Manufacturer-suggested Wires That Were Successfully Tested in Experiment 1 and Universally Evaluated in Experiment 2

Bracket Design	Names of Bracket[a]	Participating Manufacturer[b]	Archwires Size[c] Nominal Dimension (inch)	Alloy
Self-ligating	SPEED	Strite Industries	0.016 (7-stranded)	NiTi SE[d]
			0.020 × 0.025[e]	SS[f]
			0.021 × 0.021 (D-wire)[e]	SS[f]
	Time	American Orthodontics	0.012	NiTi[g]
			0.016 × 0.022	NiTi[g]
			0.019 × 0.025[e]	SS[f]
	In-Ovation	GAC International	0.016 × 0.016	NiTi SE[d]
			0.020 × 0.020	NiTi SE[d]
			0.021 × 0.025[e]	SS[f]
	Damon 2	Sybron Dental Specialties Ormco	0.014	NiTi SE[d]
			0.016 × 0.025	NiTi SE[d]
			0.019 × 0.025[e]	SS[f]
Conventional	Mini Diamond[h] (control)	Sybron Dental Specialties Ormco		

[a] Bracket slots had nominal slot dimensions of 0.022 inch.
[b] Participating manufacturers mounted their respective self-ligating brackets onto a typodont model.
[c] Investigators obtained the preformed archwires directly from the manufacturers.
[d] Superelastic nickel-titanium.
[e] Indicates the archwires that could not engage into the brackets properly and were not tested.
[f] Stainless steel.
[g] Shape memory nickel-titanium.
[h] The shaded regions under Archwise Size and Alloy were coupled with the Mini Diamond brackets.

Using the same typodonts as those used in a recent study,[12] this investigation evaluated manufacturer-suggested AW-bracket systems. Two experiments were implemented to test the performance of four self-ligating designs and one conventional design, which served as the control. The first experiment only tested the manufacturer-suggested AWs against their corresponding self-ligating design. The second experiment, which was defined as a ‘‘cross-comparison,’’ was an evaluation of any successfully tested AWs from experiment one coupled with all the self-ligating designs and the control design. The purpose of that experiment was to ultimately understand better the parameters involved in maintaining low FRs and the limitations of the self-ligating brackets under varying levels of malocclusion.

MATERIALS AND METHODS

Materials

Four participating manufacturers (Strite Industries Limited, Cambridge, Ontario, Canada; American Orthodontics, Sheboygan, Wis; GAC International Inc., Islandia, NY; and Sybron Dental Specialties Ormco, Orange, Calif) had their clinicians mount the respective self-ligating brackets (SPEED, Time, In-Ovation, and Damon 2) onto pretreatment typodonts (Allesee Orthodontic Appliances, Sturtevant, Wis) using a cyanoacrylate adhesive (Loctite 416, Loctite Corp., Rocky Hill, Conn). This laboratory later verified the anatomically correct positioning of each bracket. Each participating manufacturer suggested three AWs to be coupled with their respective self-ligating designs that were representative of the wires used in the three stages of orthodontic treatment. In total, 11 different AW sizes and three different AW alloys were chosen (Table 1). A fifth typodont model, which served as a control, was mounted with the conventional-type Mini Diamond brackets (Sybron Dental Specialties Ormco).

Methods

Typodonts were tested by quadrants (upper left [UL], upper right [UR], lower left [LL], and lower right [LR]). In the previous typodont study,[12] in which the same model was used, the order was experimentally ranked from the least maloccluded to the most maloccluded quadrant as UL, UR, LL, and LR.

In the first experiment, three AWs, which were suggested by each participating manufacturer, were drawn through the typodont model mounted with their corresponding bracket design. The testing sequence was the same in every quadrant and for all designs. Once the AWs were ligated, typodonts were vertically mounted onto the crosshead of a mechanical testing machine (Instron Model TTCM, Instron Corp., Canton, Mass) (see Figure 1 in Henao and Kusy[12]). The distal end of each AW was linked to the end of an overhead load cell. The approximate duration of each run was five minutes at a crosshead speed of 0.5 mm/min. Once movement across the brackets began, drawing forces were recorded at every 0.25-mm increment using a dial indicator (L.S. Starrett Co., Athol, Mass) that was positioned at the mesial end of the AW. All tests were run in the dry state at an oral ambient temperature of 34°C. This standard sequence tested AWs in a progressively increasing order and was repeated once for a total of two samples per AW size. Drawing forces (P) and cumulative times (t) were applied to a power regression equation, $P = Xt^Z$, in which P is in cN (where one cN ≈ one g), t is in minutes, and X and Z are fitted constants. Reported curves were the average curve between two samples.

In the second experiment, the manufacturer-suggested AWs that were successfully tested in the first experiment were used to evaluate further each design's capabilities (see Archwire Sizes and Alloys in Table 1). Such a cross-comparison was used to evaluate any successful manufacturer-suggested AWs (shaded regions of Table 1) against the control bracket design and all self-ligating bracket designs. All tests were run only in the upper quadrants to avoid testing in those quadrants that would not fully engage large AWs. In the control bracket, elastic modules (Ligature Ringlet, RMO, Denver, Colo) were used for ligation.

To determine for each round wire the overall diameter (D) and for each rectangular wire the base (b) and height (h), which are parallel with but perpendicular to the base of the bracket, respectively, five measurements were taken using a digital micrometer (μ-Mate, Sony Magnescale America, Orange, Calif). Moreover, for the 0.016-inch multistranded AW, the outer strand diameter (d_o), inner strand diameter (d_i), and the axial displacement per twist of a wire strand (ℓ^*)[13] were measured using the optics of a Kentron microhardness tester (Kent Cliff Labs, Peekskill, NY). The cross-sectional areas (A) of the multistranded wires were measured after transversely potting this AW in epoxy resin, followed by polishing with wet carbide papers. For the multistranded AW, the area is defined by

$$A = \pi[6(d_o/2)^2 + (d_i/2)^2].$$

The moments of inertia (I) for the round (single stranded) and the rectangular AWs were defined by $I = \pi D^4/64$ and $I = bh^3/12$, respectively. For the multistranded AW, the moment of inertia was calculated by

$$I = \pi(6d_o^4\kappa + d_i^4)/64,$$

where the helical spring shape factor[14] is $\kappa = 2\sin\alpha(2 + \gamma\cos^2\alpha)$ and α and γ are the helix angle and Poisson's ratio ($\gamma = 0.34$ for nickel-titanium [NiTi]), respectively. The helix angle was calculated by

$$\alpha = \tan^{-1}\{\ell^*/[\pi(D - d_o)]\}.$$

The storage moduli (E) of these AWs were determined using a Model 2980 dynamic mechanical analyzer in the 3-point bending mode with a 5-mm outer span (TA Instruments, New Castle, Del). This permitted the calculation of bending stiffness ($I \cdot E$) at 34°C.

Statistics

Multivariate analyses of variance (Systat Version 10.2, Systat Software Inc., Richmond, Calif) were used to determine the statistical significances and the interactions between bracket designs (SPEED, Time, In-Ovation, and Damon 2) and quadrants (UL, UR, LL, and LR). Nonsignificant (NS) values were defined when $P < .05$.

RESULTS

Overview of the manufacturer-suggested AWs (experiment 1)

Because of the varying degree of malocclusion, some of the manufacturer-suggested AWs were unable to fully engage in all the bracket slots of the quadrants (Table 1). None of the suggested third-stage AWs could engage the suggested brackets in any of the quadrants.

The SPEED brackets could successfully engage the 0.016-inch (multistranded) superelastic NiTi (NiTi SE) AWs in all the quadrants (Table 2). Drawing force values were nearly frictionless in the UL quadrant and progressively increased from the UR to the LR and LL quadrants; very little scatter was seen in the P values (Figure 1).

The Time brackets were successfully coupled with the 0.012-inch NiTi AWs in all quadrants (Table 2). For these AWs, the UL and UR quadrants produced the same maximum P (P_{max}) values, 25 cN. In the LL and LR quadrants, the averages of the P_{max} values were 350 and 288 cN, respectively, resulting in the following rank order: UL or UR, LR, and LL. The scatter of the data points was minimal (Figure 2). For the 0.016- × 0.022-inch NiTi AWs, only the upper quadrants could be tested. Scatter among data points was more pronounced in the UR quadrant than in the UL quadrant.

The In-Ovation brackets were successfully coupled with 0.016- × 0.016-inch and 0.020- × 0.020-inch NiTi SE AWs in all quadrants (Table 2). As AW size increased, the P_{max} values increased from quadrant to quadrant. For the 0.016- × 0.016-inch AWs, the UL and UR quadrants produced P_{max} values that averaged 200 and 150 cN, respectively, resulting in the following rank order: UR, UL, LL, and LR. The 0.020- × 0.020-inch AWs followed the same rank order. Scatter among data points was very small in the upper quadrants but increased from the LL to the LR quadrant as the malocclusion increased (Figure 3).

The Damon 2 brackets were successfully coupled with the 0.014-inch and 0.016- × 0.025-inch NiTi SE AWs (Table 2). For the 0.014-inch AWs, the P_{max} values increased from quadrant to quadrant in the following order: UL, UR, LL, and LR. The 0.016- × 0.025-inch AWs produced P_{max} values in the LL quadrant that were higher than those produced in the LR quadrant. In addition, the scatter between data points was highest in the UR and LL quadrants (Figure 4).

Among all four designs, a statistical analysis indicated that there was NS among the four quadrants. On further evaluation, a least-squares mean plot (not shown) of P val-

TABLE 2. For Experiment 1 in the Dry State, Ranges of Drawing Force (P) Values for the Self-ligating Brackets That Were Coupled With Their Manufacturer-suggested Archwires in Four Quadrants

Names of Bracket	Wire Size (inch)	Wire Sample	P (cN)							
			At Upper Left[a]		At Upper Right[a]		At Lower Left[a]		At Lower Right[a]	
			Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
SPEED	0.016[b,c]	1	0	0	50	50	175	300	100	200
		2	0	0	50	50	200	300	150	225
	0.020 × 0.025[d]	1	—	—	—	—	—	—	—	—
		2	—	—	—	—	—	—	—	—
	0.021 × 0.021[d,e]	1	—	—	—	—	—	—	—	—
		2	—	—	—	—	—	—	—	—
Time	0.012[f]	1	25	25	25	25	175	200	175	250
		2	25	25	25	25	275	500	225	325
	0.016 × 0.022[f]	1	750	1375	625	1450	—	—	—	—
		2	625	1550	425	1925	—	—	—	—
	0.019 × 0.025[d]	1	—	—	—	—	—	—	—	—
		2	—	—	—	—	—	—	—	—
In-Ovation	0.016 × 0.016[b]	1	175	225	100	150	400	700	450	1150
		2	125	175	150	150	125	575	250	1900
	0.020 × 0.020[b]	1	550	625	500	575	800	2050	900	3875
		2	525	650	425	525	675	1550	600	3225
	0.021 × 0.025[d]	1	—	—	—	—	—	—	—	—
		2	—	—	—	—	—	—	—	—
Damon 2	0.014[b]	1	10	10	200	300	250	450	425	600
		2	10	10	250	250	200	475	225	525
	0.016 × 0.025[b]	1	550	1100	1175	3175	925	5500	1300	4500
		2	450	875	875	2425	1625	5500	1600	5350
	0.019 × 0.025[d]	1	—	—	—	—	—	—	—	—
		2	—	—	—	—	—	—	—	—

[a] Quadrants in which any or all of the wires could not engage into the bracket slot, as denoted with dashes.
[b] Superelastic nickel-titanium.
[c] This wire is a 7-stranded supercable archwire.
[d] Stainless steel.
[e] This wire is a SPEED D-wire.
[f] Shape memory nickel-titanium.

ues against bracket designs indicated that the Damon 2 design was an outlier among the group.

Overview of cross-comparisons (experiment 2)

Using only the upper quadrants, four self-ligating designs were tested in this experiment along with one conventional design as a control, which was tested in all four quadrants. The average P_{max} values generally increased with wire size, when those successfully tested AWs of the previous experiment were coupled with control or self-ligating brackets (Table 3). For the round AWs, the 0.012-inch and the 0.016-inch AWs interchangeably exhibited the lowest regression curves (Figures 5 through 9). For the rectangular AWs, the regression curves generally increased as the height of the AWs increased, except when the AWs were coupled with the Mini Diamond or the SPEED brackets in the UR and UL quadrants, respectively (Table 3).

The Mini Diamond brackets displayed a scatter in data points consistent with the variability that was expected from sample to sample (Figure 5). For the 0.016- × 0.022-inch and 0.016- × 0.025-inch AWs coupled with the SPEED brackets, the regression curves were very similar (Figure 6). The Time brackets displayed a 0.016- × 0.022-inch regression curve that either paralleled the 0.016- × 0.025-inch curve or eventually reached similar maximum values (Figure 7, UL and UR, respectively).

With respect to the larger AWs, the In-Ovation brackets yielded very little scatter in data points and displayed good separation between regression curves from AW size to AW size (Figure 8 vs Figures 5 through 7 and 9). Among all the bracket designs, the Damon 2 brackets produced one of the lowest regression curves and the highest regression curve (Figure 9, bottom left and top right, vs Figures 5 through 8). The 0.012-inch AWs coupled with the SPEED brackets in the UL quadrant produced the same regression curve as the Damon 2 brackets coupled with the same-size wire in the same quadrant (cf Figures 6 and 9). Statistically, the four designs were found to be significantly different ($P < .1$).

As expected for each AW size tested, the scatter of the data points generally increased with increasing wire size (Figures 5 through 9). The only exception to this was the 0.014-inch AW-SPEED bracket combination, which showed higher scatter than the larger AWs coupled with the same design (Figure 6).

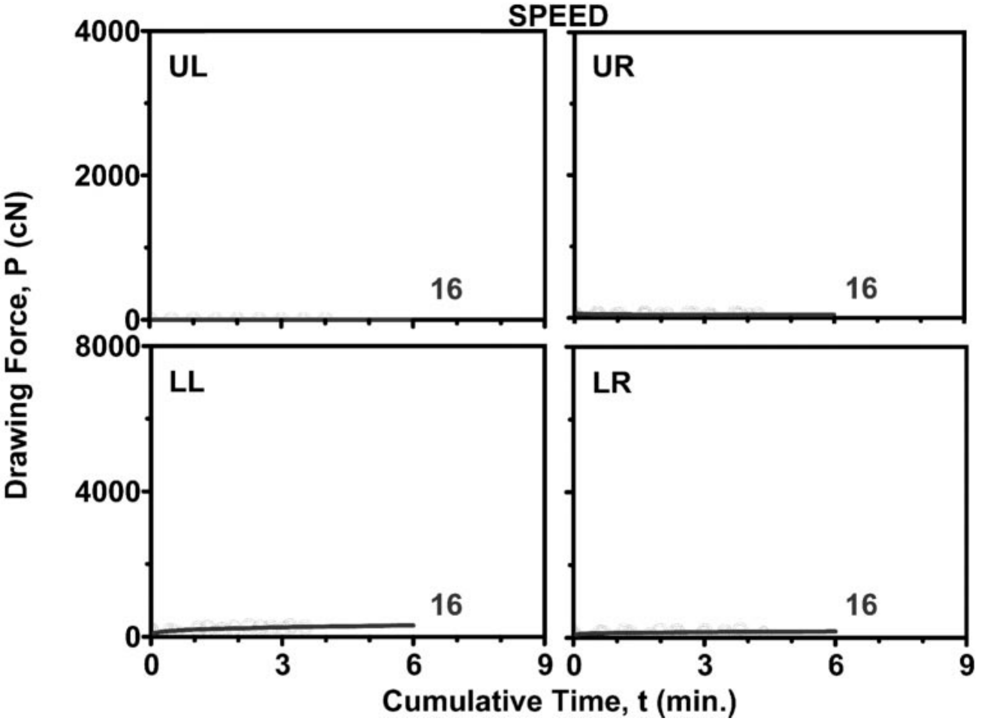

FIGURE 1. For the SPEED brackets of experiment 1, influence of drawing force (P) values (in cN, where one cN ≈ one g) against cumulative time (t) (in minutes) in four quadrants using one size of the three manufacturer-suggested AWs: 16 mils (7 stranded) superelastic nickel-titanium (NiTi SE) (where 1 mil = 0.001 inch). Graph displays the combined regression curve of two samples and all recorded data points for each AW size tested.

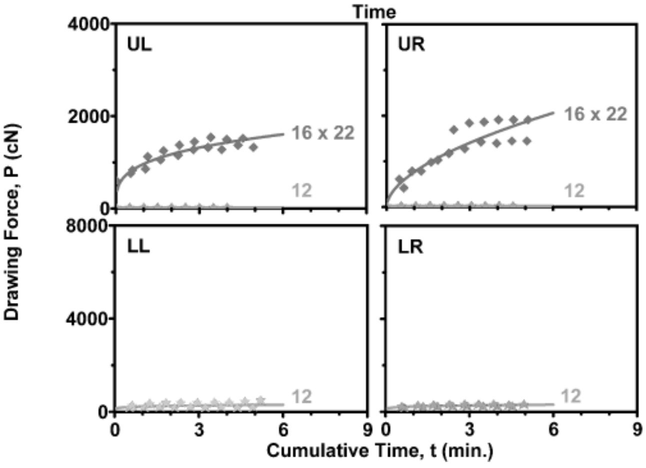

FIGURE 2. For the Time brackets of experiment 1, influence of the P values against t as detailed in Figure 1 using two sizes of the three manufacturer-suggested AWs: 12 mils (0.012 inch) NiTi and 16 × 22 mil (0.016 × 0.022 inch) NiTi.

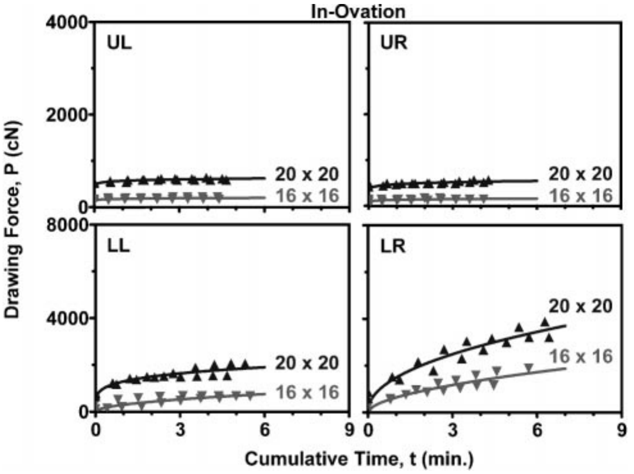

FIGURE 3. For the In-Ovation brackets of experiment 1, influence of the P values against t as detailed in Figure 1 using two sizes of the three manufacturer-suggested AWs: 16 × 16 mils (0.016 × 0.016 inch) NiTi SE and 20 × 20 mils (0.020 × 0.020 inch) NiTi SE.

DISCUSSION

Influence of AW size

Two trends were evident when the bracket designs were coupled with all the successful manufacturer-suggested AWs (Figures 5 through 9, experiment 2). The smallest wires and the multistranded wires yielded the lowest values, and the values for the rectangular wires increased as the height of the AWs increased. The P values for the 0.016- × 0.022-inch AWs either paralleled or reached similar maximum values as those for the 0.016- × 0.025-inch AWs (Figures 5 through 8). Because the bracket slots were 0.022 inch, the 0.020- × 0.020-inch AWs had a more secure fit

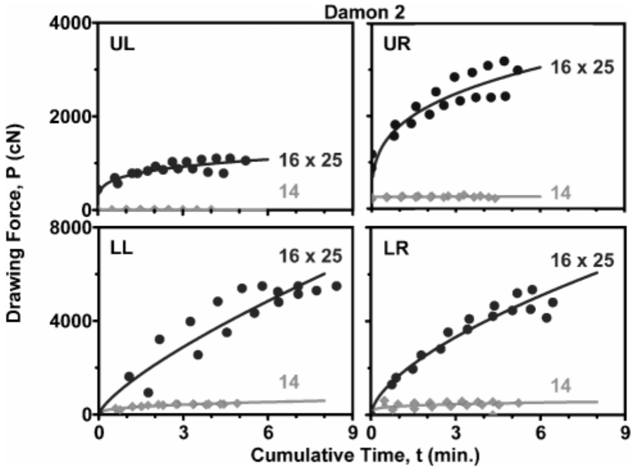

FIGURE 4. For the Damon 2 brackets of experiment 1, influence of the P values against t as detailed in Figure 1 using two sizes of the three manufacturer-suggested AWs: 14 mils (0.014 inch) NiTi SE and 16 × 25 mils (0.016 × 0.025 inch) NiTi SE.

in the base of the slots, whereas the 0.016- × 0.025-inch AWs had more clearance (16 vs 20) and height (25 vs 20) than the 0.020- × 0.020-inch AWs. Consequently, the 0.016- × 0.022-inch AWs also had disadvantages in size that allowed more movement within the slots and influenced the values to simulate a larger AW, like the 0.016- × 0.025-inch wire. These results confirmed past studies that found clearance and AW size to be important factors in the RS.[4] A least-squares mean plot (not shown) of P values against AW size indicated that the results for stage 1 AWs (ie, 0.014 inch) were significantly different from the results for stage 2 AWs (ie, 0.016 × 0.025 inch).

Influence of malocclusion

The rank order, determined by a previous study[12] (namely, UL, UR, LL, and LR) that used standardized AWs, was not always consistent with the present study. Although two of the four designs (SPEED and Damon 2) suggested that the UL quadrant remained the least malocclused quadrant (Table 2), the UR quadrant gave comparable (see 0.012-inch AW) or mixed (see 0.016- × 0.022-inch AW) P values compared with the UL quadrant for the Time brackets. For the In-Ovation brackets, however, the P_{max} values of the UR quadrant were generally lower than those of the UL quadrant by 25–125 cN.

On the other hand, the most malocclused quadrant was defined as the quadrant that had the highest P_{max} values. Among the bracket designs and the wire sizes, the highest P values occurred in the LL and the LR quadrants (Table 2). A statistical analysis indicated that there was NS among the four quadrants. That outcome was attributed to the diversity of AW sizes and alloys that were engaged from quadrant to quadrant. Insofar as P values were generally concerned, however, the lower arch with its higher radius of curvature nonetheless limited sliding by manyfold (Table 2).

Influence of bracket design

The self-ligating designs yielded lower P_{max} values than the control design in 49 of 56 cases (Figures 10 and 11). Up to 0.020- × 0.020-inch AWs yielded lower P_{max} values when coupled with a self-ligating design. The P_{max} values of both bracket designs were most comparable when coupled with the 0.016- × 0.022-inch, 0.016- × 0.025-inch, and 0.020- × 0.020-inch AWs.

In the UL quadrant, the 0.016- × 0.022-inch AW coupled with the Time brackets produced a maximum drawing force (P_{max}) value that exceeded the P_{max} value of the Mini Diamond brackets (Figure 10). For the 0.016- × 0.025-inch AWs, the Time, In-Ovation, and Damon 2 designs produced P_{max} values that exceeded the P_{max} value of the Mini Diamond design. In the UR quadrant, the 0.016- × 0.022-inch AWs coupled with the Time brackets produced a P_{max} value that exceeded the P_{max} value of the Mini Diamond brackets (Figure 11). For the 0.016- × 0.025-inch AWs, the Time and Damon 2 designs produced P_{max} values that exceeded the P_{max} value of the Mini Diamond design. For the 0.020- × 0.020-inch AWs in both quadrants, the P_{max} values of the self-ligating designs were less than or equal to those of the conventional design (Figures 10 and 11). This confirmed earlier observations[12] that smaller wires coupled with self-ligating brackets showed the lowest P values, whereas larger wires coupled with self-ligating brackets gave P values that were more comparable to those displayed by conventional brackets.

Among the self-ligating designs in the UL quadrant, the Damon 2 brackets gave the lowest P_{max} values with one exception (Figure 10). The 0.016- × 0.025-inch AWs coupled with the SPEED brackets yielded an average P_{max} value that was slightly lower than the value for the Damon 2 brackets (Table 3). Earlier studies have found that self-ligating brackets with passive slides, like the Damon 2 brackets, exhibited negligible levels of RS when second-order angulations were less than the critical contact angle.[15–16] In the UR quadrant (Figure 11), the In-Ovation brackets produced the lowest P_{max} value, whereas the Damon 2 brackets yielded the highest P_{max} value, followed by the Time brackets, when coupled with the 0.016- × 0.025-inch AWs.

Overall, within both quadrants, the Time brackets gave average P_{max} values that were higher than those of the other three self-ligating designs for 10 of 14 possible cases (Table 3). More generally, these results confirmed previous work that showed that self-ligating brackets with clips exhibited higher frictional values than self-ligating brackets with slides, when the second-order angulations were below the critical contact angle.[16] Statistically, the four designs were significantly different ($P < .1$). On further evaluation, a least-squares mean plot (not shown) of P values against

TABLE 3. For Experiment 2 in the Dry state, Ranges of Drawing Force (P) Values for the Conventional Brackets (Control) and Self-ligating Brackets That Were Coupled With All Successfully Tested Archwires (AWs) That Were Suggested by Manufacturers. The Values Are the Averages of the Minimum and Maximum P Values From the Two Wire Samples Tested for Each Wire Size

Names of Bracket	Wire Size (inch)	P (cN)			
		At Upper Left		At Upper Right	
		Minimum	Maximum	Minimum	Maximum
Mini Diamond (control)	0.016[a,b]	375	513	475	813
	0.012[c]	225	425	400	600
	0.014[a]	350	550	425	675
	0.016 × 0.016[a]	363	525	588	875
	0.020 × 0.020[a]	613	825	813	1563
	0.016 × 0.022[c]	388	963	838	1750
	0.016 × 0.025[a]	588	988	875	1538
SPEED	0.016[a,b]	0	0	50	50
	0.012[c]	0	0	50	50
	0.014[a]	25	25	100	175
	0.016 × 0.016[a]	150	175	375	450
	0.020 × 0.020[a]	388	400	713	863
	0.016 × 0.022[c]	600	900	763	1363
	0.016 × 0.025[a]	525	863	913	1463
Time	0.016[a,b]	10	10	25	50
	0.012[c]	25	25	25	25
	0.014[a]	125	200	138	338
	0.016 × 0.016[a]	275	300	325	425
	0.020 × 0.020[a]	675	863	963	1525
	0.016 × 0.022[c]	688	1463	525	1688
	0.016 × 0.025[a]	825	1688	788	1975
In-Ovation	0.016[a,b]	10	15	15	20
	0.012[c]	15	15	20	20
	0.014[a]	75	100	50	88
	0.016 × 0.016[a]	150	200	125	150
	0.020 × 0.020[a]	538	638	463	550
	0.016 × 0.022[c]	450	775	450	825
	0.016 × 0.025[a]	775	1288	613	1425
Damon 2	0.016[a,b]	0	0	25	50
	0.012[c]	0	0	75	150
	0.014[a]	10	10	225	275
	0.016 × 0.016[a]	13	18	325	450
	0.020 × 0.020[a]	225	250	600	875
	0.016 × 0.022[c]	263	413	450	1363
	0.016 × 0.025[a]	500	988	1025	2800

[a] Superelastic nickel-titanium.

[b] This wire is a 7-stranded supercable archwire.

[c] Shape memory nickel-titanium.

bracket designs indicated that the Damon 2 design was an outlier among the group. In other words, more comparable values were observed among the three remaining bracket designs, which contained clips.

Comparison of present manufacturer-suggested AWs with previous standardized AWs

Although a variety of AWs were provided for the frictional evaluations of this study, none of the larger and stiffer stainless steel AWs could fully engage the bracket slots of any of the four quadrants. In a previous study,[12] three austenitic NiTi (NiTi-A) AWs, a 0.014-inch, 0.016- × 0.022-inch, and 0.019- × 0.025-inch, were coupled with the same self-ligating designs as the present study. Previously, the 0.019- × 0.025-inch NiTi-A AWs could not be tested in the LR quadrant. The remaining two AW sizes, which were tested previously, confirmed the reproducibility of self-ligating brackets from study to study.

The SPEED brackets exhibited lower P_{max} values when coupled with 0.016-inch NiTi SE multistranded AWs than when coupled with 0.014-inch NiTi-A AWs tested previously (cf Table 2 with Table 3 in Henao and Kusy[12]). This outcome was expected because the multistranded AW is not a true 0.016-inch wire. Indeed, for another bracket, the Time design, the P values were comparable with those of the SPEED design.

The Time brackets yielded lower P_{max} values when coupled with the 0.012-inch AWs than when coupled with the

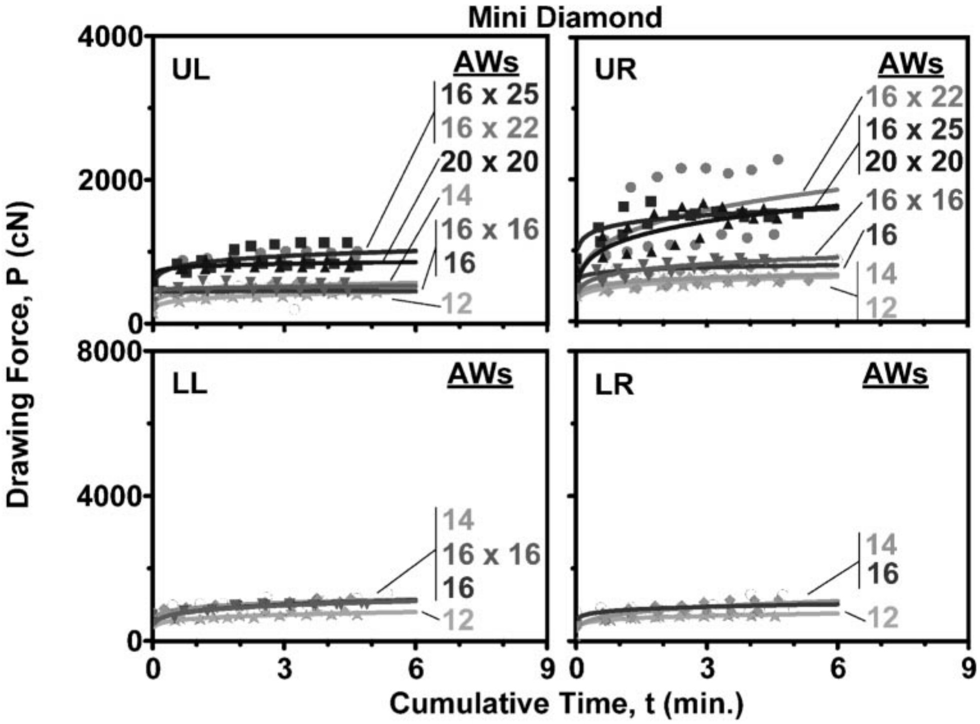

FIGURE 5. For the Mini Diamond brackets (control) of experiment 2, variability of the P values against t for the seven AWs (mils) tested (see shaded regions of Table 1 for AW material information). Graph displays the regression curves and data points for each AW tested.

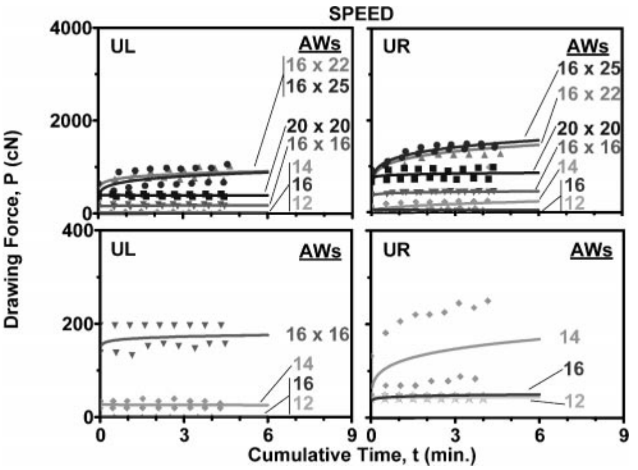

FIGURE 6. For the SPEED brackets of experiment 2, variability of the P values against t in two quadrants for the seven AWs (mils) tested (see shaded regions of Table 1 for AW material information). The lower frames amplify the upper frames that had P values less than 400 cN. For each AW size tested, the graph displays the combined regression of two samples. Data points not seen here were reported in a previous figure corresponding to SPEED brackets (Figure 1).

standardized 0.014-inch AWs (cf Table 2 with Table 3 in Henao and Kusy[12]). For the 0.016- × 0.022-inch AWs, the NiTi-A AWs from the previous study yielded lower P values and were also able to remain fully engaged in the LL quadrant unlike the shape memory NiTi AWs coupled with the Time brackets in this study (cf Figure 2 with Figure 7 in Henao and Kusy[12]). The shape memory AWs are martensitic-active alloys that use thermoelasticity to achieve reversible transformations (martensite ⇌ austenite).[17]

Regarding the manufacturing process, minute differences have been purported to influence the properties of a product.[18–19] Therefore, a slight difference in the P values between these wires was expected. Although the shape memory AWs were preformed, the displacement of the wires was only 2 mm; therefore, the arch segment of the wires was considered an inconsequential parameter.

As expected, the In-Ovation brackets coupled with the 0.016- × 0.016-inch NiTi SE AWs gave higher P_{max} values than the 0.014-inch NiTi-A AWs tested previously. Yet, P_{max} values differed by as little as 30 cN in the UR quadrant from study to study (cf Table 2 with Table 3 in Henao and Kusy[12]). Similarly, the 0.020- × 0.020-inch NiTi SE AWs gave lower P values than the 0.016- × 0.022-inch NiTi-A AWs from the previous study. Yet, P_{max} values differed by as little as 80 cN in the UL quadrant from study to study. Moreover, in the present study, the 0.020- × 0.020-inch AW was tested in all four quadrants, whereas the standardized 0.016- × 0.022-inch AWs could not be tested in the LR quadrant (cf Figure 3 with Figure 6 in Henao and Kusy[12]). The cross-comparison experiments suggested that the height of the wires influenced the P values (Figures 5 through 9).

The Damon 2 brackets in this study and the previous one were coupled with 0.014-inch NiTi-A and NiTi SE AWs, respectively (cf Table 2 with Table 3 in Henao and Kusy[12]).

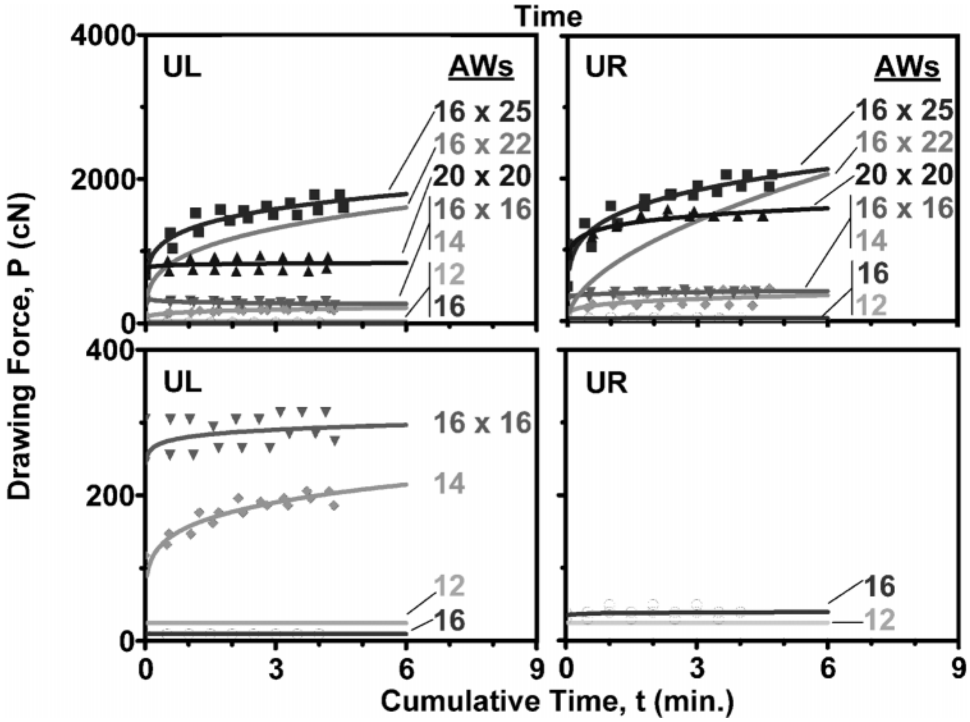

FIGURE 7. For the Time brackets of experiment 2, variability of the P values against t as detailed in Figure 6.

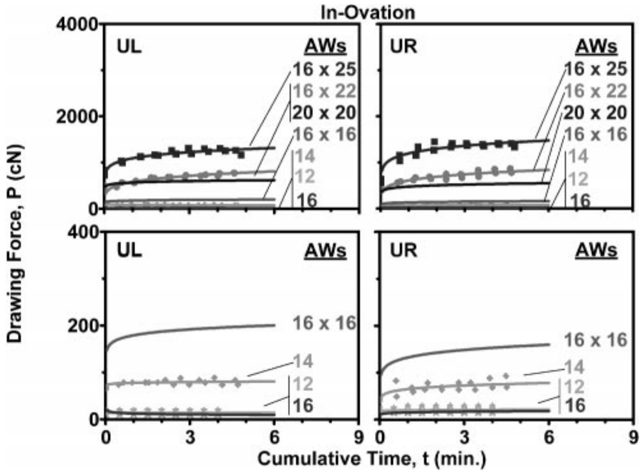

FIGURE 8. For the In-Ovation brackets of experiment 2, variability of the P values against t as detailed in Figure 6.

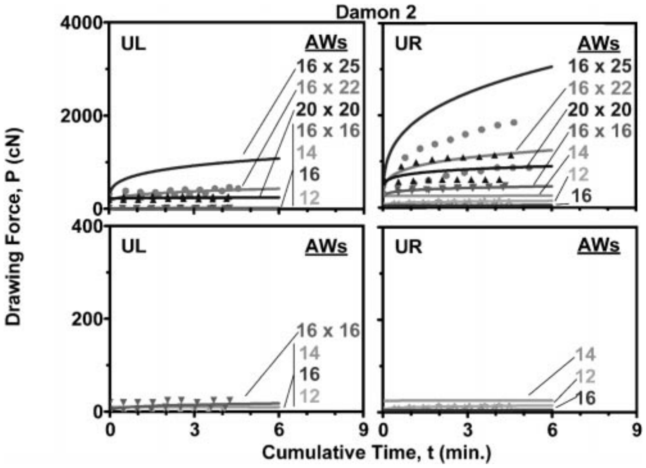

FIGURE 9. For the Damon 2 brackets of experiment 2, variability of the P values against t as detailed in Figure 6.

The results from both studies were the same for the UL quadrant but were different from one another in the other three quadrants. This outcome was expected due to the variability from sample to sample as evaluated. The 0.016- × 0.025-inch NiTi SE AWs gave higher P_{max} values than the 0.016- × 0.022-inch NiTi-A AWs from the previous study and, unlike the 0.016- × 0.022-inch AW, was able to fully engage in the LR quadrant (cf Table 2 with Table 3 in Henao and Kusy[12]). Given that these two rectangular wires had equal bases and differed only in heights, the greater overall clearance and the lower overall stiffness justified why the 0.016- × 0.022-inch AWs gave lower P values than the 0.016- × 0.025-inch AWs. But in the more maloccluded quadrants, such as the LR quadrant, the smaller height of the 0.016- × 0.022-inch AW tested previously had enough clearance inside the bracket slot to permit twisting and compromise engagement.[12]

Parametric investigation

Various parameters were examined to determine what factor(s) influenced the P values of self-ligating brackets (Figure 12). The storage modulus (E), bending stiffness (S

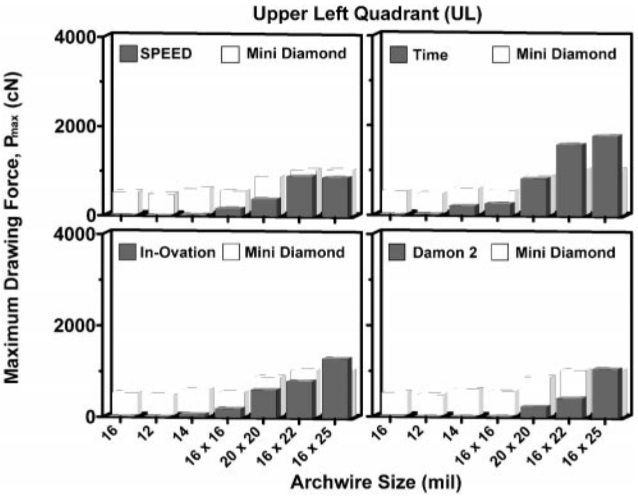

FIGURE 10. For the UL quadrant of experiment 2, the maximum drawing force (P_{max}) values for all seven AW sizes tested. The graph compares the P_{max} values of the self-ligating designs (□) with the P_{max} values of the conventional (■) design.

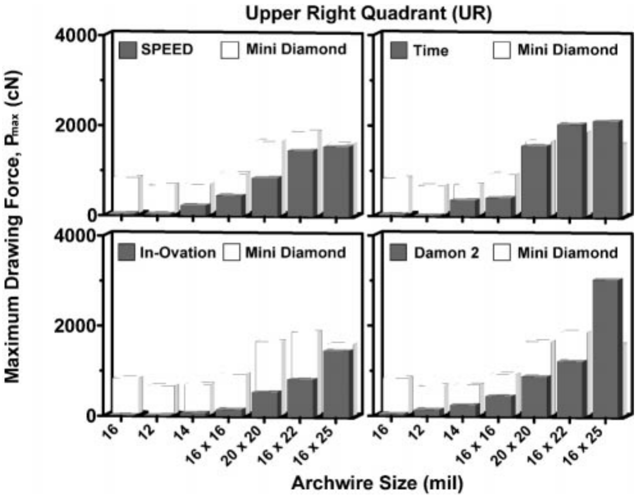

FIGURE 11. For the UR quadrant of experiment 2, the P_{max} values for all seven AW sizes tested in the present study as detailed in Figure 10.

= I · E), cross-sectional area (A), and the diagonal length (d) were calculated. When compared with the dimensional trends displayed in the P_{max} values of Figures 10 and 11, the bending stiffness most closely resembled the behavior of the self-ligating brackets (Figure 12, upper right-hand frame). The wire sizes shown on the x-axis followed an increasing trend as seen in the increasing order of the AWs that corresponded to the regression curves in Figures 5 through 9. The same observation could not be made for the control brackets. As observed in the earlier study,[12] conventional brackets exhibited low reproducibility or high intravariance between samples (or both)—thereby making any differentiation between frictional behavior and sample variance difficult.

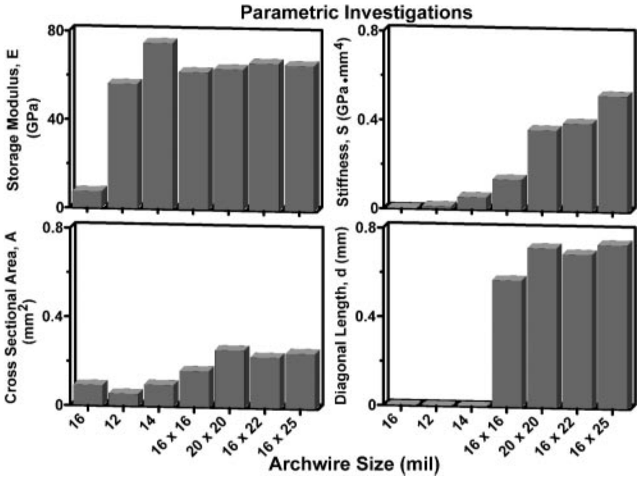

FIGURE 12. Bar graphs of four parameters (storage modulus [E], bending stiffness [S = I · E], cross-sectional area [A], and diagonal length [d]) calculated by dimensional measurements or thermal analyses for the seven AW sizes tested. For experiment 2, the best correlation occurred when S = I · E.

CONCLUSIONS

The precision of the present experiment emphasized the efficiency and the reproducibility of the self-ligating brackets. With the appropriate AW-bracket couple, the influence of different levels of malocclusion could be minimized. Hence, frictional values were dictated by a combination of AW size, malocclusion, bracket design, and bending stiffness. The influence exhibited by the height of the AWs underscored the effectiveness of decreasing clearances and AW stiffness. When clearance was substantial, the self-ligating brackets with slides performed better than those with clips. Indeed, these self-ligating brackets maintained low frictional values for wires up to 0.020- × 0.020-inch. However, as malocclusion became more prevalent and AW size reduced overall clearance, the two self-ligating designs of slides and clips lost distinction. On further analyses, the frictional behavior of these self-ligating designs correlated with the bending stiffness of the AWs, which were directly related to the elastic moduli and nominal dimensions of the AWs. Taking these parameters into account along with the type of malocclusion present will facilitate the selection of the proper AW-bracket system for the type of treatment required.

ACKNOWLEDGMENTS

The authors thank the four participating manufacturers for choosing the wires used in the first experiment and for mounting their respective self-ligating and conventional brackets (see Table 1).

REFERENCES

1. Bednar JR, Gruendeman GW, Sandrik JL. A comparative study of frictional forces between orthodontic brackets and arch wires. *Am J Orthod Dentofacial Orthop.* 1991;100:513–522.
2. Frank CA, Nikolai RJ. A comparative study of frictional resis-

tances between orthodontic bracket and arch wire. *Am J Orthod.* 1980;78:593–609.

3. Pizzoni L, Ravnholt G, Melsen B. Frictional forces related to self-ligating brackets. *Eur J Orthod.* 1998;20:283–291.
4. Thostenson GA, Kusy RP. The effect of archwire size and material on the resistance to sliding of self-ligating brackets with second-order angulation in the dry state. *Am J Orthod Dentofacial Orthop.* 2002;122:295–305.
5. Kusy RP, Whitley JQ. Resistance to sliding of orthodontic appliances in the dry and wet states: influence of archwire alloy, interbracket distance, and bracket engagement. *J Biomed Mater Res.* 2000;52:797–811.
6. Damon DH. The Damon low-friction bracket: a biologically compatible straight-wire system. *J Clin Orthod.* 1998;32:670–680.
7. Shivapuja PK, Berger J. A comparative study of conventional ligation and self-ligation bracket systems. *Am J Orthod.* 1994;106:472–480.
8. Hanson GH. The SPEED system: a report on the development of a new edgewise appliance. *Am J Orthod.* 1980;78:243–265.
9. Berger J. Self-ligation in the year 2000. *J Clin Orthod.* 2000;34:74–81.
10. Heiser W. Time: a new orthodontic philosophy. *J Clin Orthod.* 1998;32:44–53.
11. Maijer R, Smith DC. Time savings with self-ligating brackets. *J Clin Orthod.* 1990;24:29–31.
12. Henao SP, Kusy RP. Evaluation of the frictional resistance of conventional and self-ligating bracket designs using standardized archwires and dental typodonts. *Angle Orthod.* 2004;74:202–211.
13. Kusy RP, Dilley GJ. Elastic modulus of a triple-stranded stainless steel archwire via three- and four-point bending. *J Dent Res.* 1984;63:1232–1240.
14. Rucker BK, Kusy RP. Elastic properties of alternative versus single-stranded leveling archwires. *Am J Orthod Dentofacial Orthop.* 2002;122:528–541.
15. Kusy RP, Whitley JQ. Influence of archwire and bracket dimensions on sliding mechanics: derivations and determinations of the critical contact angles for binding. *Eur J Orthod.* 1999;21:199–208.
16. Thorstenson GA, Kusy RP. Comparison of resistance to sliding between different self-ligating brackets with second-order angulation in the dry and saliva states. *Am J Orthod Dentofacial Orthop.* 2002;121:472–482.
17. Brantley WA, Eliades T. *Orthodontic Materials Scientific and Clinical Aspects.* New York, NY: Thieme Stuttgart; 2001:84–97.
18. Segnar D, Ibe D. Properties of superelastic wires and their relevance to orthodontic treatment. *Eur J Orthod.* 1995;17:395–402.
19. Waters NE. Superelastic nickel-titanium wires. *Br J Orthod.* 1992;19:319–322.