Original Article

Effects of Ligation Type and Method on the Resistance to Sliding of Novel Orthodontic Brackets with Second-Order Angulation in the Dry and Wet States

Glenys A. Thorstenson, BS, PhD[a]; Robert P. Kusy, BS, MS, PhD[b]

Abstract: Rectangular stainless steel (SS) archwires were coupled with four SS bracket designs: Mini Diamond Twin, which was a conventional twin bracket; VersaT, which had bumps along the slot floor and rounded slot walls; Shoulder, which had bosses outside the tie-wings to lift the ligation off the archwire; and Synergy, which had bosses between the outer and inner tie-wings, bumps along the slot floor, and rounded slot walls. For all designs, the values of resistance to sliding (RS) were measured at five normal forces and 32 second-order angulations in the dry and wet (saliva) states. RS values at these same angles and states were also measured for the following: Mini Diamond Twin brackets ligated with rings and SS ligature wires; VersaT brackets ligated with rings; Shoulder brackets ligated with rings in a figure-8 and a figure-O around the tie-wings; and Synergy brackets ligated with rings around the outer tie-wings and around the inner tie-wings. In both states, the coefficients of friction were similar for the Mini Diamond Twin, VersaT, and Synergy brackets; the values for the Shoulder brackets were slightly greater than for the other three designs. In the passive configuration, the features of the Shoulder and Synergy brackets reduced RS when the rings were not in contact with the archwires. In the active configuration, the binding behavioral patterns of the brackets were not influenced by ligation methods. Thus, these different ligation types and methods only affected the classical frictional component of RS in the passive configuration. (*Angle Orthod* 2003;73:418–430.)

Key Words: Brackets; Friction; Stainless steel; Angulation; Ligation; Binding

INTRODUCTION

Recently, methods of reducing the resistance to sliding (RS) of stainless steel (SS) archwire-bracket couples have focused on bracket design and ligation technique. Previous studies have established that, when clearance exists between the archwire and the bracket's slot walls (the passive configuration), only classical friction (FR) contributes to RS.[1–3] The value of FR is equal to the normal force (F_N) applied by the ligation multiplied by the kinetic coefficient of friction ($\mu_{k\text{-}FR}$) of the orthodontic couple.[4] Because F_N and $\mu_{k\text{-}FR}$ differ for different ligation types (ie, elastomeric O-rings, SS ligature wires) and methods (ie, ''figure-O,'' ''figure-8,'' number of twists), previous measurements of FR for similar SS archwire-bracket couples have varied considerably.[5–12] Although some studies concluded that couples ligated with O-rings had greater FR values than those tied with SS ligature wires,[5,6,8,10,11] others have disagreed.[7] Apparently, the methods that were used to tie the SS ligature wires caused the FR values to vary.[13] The ligation method also affected the FR values of the elastomeric O-rings; O-rings ligated in a figure-8 exhibited greater FR values than those placed in a figure-O around the tie-wings.[10,11] Dowling et al and Matassa attributed the differences in FR values to the shapes that the O-rings formed as they passed over the archwires and under the brackets' tie-wings when placed in a figure-O.[12,14]

When clearance no longer exists (the active configuration), elastic binding (BI) additionally contributes to RS.[1–3] The second-order angulation at which the archwire first contacted the bracket's slot walls is defined as the critical contact angle for binding (θ_c).[3,15] At low angles (θ) relative to θ_c (in other words, small relative angulations [$\theta_r = \theta - \theta_c \approx 0$]), the BI contribution to RS is small.[2,3,16] As θ_r increases, the BI component overwhelms FR, and the overall effects of the ligation type and method decrease.[17]

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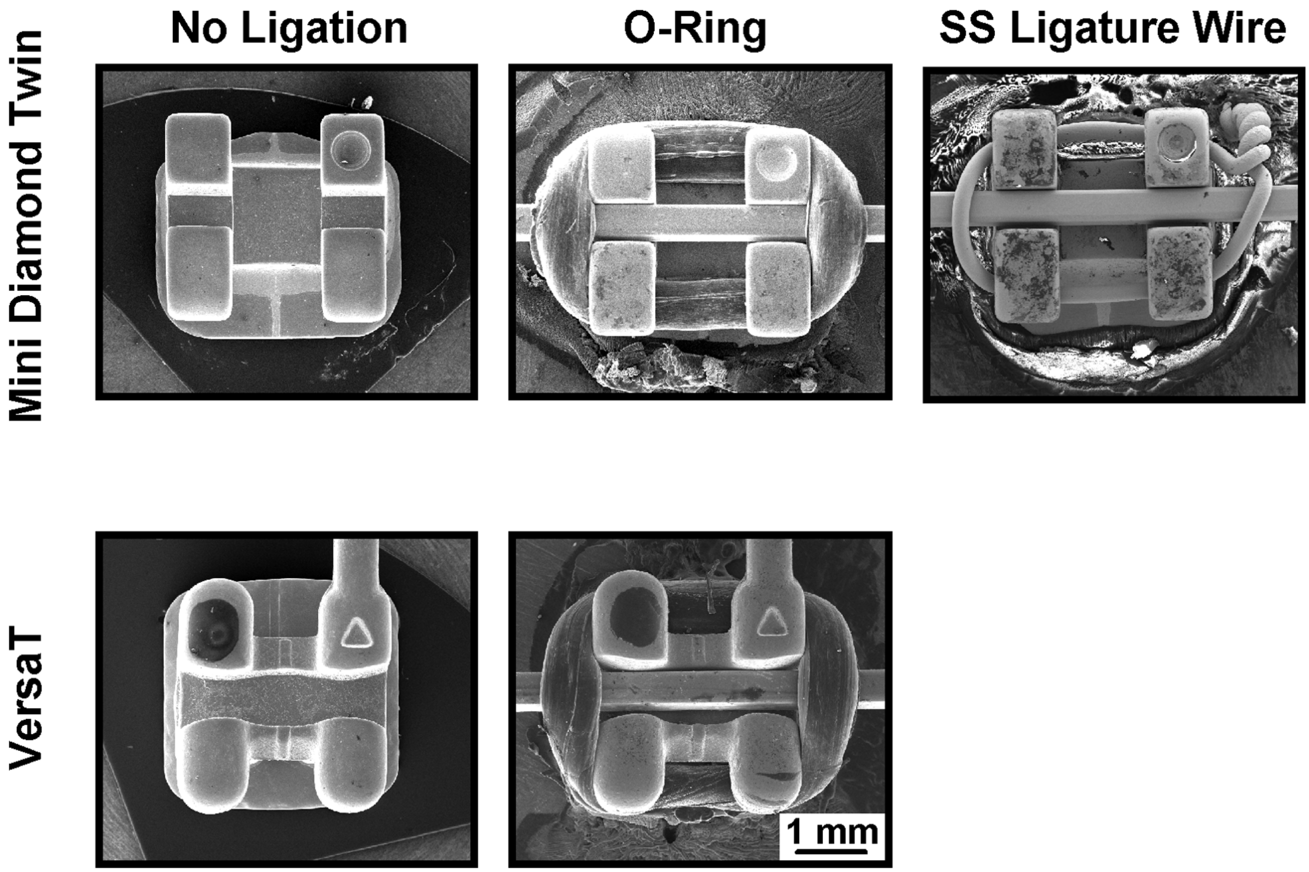

FIGURE 1. From a top view, scanning electron micrographs of the Mini Diamond Twin brackets (top row) and of the VersaT brackets (bottom row). In the left column, only the bracket is shown. Middle column: the archwire was ligated into the bracket using an elastomeric O-ring. Right column: the archwire was tied into the bracket with a SS ligature wire, which was twisted until taut and then untwisted a quarter turn. For the VersaT brackets, the bumps along the slot floor are not obvious, but the rounded slot walls are.

TABLE 1. Brackets, Archwires, and Ligatures Evaluated

Product	Design Features	Nominal Dimensions, mm (inches)[a]	Material
Bracket			
Mini Diamond Twin[b]	Conventional twin	0.559 (0.022)[c]	SS[d]
VersaT[e]	Bumps along slot floor; rounded slot walls	0.559 (0.022)[c]	SS
Shoulder[f]	Outer tie-wing bosses	0.559 (0.022)[c]	SS
Synergy[e]	Inner tie-wing bosses; bumps along slot floor; rounded slot walls	0.559 (0.022)[c]	SS
Archwire			
Rectangular[b]		0.457 × 0.635 (0.018 × 0.025)[g]	SS
Ligation			
Clear ringlets[e]		2.79 (0.110)[h]	Elastomer
Ligature wires[f]		0.254 (0.010)[h]	SS

[a] 1 mm = 0.03937 inches.
[b] Sybron Dental Specialties Ormco, Orange, CA.
[c] SLOT dimension measured in occlusogingival direction along floor of bracket.
[d] Stainless steel.
[e] Rocky Mountain Orthodontics, Denver, CO.
[f] GAC International, Inc., Islandia, NY.
[g] SIZE × HEIGHT dimensions measured in occlusogingival direction of wire and in labial-lingual direction of wire, respectively.
[h] Diameter dimension measured across ligature.

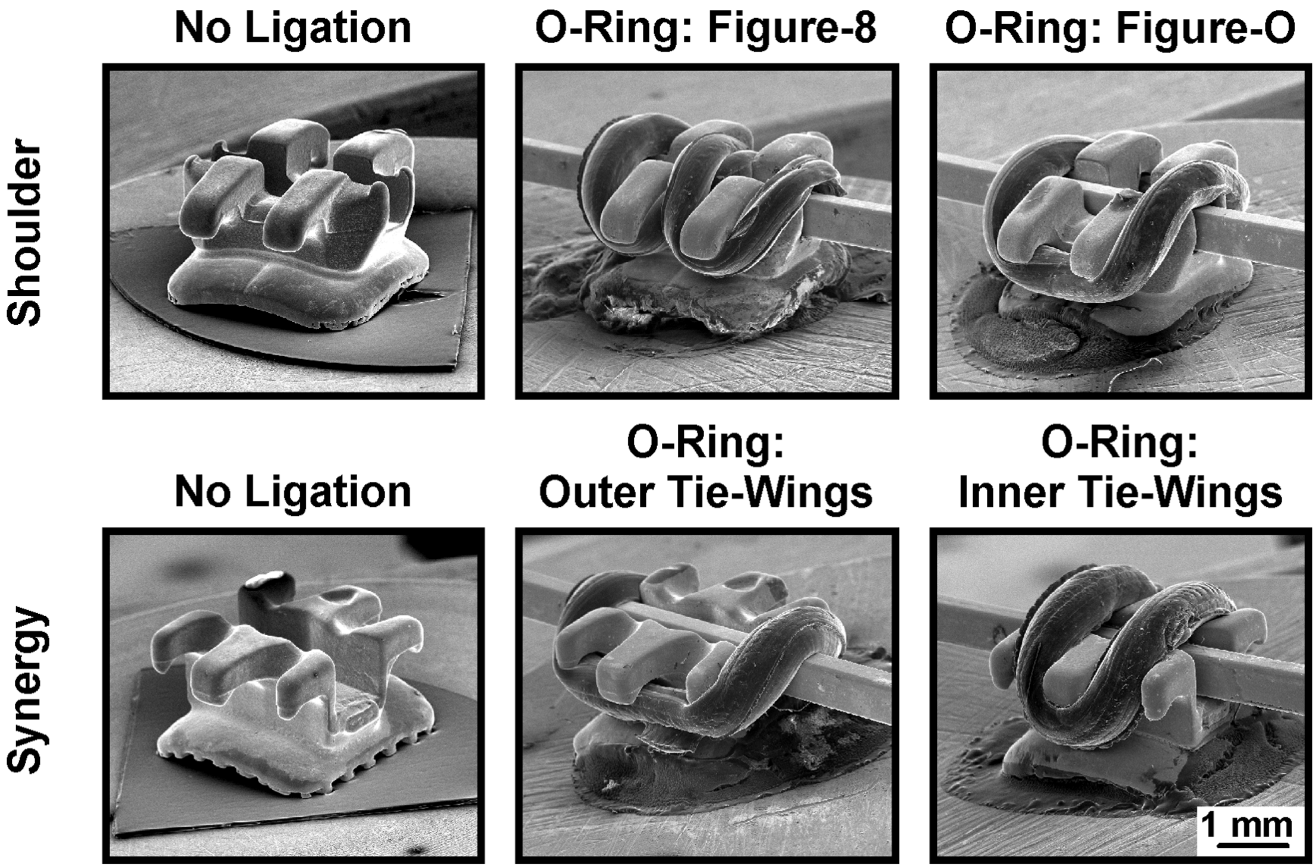

FIGURE 2. From a side view, scanning electron micrographs of the brackets with bosses. For the Shoulder brackets (top row), note the bosses outside of the tie-wings. Left column: only the bracket is shown; middle column: the O-ring was placed in a figure-8 around the four tie-wings; right column: the O-ring was placed in a figure-O around the four tie-wings. For the Synergy brackets (bottom row), note the inner tie-wings (which formed the "triple" bracket); the bumps along the slot floor and the rounded slot walls are not obvious. Left column: only the bracket is shown; middle column: the O-ring was placed around the outer tie-wings; right column: the O-ring was placed around the inner tie-wings such that it sat on the bosses between the inner and outer tie-wings.

In the present study, the RS values of two SS bracket designs with bosses that prevent contact between the ligation and the archwire were compared with those of two SS bracket designs without these bosses. The placement of the ligation over the bosses was hypothesized to reduce the FR component of RS but not the BI component. To test this hypothesis, the manufacturers' suggested ligation methods were used to restrain the archwires in the brackets using O-rings. Additionally, SS ligatures were used to tie the archwires into the SS brackets without bosses, bumps, or rounded slot walls. The outcomes show that the bosses did reduce or eliminate the FR component of RS. The BI component, however, increased at a constant rate with angulation regardless of the different ligation types and methods that were used.

MATERIALS AND METHODS

Materials—dimensions and morphologies

All brackets were made of SS and had a prescription of 0° angulation and −7° torque. The Mini Diamond Twin bracket (Figure 1, top row; Table 1), which was the control bracket, was a conventional bracket. The VersaT bracket (Figure 1, bottom row; Table 1) served as a secondary control bracket with the addition of bumps in the slot floor and rounded slot walls. The Shoulder bracket (Figure 2, top row; Table 1) had a small boss on the outside of each tie-wing that lifted the ligation off the archwire. The Synergy bracket (Figure 2, bottom row; Table 1) could be considered a "triple" bracket. When the ligation was placed around the inner tie-wing, the bosses prevented the ligation from contacting the archwire. Like the VersaT bracket, the Synergy bracket also had bumps in the slot floor and rounded slot walls. The brackets were coupled with SS archwires (Table 1) and then were ligated with either elastomeric O-rings or SS ligature wires (Table 1).

For each archwire, the occlusogingival SIZE dimension was measured.[3] For each Mini Diamond or Shoulder bracket, the occlusogingival $SLOT_{true}$ and the mesiodistal $WIDTH_{true}$ dimensions were measured.[3] For each Synergy and VersaT bracket, the $SLOT_{true}$ dimension at the narrow-

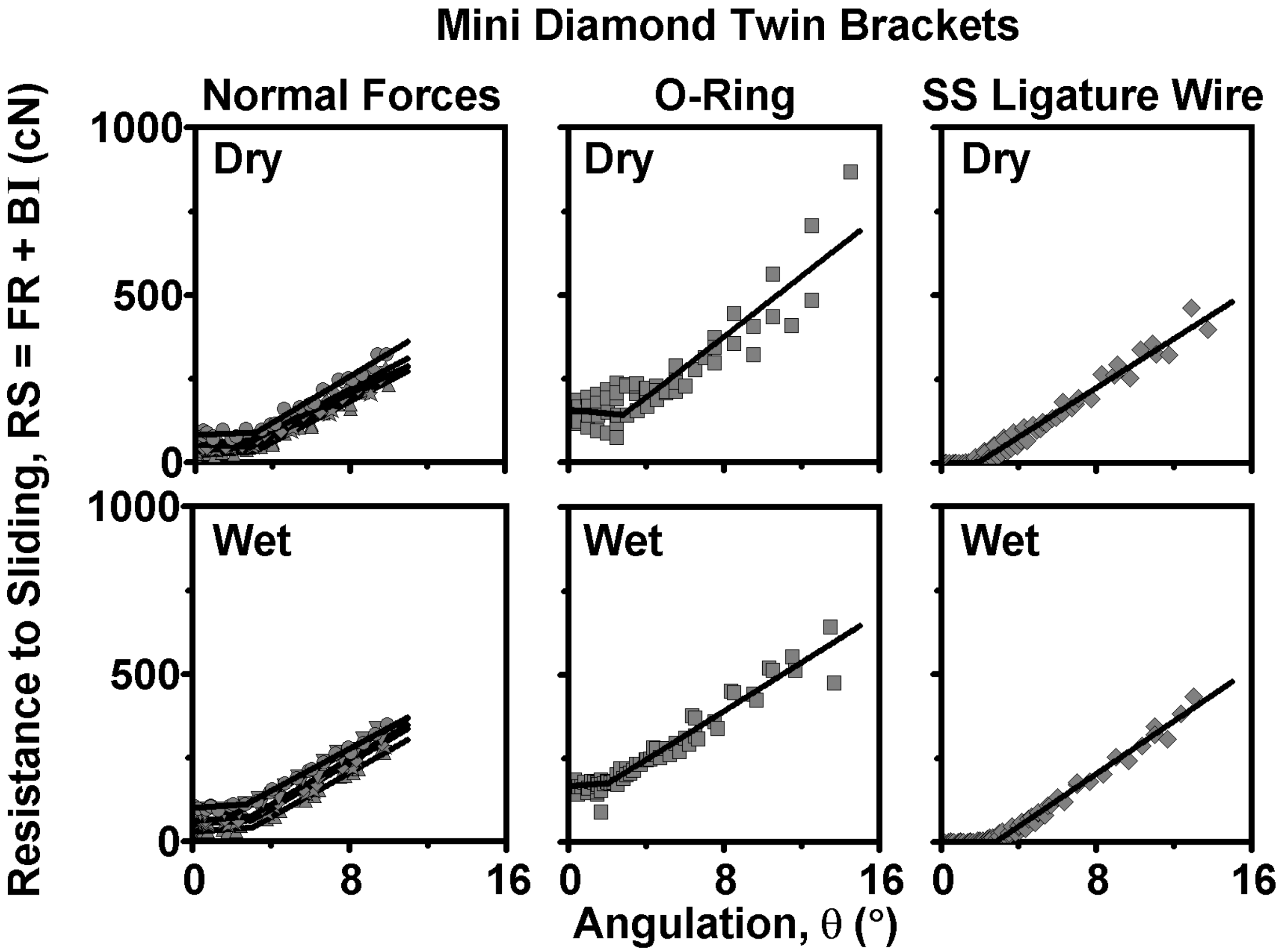

FIGURE 3. For the Mini Diamond Twin brackets, plots of RS (= FR + BI) as a function of θ in the dry (top row) and wet (bottom row) states. Left column: constant normal forces of 200, 300, 400, 500, and 600 cN (1 cN = 1.02 g) were applied to the archwires using SS ligature wires; middle column: O-rings were placed around the tie-wings (see Figure 1, top row, middle column); right column: the archwires were tied into the brackets with SS ligature wires (see Figure 1, top row, right column).

est regions of the opposing bumps of the slot walls, the $SLOT_{apparent}$ dimension at the widest regions of the opposing bumps, the $WIDTH_{true}$ dimension between the adjacent bumps, and the mesiodistal $WIDTH_{apparent}$ dimension were measured (unpublished data).

Using a scanning electron microscope (JEOL JSM-6300, JEOL America, Peabody, Mass) at 15 keV in the secondary electron mode, the bracket morphologies were evaluated in the as-received condition and after ligation. The ligated archwire-bracket couples were carbon-coated prior to viewing.

Frictional testing

The RS values were measured using a frictional testing apparatus that was mounted to the transverse beam on a mechanical testing machine (Instron Model TTCM, Instron Corp, Canton, Mass).[16] For the brackets tested at known F_N values, a constant F_N was applied using a machined SS tube, which was fitted with a SS ligature wire, and maintained by a feedback loop. All O-rings were stretched over the tie-wings using a blunt probe. The archwire-bracket couples were serially translated two mm in 12 seconds at 34°C at these second-order angulations (θ values): 0°, −12°, −10°, −8°, −6°, −5°, −4.5°, −4°, −3.5°, −3°, −2.5°, −2°, −1.5°, −1°, −0.5°, 0°, 0°, 0.5°, 1°, 1.5°, 2°, 2.5°, 3°, 3.5°, 4°, 4.5°, 5°, 6°, 8°, 10°, 12°, and 0°. To prevent any interaction between the test bracket and the simulated adjacent brackets,[16] the interbracket distances were maintained at 18 mm. For the wet state, a peristaltic pump dripped saliva at a flow rate of 3 cm^3/min; the saliva's viscosity was certified to be between 1.3 and 2.0 milliPascal-seconds (mP-sec) at 34°C (Brookfield Model LVTDV-II CP viscometer, Brookfield Engineering Laboratories Inc, Stoughton, Mass).[18]

Couples evaluated

For the Mini Diamond Twin brackets, the data for the RS values at normal forces (F_N) of 200, 300, 400, 500, and

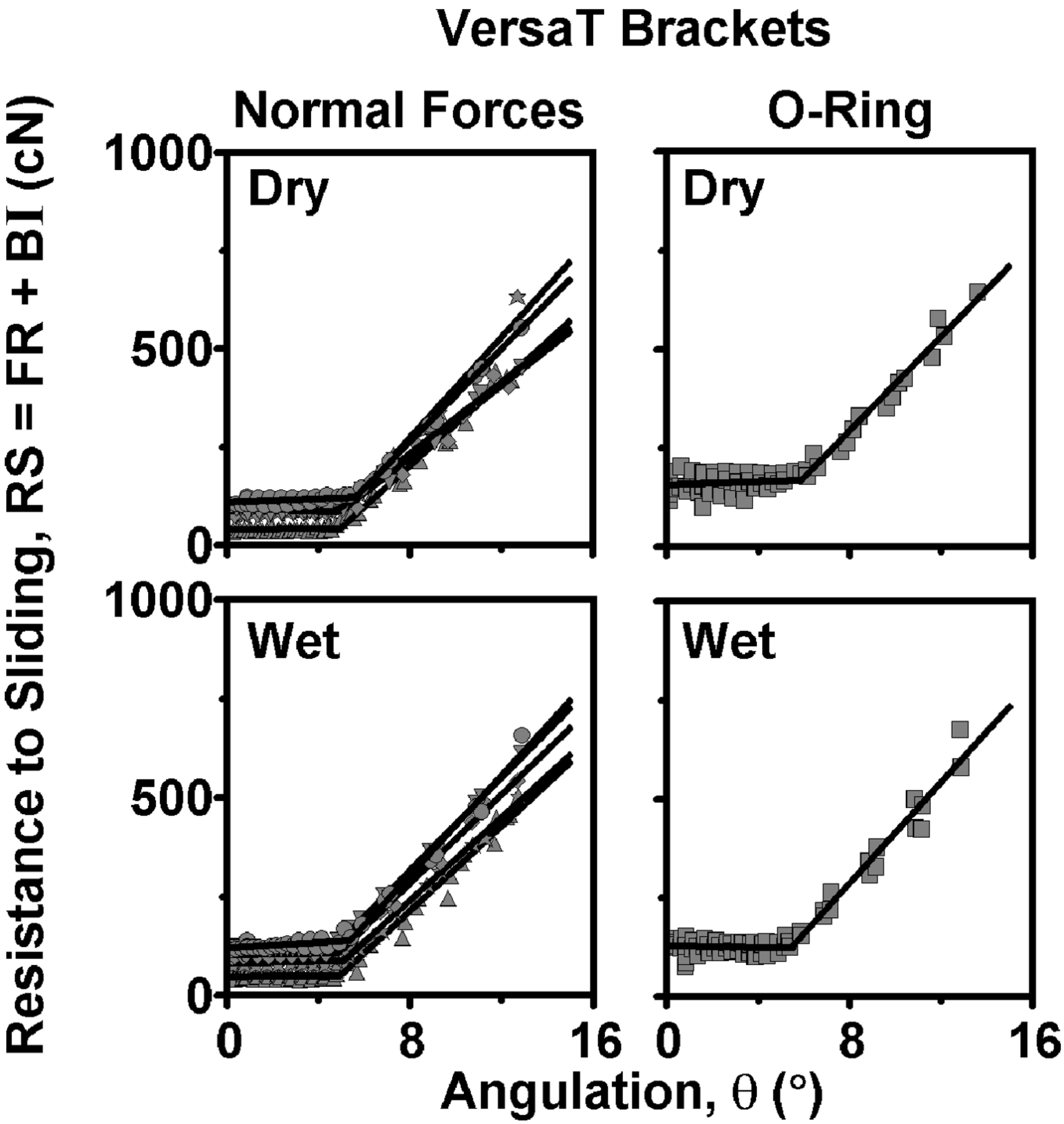

FIGURE 4. For the VersaT brackets, plots of RS (= FR + BI) as a function of θ in the dry (top row) and wet (bottom row) states. Left column: constant normal forces of 300, 500, 600, 700, and 800 cN were applied; right column: O-rings were placed around the tie-wings (see Figure 1, bottom row, middle column).

600 cN (1 cN = 1.02 g) were restated.[19] Two of the Mini Diamond Twin brackets, ligated with O-rings or SS ligature wires (Figure 1; top row, middle and right columns, respectively), were tested in the dry and wet states. All the O-rings were used as received, without prestretching.[20] The SS ligature wires were first twisted until they were taut against the archwire and then untwisted a quarter turn.[13,21]

For the VersaT brackets, the RS values of four brackets in each state were measured at 500, 600, 700, and 800 cN, using one bracket at each F_N value. Data obtained with a F_N value of 300 cN were also included (unpublished data). In each state, two additional VersaT brackets were tested with O-rings ligated around the tie-wings (Figure 1, bottom row, middle column).

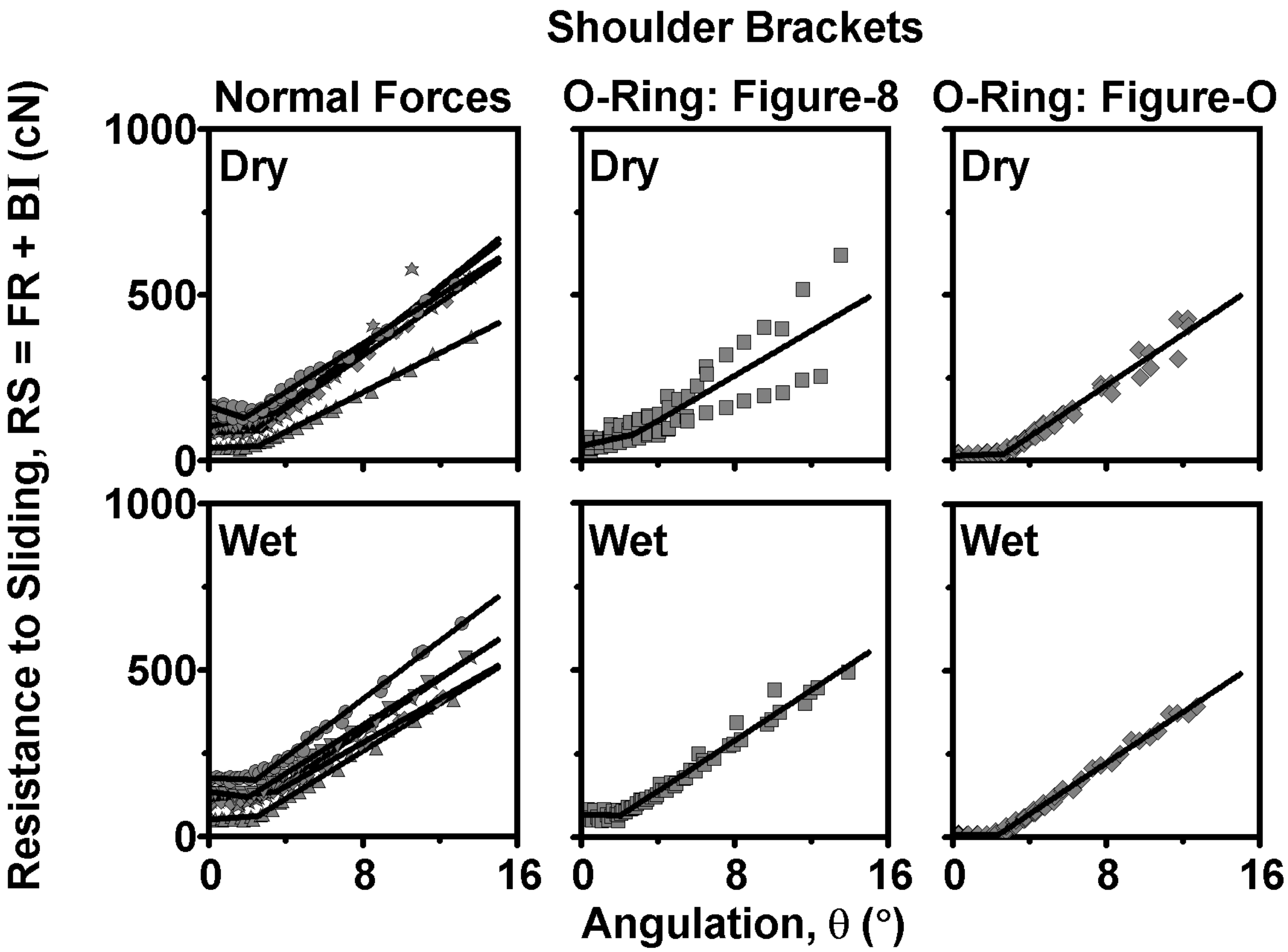

FIGURE 5. For the Shoulder brackets, plots of RS (= FR + BI) as a function of θ in the dry (top row) and wet (bottom row) states. Left column: constant normal forces of 300, 500, 600, 700, and 800 cN were applied; middle column: O-rings were placed in a figure-8 around the tie-wings (see Figure 2, top row, middle column); right column: O-rings were placed in a figure-O around the tie-wings (see Figure 2, top row, right column).

For the Shoulder bracket, one bracket was tested in each state at each of five F_N values: 300, 500, 600, 700, and 800 cN. Additionally, four brackets were ligated with O-rings in a figure-8 (Figure 2, top row, middle column) and in a figure-O around the tie-wings (Figure 2, top row, right column). Two brackets were tested in each of the dry and wet states.

For the Synergy bracket, the RS values were either evaluated or included (unpublished data) at the same F_N values as the VersaT brackets. Two brackets in each state were studied with the O-rings ligated around the outer tie-wings (Figure 2, bottom row, middle column) and around the inner tie-wings (Figure 2, bottom row, right column).

Data analysis and statistics

For the brackets with straight slot walls, the theoretical critical contact angle (θ_c) was calculated using the SIZE, $SLOT_{true}$, and $WIDTH_{true}$ values.[15] For the brackets with the rounded slot walls, a model was used in which the changes from $SLOT_{true}$ and $WIDTH_{true}$ to $SLOT_{apparent}$ and $WIDTH_{apparent}$ were considered, and the theoretical θ_c value was determined (unpublished data). Using the theoretical θ_c value, linear regression lines[22] were fitted to the passive and active regions, whose intersection was at the experimental θ_c.[3,16]

When RS = FR, the FR value may be determined by averaging FR or calculating the y-axis intercept (b) of the linear regression line.[16] When RS = FR + BI, the FR component can be subtracted from the RS value.[16] The isolated BI component was plotted against the relative angulation ($\theta_r = \theta - \theta_c$, where θ_c was the experimental value).[16]

RESULTS

For all bracket designs, the theoretical θ_c values that were calculated from the average dimensions of each bracket design and those of the archwires were within 0.7° of the experimental θ_c value (Table 2). For all bracket designs in

TABLE 2. Nominal Bracket Dimensions and Critical Contact Angles for Binding (θ_c)

Bracket	Dimensions, mm (inches)				θ_c (°)	
	$SLOT_{true}$[a]	$SLOT_{apparent}$[b]	$WIDTH_{true}$[a]	$WIDTH_{apparent}$[b]	Theoretical[c]	Experimental[d]
Mini Diamond Twin	0.5791 (0.0228)	—	3.122 (0.1229)	—	2.2	2.7
VersaT	0.6045 (0.0238)	0.7899 (0.0311)	1.582 (0.0623)	2.964 (0.1167)	4.6	5.1
Shoulder	0.5740 (0.0226)	—	3.553 (0.1399)	—	1.9	2.6
Synergy	0.6071 (0.0239)	0.8458 (0.0333)	1.494 (0.0588)	3.185 (0.1254)	4.8	5.1

[a] The SLOT value was equal to the average value of the measured occlusogingival slot dimensions of the brackets (unpublished data).[15]

[b] The WIDTH value was equal to the average value of the measured mesiodistal width dimensions of the brackets (unpublished data).[15]

[c] The theoretical θ_c value was calculated using the appropriate equations and dimensions of the brackets and archwires (unpublished data).[14] The average SIZE dimension of the archwires was 0.4572 mm (0.018 inches).[15]

[d] The experimental θ_c value was defined as the intersection of the best-fit regression lines fitted to the data for the passive and active configurations.[15,16]

TABLE 3. Average RS Values and Kinetic Coefficients of Friction ($\mu_{k\text{-}FR}$) in Dry and Wet States for the Passive Configuration

Bracket	Ligation	Dry State		Wet State	
		Average RS (cN)[a]	$\mu_{k\text{-}FR}$[b]	Average RS (cN)[a]	$\mu_{k\text{-}FR}$[b]
Mini Diamond Twin	Normal force = 200 cN	26		33	
	Normal force = 300 cN	38		56	
	Normal force = 400 cN	56	0.14	66	0.17
	Normal force = 500 cN	60		90	
	Normal force = 600 cN	85		103	
	O-ring	154		170	
	SS ligature wires	1		1	
VersaT	Normal force = 300 cN	40		49	
	Normal force = 500 cN	86		84	
	Normal force = 600 cN	89	0.13	105	0.16
	Normal force = 700 cN	91		122	
	Normal force = 800 cN	113		127	
	O-ring	161		127	
Shoulder	Normal force = 300 cN	40		55	
	Normal force = 500 cN	86		108	
	Normal force = 600 cN	113	0.21	116	0.22
	Normal force = 700 cN	115		128	
	Normal force = 800 cN	151		174	
	O-ring: figure-8	52		67	
	O-ring: figure-O	16		8	
Synergy	Normal force = 300 cN	44		52	
	Normal force = 500 cN	74		77	
	Normal force = 600 cN	85	0.14	103	0.18
	Normal force = 700 cN	99		121	
	Normal force = 800 cN	114		137	
	O-ring: outer tie-wings	110		114	
	O-ring: inner tie-wings	2		2	

[a] The average RS value, equal to the average FR, was the average value of the data in the passive configuration.[16]

[b] The $\mu_{k\text{-}FR}$ value was equal to the slope of the best-fit linear regression for a plot of the average RS values vs the five normal forces (not shown).[3]

which the O-rings contacted the archwire, except the VersaT brackets, the RS value (= FR) in the passive configuration was greater in the wet than in the dry state (Figures 3, 5, and 6, left side of each plot in the middle column; Figure 4, left side of each plot in the right column; Table 3). For the Mini Diamond Twin brackets ligated with SS ligature wires, the Shoulder brackets ligated with O-rings in a figure-O, and the Synergy brackets ligated with O-rings around the inner tie-wing, the FR values in both states were negligible (Figures 3, 5, and 6, left side of each plot in the right column; Table 3). For all the brackets tested, the intercepts (b values) were within 19 cN of the average FR values (cf. Tables 3 and 4). The values of RS (= FR) in the passive configuration generally were independent of θ,

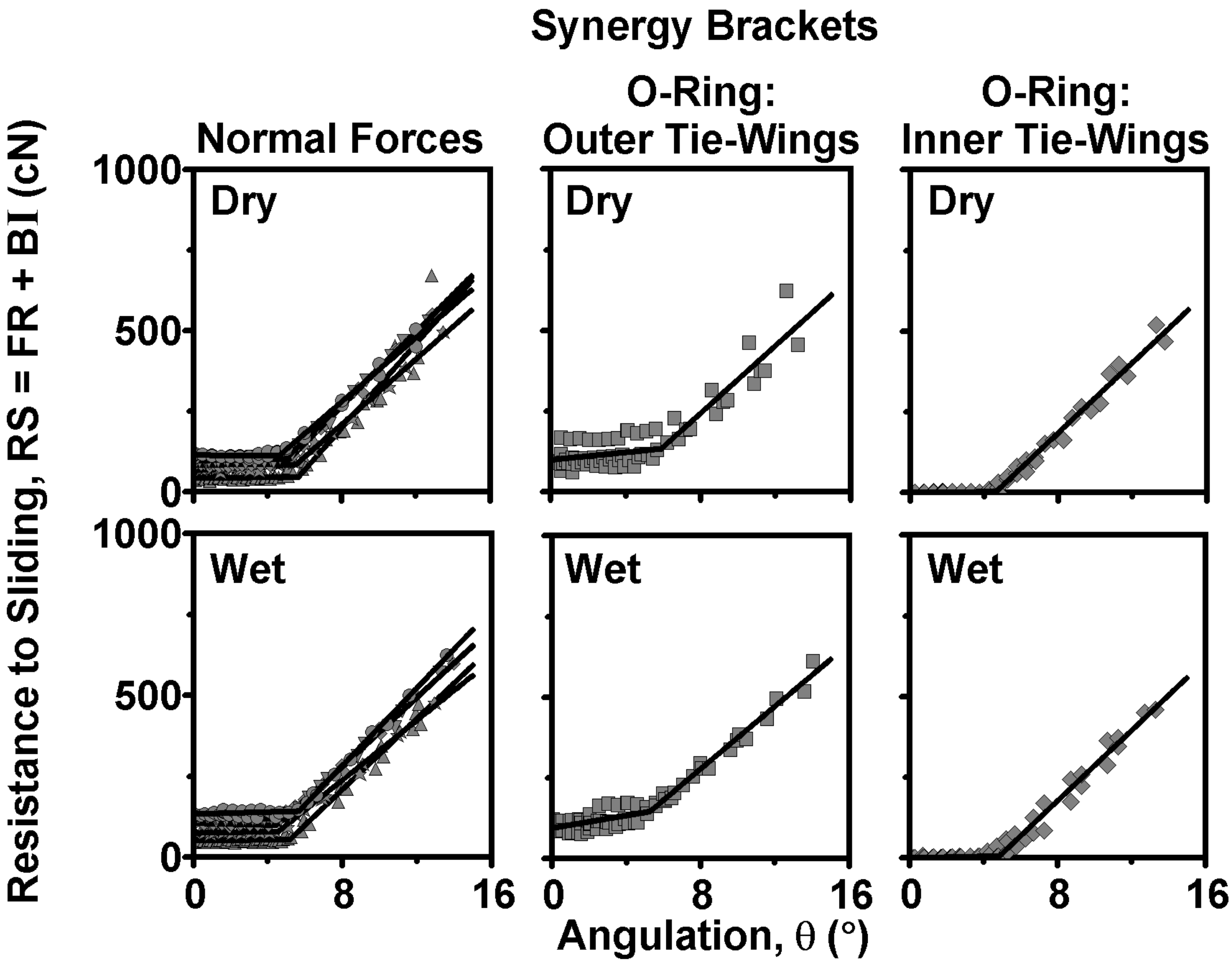

FIGURE 6. For the Synergy brackets, plots of RS (= FR + BI) as a function of θ in the dry (top row) and wet (bottom row) states. Left column: constant normal forces of 300, 500, 600, 700, and 800 cN were applied; middle column: O-rings were placed around the outer tie-wings (see Figure 2, bottom row, middle column); right column: O-rings were placed around the inner tie-wings such that the O-rings were over the bosses between the inner and outer tie-wings (see Figure 2, bottom row, right column).

as shown by the low *P* values of the linear regression lines even when the number of data points (n) was great (Table 4).[22]

In the active configuration, the RS values increased as θ increased (Figures 3–6, right side of each plot). In both states, the slopes (m values) of the regression lines were similar for the Mini Diamond Twin and Shoulder brackets regardless of ligation method (Table 5). The m values of the VersaT and Synergy brackets were also similar regardless of ligation method, but were greater than those of the Mini Diamond Twin and Shoulder brackets.

DISCUSSION

The control brackets (Figure 1)

For a specific archwire-bracket-ligature combination, the slope of an average FR against F_N regression (not shown) equaled the kinetic coefficient of friction ($\mu_{k\text{-}FR}$).[4] For SS couples, the $\mu_{k\text{-}FR}$ values in the dry state are generally lower than those in the wet state (Table 3).[23] The addition of bumps to the VersaT brackets did not reduce FR or $\mu_{k\text{-}FR}$ value, but the rounded slot walls did increase the value of the experimental θ_c substantially beyond that of the Mini Diamond Twin brackets (Table 2) (unpublished data).

With the $\mu_{k\text{-}FR}$ value of the Mini Diamond Twin brackets (Table 3),[19] the FR value of the O-rings corresponded to F_N values of 1100 cN in the dry state and 1000 cN in the wet state (Figure 7), but whether those high values were attributable to a greater $\mu_{k\text{-}FR}$ value (because of the elastomeric material) or a greater F_N value than in SS ligatures is not presently known. For the VersaT brackets ligated with O-rings, FR corresponded to F_N = 1150 cN in the dry state, but to F_N = 800 cN in the wet state (Figure 7). Frank and Nikolai found no difference between O-rings and SS ligature wires that applied F_N = 220 cN to the archwire.[17] Ed-

TABLE 4. Linear Regression Analyses of RS vs Angulation in the Dry and Wet States for the Passive Configuration

Bracket	Ligation	Dry State m (cN/°)[a]	Dry State b (cN)[a]	Dry State r[b]	Dry State n[b]	Dry State *P*[b]	Wet State m (cN/°)[a]	Wet State b (cN)[a]	Wet State r[b]	Wet State n[b]	Wet State *P*[b]
Mini Diamond Twin	Normal force = 200 cN	+3	+22	0.47	12	NS	+4	+29	0.59	12	<0.05
	Normal force = 300 cN	+4	+34	0.84	11	<0.001	+4	+53	0.29	12	NS
	Normal force = 400 cN	−2	+54	0.18	11	NS	+5	+61	0.55	12	NS
	Normal force = 500 cN	+3	+57	0.40	12	NS	−3	+92	0.22	11	NS
	Normal force = 600 cN	+2	+82	0.16	12	NS	−4	+100	0.48	11	NS
	O-ring	−5	+158	0.07	13	NS	+4	+167	0.12	11	NS
	SS ligature wires	+2	−1	0.55	15	<0.05	+1	0	0.19	17	NS
VersaT	Normal force = 300 cN	+1	+39	0.40	39	<0.02	+1	+48	0.13	38	NS
	Normal force = 500 cN	+1	+83	0.27	19	NS	+1	+82	0.15	19	NS
	Normal force = 600 cN	0	+89	0.02	19	NS	+1	+103	0.23	19	NS
	Normal force = 700 cN	−2	+95	0.39	20	NS	−1	+124	0.57	19	<0.02
	Normal force = 800 cN	+2	+109	0.31	19	NS	+4	+121	0.52	19	<0.02
	O-ring	+2	+157	0.09	38	NS	−1	+129	0.07	38	NS
Shoulder	Normal force = 300 cN	+2	+38	0.88	5	<0.05	+4	+51	0.45	9	NS
	Normal force = 500 cN	+3	+85	0.25	5	NS	+5	+106	0.61	5	NS
	Normal force = 600 cN	−8	+118	0.40	9	NS	+7	+113	0.21	9	NS
	Normal force = 700 cN	+12	+113	0.58	9	NS	−7	+135	0.57	9	NS
	Normal force = 800 cN	−19	+165	0.39	9	NS	−2	+176	0.19	9	NS
	O-ring: figure-8	+13	+44	0.33	13	NS	−1	+68	0.02	14	NS
	O-ring: figure-O	+2	+15	0.14	18	NS	0	+8	0.06	18	NS
Synergy	Normal force = 300 cN	+1	+43	0.21	40	NS	+1	+51	0.14	41	NS
	Normal force = 500 cN	+3	+68	0.43	19	NS	+1	+75	0.01	20	NS
	Normal force = 600 cN	+1	+84	0.15	20	NS	−1	+105	0.52	19	<0.02
	Normal force = 700 cN	+1	+97	0.20	20	NS	−1	+123	0.63	20	<0.01
	Normal force = 800 cN	−1	+114	0.11	20	NS	+2	+134	0.28	19	NS
	O-ring: outer tie-wings	+6	+99	0.22	40	NS	+10	+95	0.13	38	NS
	O-ring: inner tie-wings	+1	+0	0.36	40	<0.05	+1	0	0.06	41	NS

[a] The best-fit linear regression of the form $y = mx + b$,[22] in which y was RS, m was the slope, x was the second-order angulation (θ), and b was the y-axis intercept.

[b] For the best-fit linear regression, the probability (*P*) of the line was determined by its correlation coefficient (r) and the number of data points (n).[22] If the *P* value was greater than 0.05, then the regression line was not significant (NS).

wards et al found similar FR values between O-rings and tied SS archwires that applied an estimated $F_N = 675$ cN to the archwire.[10] The variation of F_N values can be attributed to the different brands of O-rings used, which have various material properties,[12] and to the different bracket designs, which affect the force applied by the O-rings.[12,14]

For the Mini Diamond Twin brackets that were tied with SS ligature wires, the FR values were negligible (Figure 7; Table 3). These low values were attributed to a decrease in F_N caused by loosening each ligature by a quarter turn.[7,13,21] When the SS ligature wires are slack, conventional SS archwire-bracket couples act like self-ligating brackets with passive slides.[19] Note that, for self-ligating brackets, a passive slide or clip does not apply a force to an archwire, whereas an active clip does apply a force to an archwire.[19] This is not to be confused with the passive (or active) configurations, which terms refer to the clearance (or lack thereof) of an archwire within a bracket.[1–3]

In the active configuration, the BI component depended upon the angle (θ) between the bracket and the archwire. For each bracket design, plots of BI against $\theta_r = \theta - \theta_c$ (Figure 8) showed that there was little difference among the regression lines of the known normal forces, those of the O-rings, and those of the tied SS ligature wires; these regression lines were highly significant ($P < 0.001$) (Table 5). For the VersaT brackets, the rates of BI (which were equivalent to m values; Table 5) were greater than those of the Mini Diamond Twin brackets. As discussed in a previous study, this greater rate of BI was attributed to the shape of the slot walls (unpublished data). Although the archwire was tangential to the rounded slot walls where the wire entered and exited the VersaT bracket, the archwire bent where the wire contacted the curve between the two bumps (Figure 1, bottom row), leading to a greater bend of the archwire within the bracket slot than the measured θ and a greater BI than expected.

Effects of bosses on brackets with straight walls (Figures 1 and 2, top rows)

In the passive configuration for both states, the values of $\mu_{k\text{-}FR}$ were greater for the Shoulder brackets than for the

TABLE 5. Linear Regression Analyses of RS vs Angulation in the Dry and Wet States for the Active Configuration

Bracket	Ligation	Dry State m (cN/°)[a]	Dry State b (cN)[a]	Dry State r[b]	Dry State n[b]	Dry State *P*[b]	Wet State m (cN/°)[a]	Wet State b (cN)[a]	Wet State r[b]	Wet State n[b]	Wet State *P*[b]
Mini Diamond Twin	Normal force = 200 cN	30	−60	0.98	14	<0.001	33	−60	1.00	14	<0.001
	Normal force = 300 cN	30	−40	0.97	15	<0.001	33	−35	0.98	14	<0.001
	Normal force = 400 cN	31	−27	0.97	13	<0.001	33	−23	0.98	14	<0.001
	Normal force = 500 cN	31	−27	0.98	15	<0.001	33	+11	0.97	15	<0.001
	Normal force = 600 cN	35	−19	0.99	14	<0.001	32	+21	1.00	15	<0.001
	O-ring	45	+15	0.91	36	<0.001	36	+102	0.97	41	<0.001
	SS ligature wires	37	−67	0.98	42	<0.001	39	−109	0.99	36	<0.001
VersaT	Normal force = 300 cN	53	−218	0.99	18	<0.001	54	−214	0.98	18	<0.001
	Normal force = 500 cN	64	−238	0.99	10	<0.001	52	−178	1.00	10	<0.001
	Normal force = 600 cN	46	−141	0.98	9	<0.001	56	−163	1.00	10	<0.001
	Normal force = 700 cN	45	−130	0.99	11	<0.001	59	−150	1.00	11	<0.001
	Normal force = 800 cN	59	−211	1.00	8	<0.001	63	−199	0.99	9	<0.001
	O-ring	59	−181	0.99	17	<0.001	64	−223	0.97	16	<0.001
Shoulder	Normal force = 300 cN	30	−31	1.00	19	<0.001	36	−28	1.00	19	<0.001
	Normal force = 500 cN	47	−39	0.97	18	<0.001	39	+7	1.00	18	<0.001
	Normal force = 600 cN	40	−1	0.99	19	<0.001	33	+20	1.00	15	<0.001
	Normal force = 700 cN	44	−10	1.00	15	<0.001	36	+45	1.00	19	<0.001
	Normal force = 800 cN	37	+62	1.00	21	<0.001	44	+64	1.00	19	<0.001
	O-ring: figure-8	34	−13	0.81	36	<0.001	38	−10	0.99	42	<0.001
	O-ring: figure-O	39	−82	0.98	38	<0.001	38	−83	1.00	38	<0.001
Synergy	Normal force = 300 cN	65	−323	0.94	16	<0.001	55	−229	0.99	17	<0.001
	Normal force = 500 cN	51	−195	1.00	9	<0.001	46	−130	0.99	11	<0.001
	Normal force = 600 cN	58	−197	1.00	10	<0.001	53	−136	1.00	12	<0.001
	Normal force = 700 cN	56	−176	1.00	10	<0.001	54	−149	1.00	10	<0.001
	Normal force = 800 cN	50	−117	0.99	10	<0.001	60	−198	1.00	9	<0.001
	O-ring: outer tie-wings	52	−174	0.90	15	<0.001	48	−108	0.99	21	<0.001
	O-ring: inner tie-wings	54	−248	0.99	24	<0.001	54	−259	0.98	20	<0.001

[a] The best-fit linear regression of the form y = mx + b,[22] in which y was RS, m was the slope (which was equal to the coefficient of binding [μ_{BI}]), x was the second-order angulation (θ), and b was the y-axis intercept.

[b] For the best-fit linear regression, the probability (*P*) of the line was determined by its correlation coefficient (r) and the number of data points (n).[22] If the *P* value was greater than 0.05, then the regression line was not significant (NS).

Mini Diamond Twin brackets (Table 3). For the brackets ligated with O-rings in a figure-8, the FR values for both states were between the FR values for F_N values of 300 and 500 cN (Figure 7); the F_N values for the dry and wet states that were calculated using the $\mu_{k\text{-}FR}$ values (Table 3), however, were 250 and 300 cN, respectively. These FR values were much less than those estimated for O-rings with the archwires and Mini Diamond brackets. Although contact between the ligatures and the archwires did occur at the center of each figure-8, the bosses outside the tie-wings prevented the ligatures from contacting the archwires at those locations, which led to a lower F_N being applied to the archwire than for the Mini Diamond Twin brackets. For the Shoulder brackets that were ligated with O-rings in a figure-O, the negligible FR values further confirmed that the bosses did displace the ligature from the archwire (Figure 7; Table 3). Ogata et al observed greater FR values at zero mm deflection (which was equivalent to 0°) than presented in this study, but their FR values for the bracket designs without bosses were still three to four times those of the Shoulder brackets.[24]

In the active configuration, plots of θ_r vs BI again showed that the rate of BI was independent of the ligation type and method (Figure 8). The rates of BI of the Shoulder brackets were comparable to those of the Mini Diamond Twin brackets (Table 5).

Effects of bosses on brackets with bumps in the slot floors and walls (Figures 1 and 2, bottom rows)

In the passive configuration for the Synergy brackets, the values of $\mu_{k\text{-}FR}$ for both states were similar to those of the VersaT brackets (Table 3). As noted previously (unpublished data), the bumps along the slot floor did not reduce the FR values of the Synergy or VersaT brackets as compared with the Mini Diamond Twin brackets. For the Synergy brackets ligated with O-rings around the outer tie-wings, the FR values for the dry and wet states were comparable to F_N values of 800 and 650 cN, respectively (Figure 7). When the Synergy brackets were ligated with O-rings around the inner tie-wings, FR was negligible (Fig-

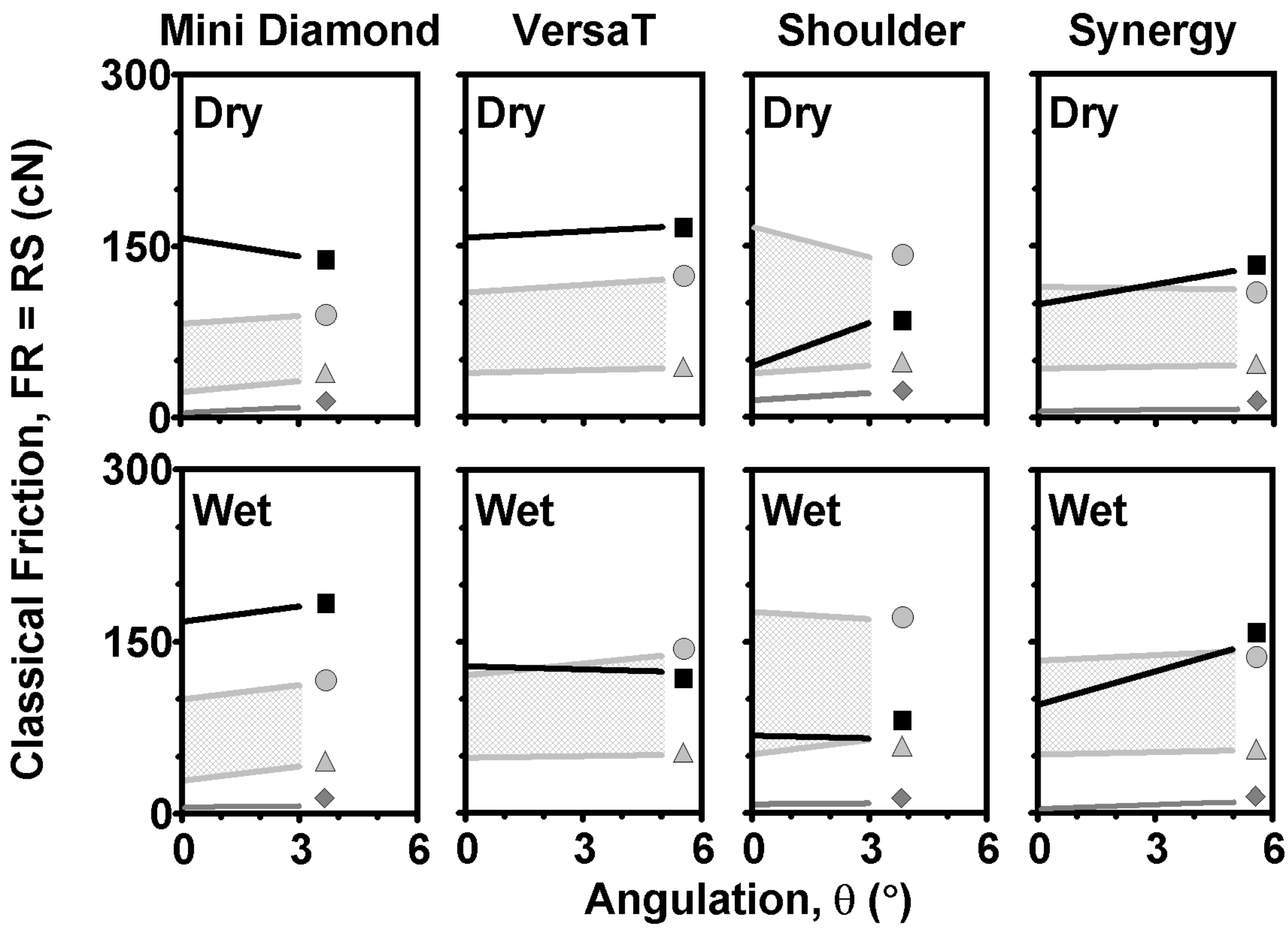

FIGURE 7. In the passive configuration for all four bracket designs, linear regression analyses for FR (= RS) as a function of θ in the dry (top row) and wet (bottom row) states. For each plot, the hatched region shows the range in which the linear regression lines for the known normal forces are situated, ranging from the least normal force (△) to the greatest normal force (○). (See Tables 3 and 4 for details.) For the Mini Diamond Twin brackets, regression lines are shown for the O-ring ligation (■) and the SS wire ligation (◆). For the VersaT brackets, regression lines are shown for the O-ring ligation (■). For the Shoulder brackets, regression lines are shown for the O-ring ligation in a figure-8 (■) and a figure-O (◆) around the tie-wings. For the Synergy brackets, regression lines are shown for the O-ring ligation around the outer tie-wings (■) and around the inner tie-wings (◆).

ure 7; Table 3), as was also observed by Ogata et al.[24] The bosses between the outer and inner tie-wings therefore prevented the ligature from applying any substantial F_N to the archwire.

In the active configuration, the rates of BI for the Synergy brackets were similar to those of the VersaT brackets, and thus greater than those for the Mini Diamond Twin brackets (Table 5). This trend was expected because the slot shapes of the Synergy and VersaT brackets were similar.

CONCLUSIONS

When clearance existed for the SS archwire-bracket couples, the coefficients of friction of all brackets ranged from 0.13 to 0.21 in the dry state and from 0.16 to 0.22 in the wet state, confirming that the bumps in the slot do not reduce friction. When the brackets without bosses were ligated with O-rings, the equivalent normal force was approximately 1000 cN (1020 g). Placing the elastomeric O-rings over bosses, whether outside the tie-wings (ie, the Shoulder brackets) or between the outer tie-wings and the inner tie-wing (ie, the Synergy brackets), reduced or eliminated the FR as compared with brackets without bosses. For the conventional SS twin brackets, ligation with loosely tied SS ligature wires also eliminated FR.

When clearance no longer existed, the shape of the rounded slot walls increased the rate of BI relative to the conventional SS twin brackets. For a given bracket design, however, the ligation type and method did not alter the rate of BI.

With regard to the overall RS (= FR + BI), the effects of the ligation type and method depended on the second-order angulation of the archwire relative to the bracket. When the angulation was just greater than the critical

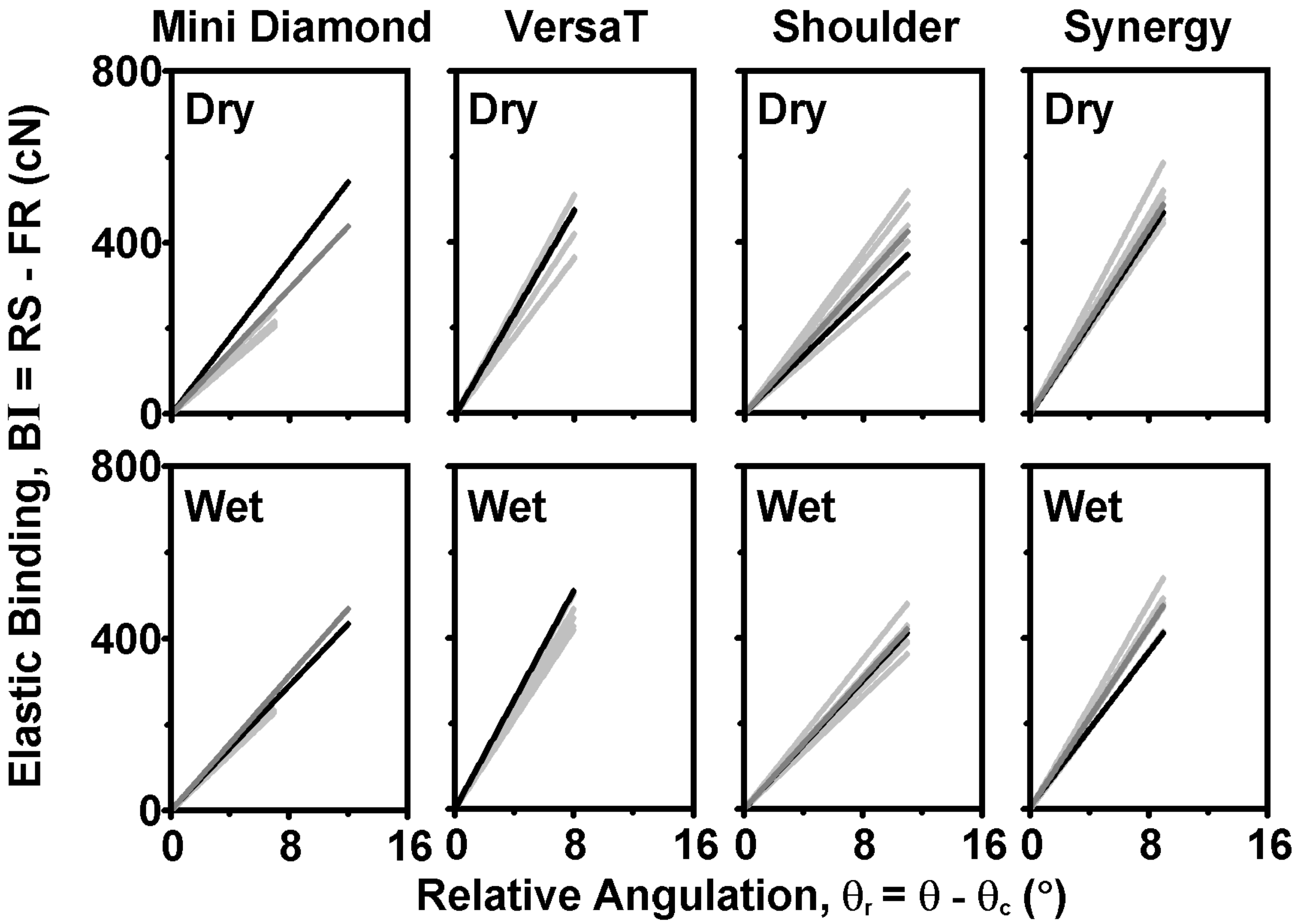

FIGURE 8. In the active configuration for all four bracket designs, linear regression analyses for BI (= RS − FR) as a function of θ_r (= $\theta - \theta_c$) in the dry (top row) and wet (bottom row) states. For all four designs, regression lines are shown for various normal forces (light colored lines). For the Mini Diamond Twin brackets, regression lines are shown for the O-ring ligation (dark colored lines) and the SS wire ligation (medium colored lines). For the VersaT brackets, regression lines are shown for the O-ring ligation (dark colored lines). For the Shoulder brackets, regression lines are shown for the O-ring ligation in a figure-8 (dark colored lines) and a figure-O (medium colored lines) around the tie-wings. For the Synergy brackets, regression lines are shown for the O-ring ligation around the outer tie-wings (dark colored lines) and around the inner tie-wings (medium colored lines). Note the profound uniformity among bracket designs.

contact angle for binding, the frictional component was greater than the binding component; thus, the ligation continued to affect the RS. When the angulation greatly exceeded the critical contact angle for binding, the binding component overwhelmed the frictional component, and the effects of ligation type and method were minimal.

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