Archwire depth is a significant parameter in the frictional resistance of active and interactive, but not passive, self-ligating brackets

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ABSTRACT

Objective: To elucidate some of the parameters determining the frictional behavior of passive, active, and interactive self-ligating brackets during sliding mechanics.

Materials and Methods: A custom jig mimicking the three-dimensional tooth movements that occur during sliding mechanics and an Instron testing machine were used to determine the resistance to sliding of six different self-ligating brackets (SPEED, In-Ovation C, CarrièreSLB, ClaritySL, SmartClip, VisionLP). Each bracket was tested on three rectangular stainless steel wires: 0.017 × 0.022 inch, 0.017 × 0.025 inch, and 0.019 × 0.025 inch. A two-way balanced analysis of variance was used for statistical analysis.

Results: The four passive self-ligating brackets (CarrièreSLB, ClaritySL, SmartClip, VisionLP) displayed significantly lower frictional resistance ($P < .001$) than the remaining brackets, which featured an active (SPEED) or interactive (In-Ovation C) clip. The SPEED bracket consistently demonstrated the highest resistance to sliding.

Conclusions: The mode of self-ligation appears to be the primary variable in determining the frictional behavior of orthodontic brackets undergoing sliding mechanics. Passive self-ligating brackets demonstrated significantly lower frictional resistance to sliding. With regard to the resistance of active self-ligating brackets, the depth (buccolingual thickness) of the wire had a more significant influence than its height. (*Angle Orthod.* 2011;81:1036–1044.)

KEY WORDS: Friction; Self-ligating; Sliding mechanics; Resistance to sliding; Archwire size; Bracket

INTRODUCTION

Friction is a force that resists the relative motion of two contacting bodies in a direction tangential to the plane of contact. Its magnitude (F_T) is the product of the normal force (F_N) multiplied by the coefficient of friction (μ), as per the formula $F_T = \mu \times F_N$.[1] *Normal force* is any force whose line of action is perpendicular to the plane of contact. In orthodontics, friction has been implicated in reducing the rate and efficiency of sliding mechanics.

The method of ligation determines how tightly the wire is engaged within the bracket slot and is therefore directly related to frictional resistance to sliding. Although several studies have attempted to compare various ligation methods, the results are conflicting, particularly with respect to conventional ligation (ie, elastomeric or stainless steel ligatures).[2–10] This is largely due to the inability to standardize the application of such ligatures and thus the magnitude of force that they impart upon the wire. Self-ligating brackets have a built-in mechanism (ie, "clip," "slide," or "door") that engages the archwire in a specific way. As such, these brackets offer a distinct advantage from a research standpoint, as they can be ligated consistently without introducing an additional source of variability.

With regard to the mode of self-ligation, brackets can be characterized as passive or active. *Active* self-ligating brackets have clip mechanisms that exert force upon the archwire to seat it against the base of the bracket slot, whereas *passive* self-ligating brackets

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have "doors" that usually close to form a passive tube within which the archwire sits. A third type of self-ligation has been described as *interactive* (In-Ovation C, GAC International, Islandia, NY). Below a particular archwire size, such brackets behave passively, but once a critical archwire dimension is exceeded, the clip exerts a seating force on the archwire and the bracket becomes active. With regard to passive versus active or conventional ligation, several investigations have concluded that passive brackets demonstrate lower frictional resistance to sliding.[6,8,11,12]

Another important parameter that would influence the results of in vitro frictional testing is the methodology used to simulate the motion of the tooth as it moves along the archwire. Since the force is applied at a certain distance from the tooth's center of resistance, the tooth has tendencies to both tip until a critical angle is reached and contact is made between the archwire and the edges of the bracket slot and to rotate until the archwire has contacted the outer wall of the bracket, as determined by the mode of ligation. As a consequence of contact at these locations, forces are generated in directions perpendicular to these planes of contact along both the occlusogingival (tipping) and buccolingual (rotation) axes. By definition, these forces are *normal* forces (ie, they act perpendicular to the direction of motion), and as such, they directly contribute to frictional resistance. The larger the angulation is between the slot and the wire, the greater the normal forces and the greater the potential for notching and binding, which further influences friction. Therefore, it is essential that a testing apparatus allow uprighting and derotation of the tooth being moved after critical contact angles have been reached. Several studies have attempted to reproduce this situation in vitro, with varying degrees of success.[13–15] The results of such studies should be interpreted with caution.

The present study was designed to compare the frictional resistance of six popular self-ligating bracket systems, while sliding on rectangular stainless steel archwires of three different dimensions under dry conditions, in a setup that approximates the clinical situation by allowing free movement following force application to the degree dictated by the interplay between bracket and archwire.

MATERIALS AND METHODS

The methodology employed closely followed that of Budd et al.[11] The same custom-built testing assembly (Figure 1) and resistance material (200 Fluid, Dow Corning, Midland, Mich) (see Table 1 for properties) were utilized.

Six commercially available self-ligating brackets were compared: SPEED (Strite Industries, Cambridge, Ont,

Canada), In-Ovation C, CarrièreSLB (Cerum Ortho Organizers, San Marcos, Calif), ClaritySL (3M Unitek, Monrovia, Calif), SmartClip (3M Unitek), and VisionLP (American Orthodontics, Sheboygan, Wisc). Their specifications are listed in Table 2. Each bracket was bonded to a maxillary right first premolar melamine typodont tooth (Kilgore International Inc, Coldwater, Mich) using Transbond XT adhesive resin (3M Unitek) and light-cured for 20 seconds. A height gauge and graph paper were used to ensure that the various brackets were bonded with the slot at 4.0 mm from the buccal cusp tip (Figure 2). After the first bracket of each type was bonded in this manner, a positioning jig was constructed out of polyvinyl siloxane material to ensure consistent placement of subsequent brackets of the same type (Figure 3).

The testing jig used for the investigation incorporated a tank filled with a fluid polymer (200 Fluid, Dow Corning). Resistance to movement of the tooth root through this polymer was the basic mechanism simulating the clinical behavior of a tooth tipping and rotating following the application of force. On either side of the fluid tank, two viselike holders clamped the ends of a straight length of wire that would guide the tooth movement.

Low-creep traction cord (Crystal FireLine, Berkley Pure Fishing, Portage-la-Prairie, MB, Canada), able to sustain 10 lbs (44.5 N) of force prior to breakage, was then tied around the bracket base. The root of the tooth was submerged by 13 mm into the fluid bath in the testing jig, and the bracket to be tested was engaged on the wire, with care taken to prevent fluid from touching the bracket, wire, or traction cord. The traction cord was attached via a pulley system to the vertically mounted crosshead of an Instron universal testing machine (Instron Inc, Canton, Mass).

After everything was in place, the bracket/tooth assembly was left to stand for a minimum of 2 minutes while engaged onto the wire in the testing jig. This time lapse allowed the fluid to settle into a passive state prior to initiation of tooth movement. It also permitted the establishment of zero bracket/wire angulation and rotation at baseline. In this way, the clinical situation at the completion of leveling and alignment was represented. No additional means of ligation was used. The Instron machine was fitted with a 50-N load cell, calibrated to a full-scale load of 5 N to increase sensitivity. The crosshead speed was set at a constant rate of 1 mm/min, and each typodont tooth was translated for a distance of 12 mm.

Eleven test runs were conducted for each bracket type/wire combination. Six different types of brackets were tested on three wires of different size, for a total of 198 individual test runs (11 test runs × six bracket types × three wire sizes). This number of test runs was based on a sample size calculation using the standard deviations observed previously[11] with a power of 0.8.
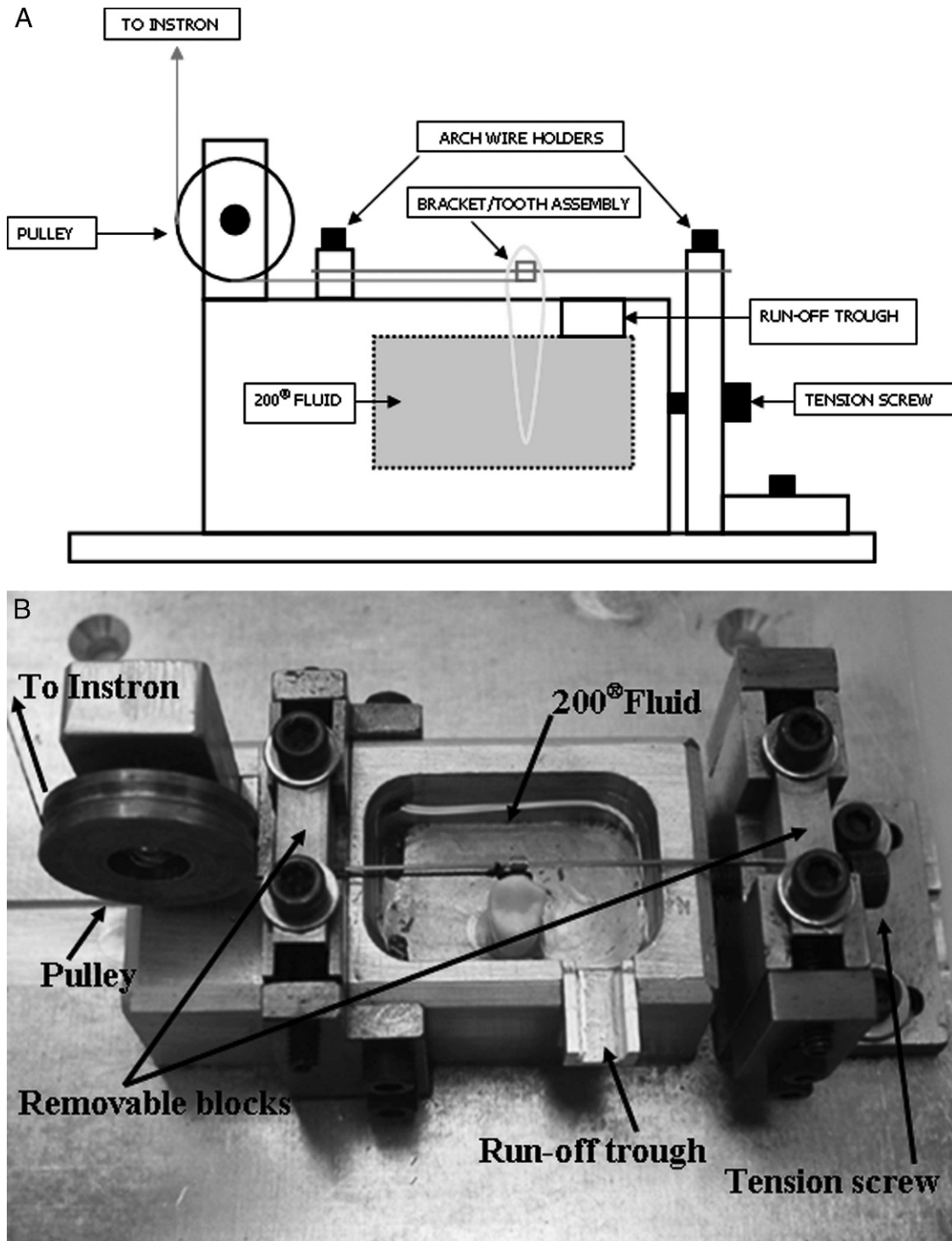
Figure 1A. Schematic diagram of custom friction testing assembly. Original from Budd et al.[11] **Figure 1B.** Photograph of custom friction testing assembly.

For each test run, a new bracket, tooth, and wire segment were mounted on the jig, as described earlier. The 200 Fluid was replenished between test runs to maintain a constant level throughout the experiment. Any excess fluid was allowed to drain off through the runoff trough on the side of the fluid tank (Figure 1).

Reliability Testing

Two randomly selected test runs per each bracket type/wire combination were repeated, for a total of 36 repeated test runs. The same bracket and tooth that were utilized for the initial test run were reused, with a

Table 1. Physical Properties of the Resistance Material[a]

Property	Specifications
Composition	Linear polydimethyl siloxane polymer
Physical form	Viscous liquid free from suspended matter and sediment
Viscosity	100,000 Centistoke
Color	Colorless
Odor	Odorless
Melting point	−23°C
Viscosity stability at 25°C after 16 h exposure at 150°C	−2.4% change

[a] 200 Fluid, Dow Corning, Midland, Mich.

new straight length of wire for each repeated test run. This was done to prevent any damage (scratching or bending) of the previous wire segment from affecting the results of the repeated test run. The same investigator performed all test runs.

Data Analysis

A single mean frictional resistance value for each of the 198 test runs was calculated by determining the average resistance recording on the y-axis once a steady state (plateau) of resistance was reached (Figure 4). Every data point within the plateau area (several thousand per test run) was utilized to calculate the mean of each test run. Descriptive statistics were then calculated for each bracket type/wire combination, and a two-way balanced analysis of variance for bracket type and wire size was performed. An intraclass correlation coefficient was also calculated to assess test/retest reliability. The level of statistical significance was set at $P < .05$. A statistician who was blinded to bracket types and wire sizes performed the analysis.

RESULTS

The results grouped according to bracket type and wire size are presented in Table 3. The intraclass correlation coefficient calculated from the reliability testing was 0.996, indicating very good test/retest agreement.

Figure 2. Bonding with graph paper. Original from Budd et al.[11]

0.017- × 0.022-Inch Wire

No significant differences were found among the four passive self-ligating brackets and the interactive In-Ovation C bracket (Figure 5). The active self-ligating SPEED bracket exhibited a significantly (approximately 12 times) higher ($P < .001$) mean resistance than all the other brackets tested.

0.017- × 0.025-Inch Wire

When sliding was performed on the 0.017- × 0.025-inch stainless steel wire, the four passive self-ligating brackets generated mean resistance values that were not significantly different from each other. They were also not significantly different from the resistance values generated by the same brackets when sliding on the 0.017- × 0.022-inch wire (Figure 6). The interactive In-Ovation C bracket demonstrated significantly higher ($P < .001$) mean resistance than the passive brackets (approximately 11 times), while the active SPEED bracket had an even higher ($P < .001$) frictional resistance (approximately 25 times) than that of the passive brackets. The resistance generated by

Table 2. Bracket Specifications (According to Manufacturers)

Specification	SPEED	In-Ovation C	SmartClip	ClaritySL	CarrièreSLB	VisionLP
Type of self-ligation	Active	Interactive	Passive	Passive	Passive	Passive
Slot size (inch)	0.022×0.028	0.022×0.028	0.022×0.028	0.022×0.028	0.022×0.028	0.022×0.028
Slot width (mm)	2.0	3.0	4.2	5.1	3.2	3.1
Tip (deg)	−2	0	0	0	0	+2
Torque (deg)	−7	−7	−7	−7	−7	−7
Slot composition	Stainless steel	Ceramic	Stainless steel	Stainless steel	Stainless steel	Stainless steel
Clip composition	Nickel-titanium	Rhodium-coated nickel-cobalt	Nickel-titanium	Nickel-titanium	Stainless steel	Nickel-titanium

Figure 3. Polyvinyl siloxane bonding jig. Original from Budd et al.[11]

the In-Ovation C and SPEED brackets was significantly higher ($P < .001$) than the frictional resistance generated by the same brackets with the smaller wire size tested.

0.019- × 0.025-Inch Wire

A similar pattern was seen for the 0.019- × 0.025-inch wire as for the 0.017- × 0.025-inch wire (Figure 7). No significant differences were found for

any bracket from the levels of resistance demonstrated with the 0.017- × 0.025-inch wire.

DISCUSSION

All four passive self-ligating brackets in this investigation consistently demonstrated low frictional resistance to sliding (less than 0.05 N) for all three sizes of wire tested. These results suggest the brackets were relatively "passive," even with the largest rectangular, near-to-full-dimension 0.019- × 0.025-inch wire.

The resistance values associated with the four passive self-ligating bracket types remained 13–25 times lower than for the active SPEED bracket for all wire sizes and approximately 9–11 times lower than those generated by the interactive In-Ovation C bracket for the 0.017- × 0.025-inch and the 0.019- × 0.025-inch wire sizes ($P < .001$). We believe that this remarkable relative difference highlights the significance of the self-ligating mechanism in the friction generated.

The ceramic In-Ovation C bracket behaved similarly to passive self-ligating brackets with the smallest wire dimension tested. However, with the larger wires, it produced significantly higher frictional resistance ($P < .001$), in essence behaving more like an active self-ligating bracket (Figure 8). Thus, the data support the interactive claims of the manufacturer. The active self-ligating SPEED bracket consistently generated the highest frictional resistance of all bracket types tested with all wire sizes ($P < .001$).

The effect of archwire size varied by the type of bracket considered, which is consistent with the findings of Budd et al.[11] An increase in wire dimension from 0.017-×0.022-inch to 0.019-×0.025-inch did not significantly influence the sliding behavior of the passive self-ligating brackets. However, the active
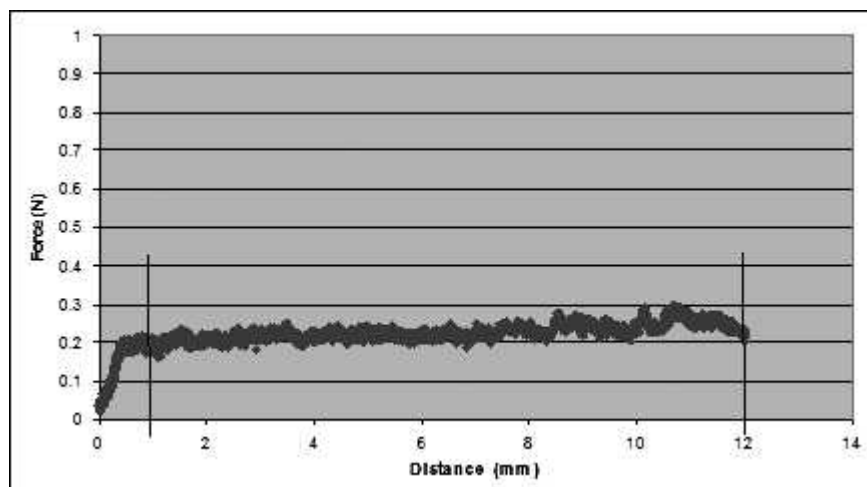

Figure 4. Raw data plot example.

Table 3. Results Grouped According to Bracket Type

| Bracket	Wire Size (in)	LS[a] Mean Resistance (N)	SD[a]	95% CI[a]
CarrièreSLB	.017 × .022	0.050	0.007	0.012–0.087
CarrièreSLB	.017 × .025	0.034	0.003	−0.004–0.071
CarrièreSLB	.019 × .025	0.039	0.003	0.001–0.076
ClaritySL	.017 × .022	0.044	0.010	0.007–0.082
ClaritySL	.017 × .025	0.038	0.007	0.001–0.076
ClaritySL	.019 × .025	0.039	0.010	0.002–0.077
SmartClip	.017 × .022	0.049	0.012	0.011–0.086
SmartClip	.017 × .025	0.035	0.004	−0.002–0.072
SmartClip	.019 × .025	0.042	0.005	0.004–0.079
VisionLP	.017 × .022	0.045	0.007	0.007–0.082
VisionLP	.017 × .025	0.034	0.005	−0.003–0.072
VisionLP	.019 × .025	0.037	0.006	−0.0003–0.075
In-Ovation C	.017 × .022	0.086	0.017	0.048–0.123
In-Ovation C	.017 × .025	0.390	0.019	0.353–0.428
In-Ovation C	.019 × .025	0.342	0.117	0.304–0.379
SPEED	.017 × .022	0.633	0.120	0.595–0.670
SPEED	.017 × .025	0.867	0.125	0.830–0.905
SPEED	.019 × .025	0.796	0.122	0.759–0.834

[a] LS indicates least squares; SD, standard deviation; and CI, confidence interval.

and interactive self-ligating brackets (SPEED and In-Ovation C) appeared to be affected only by the change in wire depth (buccolingual dimension) and not by the change in wire height (occlusogingival dimension). A significant increase in the resistance generated by the aforementioned two types of brackets was demonstrated as the wire depth increased from 0.022 to 0.025 inch and the height was kept constant at 0.017 inch. In contrast, no significant difference in frictional resistance was found when the wire height was increased from 0.017 to 0.019 inch and the depth was kept constant at 0.025 inch (Figure 9).

As determined in previous investigations, bracket composition, especially that of the slot, influences the frictional behavior of the system.[2,14,16–22] The four

passive self-ligating brackets in the current study provided a considerable range of bracket slot and clip compositions to compare. Since the results showed no significant differences in the mean frictional resistance generated by any of the four brackets with all three wire dimensions, it appears that the composition of these brackets and that of their slot or clip likely play a secondary role (if any) in the sliding frictional behavior of passive self-ligating brackets.

The active SPEED and the interactive In-Ovation C brackets feature similarly designed clips. In the case of the In-Ovation C, rhodium-coated nickel-cobalt/stainless steel couples are formed at the clip-wire interface and ceramic/stainless steel couples are formed between the remaining three walls of the slot and the
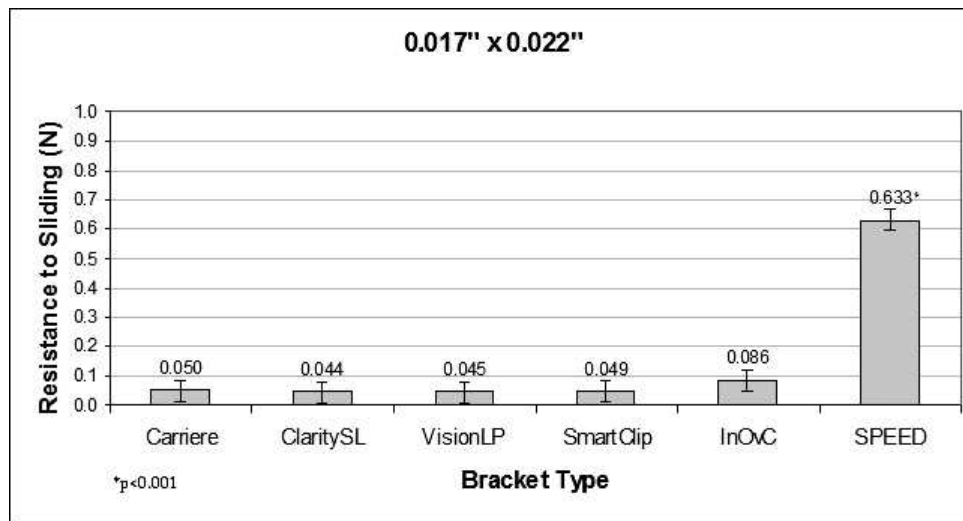
Figure 5. Mean resistance (N) for the 0.017- × 0.022- inch stainless steel wire. Mean resistance values are displayed above each bar. Error bars indicate 95% confidence intervals.
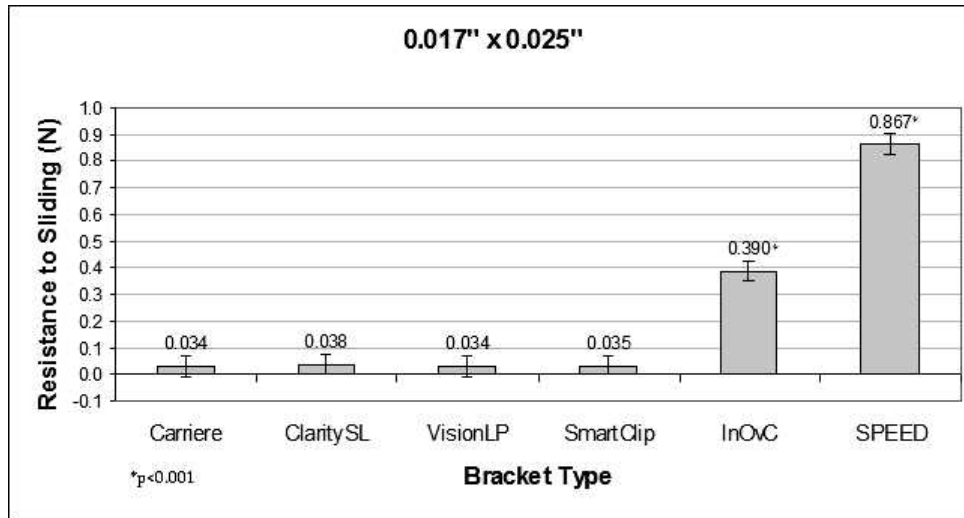
Figure 6. Mean resistance (N) for the 0.017- × 0.025- inch stainless steel wire.

wire. In contrast, in the case of the SPEED bracket, nickel-titanium/stainless steel couples are formed at the clip-wire interface, with stainless steel/stainless steel couples elsewhere. Ceramic brackets have been shown fairly consistently to exhibit higher frictional resistance during sliding than stainless steel brackets or ceramic brackets with stainless steel slots.[16,19,22] If material were the primary determinant of frictional behavior, one would expect the In-Ovation C bracket to generate the highest resistance of the group. However, the SPEED bracket consistently demonstrated a significantly higher ($P < .001$) frictional resistance to sliding. A more plausible explanation lies, therefore, in the magnitude of seating force imparted by the self-ligating mechanism (ie, active vs passive).

Unfortunately, the brackets chosen for the study could not be standardized with respect to prescription.

The SPEED and VisionLP brackets had different second-order prescriptions (-2 degrees and $+2$ degrees of angulation, respectively; see Table 2). These differences were so small that they were unlikely to cause significant variability within the data. In addition, the brackets were allowed to assume an equilibrium position during the 2-minute "rest" period after the tooth was placed into the medium bath, minimizing any effect of variances in bracket angulations.

Another potentially significant factor in frictional resistance is bracket width. The literature diverges with respect to the effect of bracket width and interbracket distance on friction.[2,3,23] In the current study, the widths of the passive brackets ranged from approximately 2 to 5 mm. Despite this, no significant differences were found between any of the bracket/archwire combinations tested. Therefore, it appears
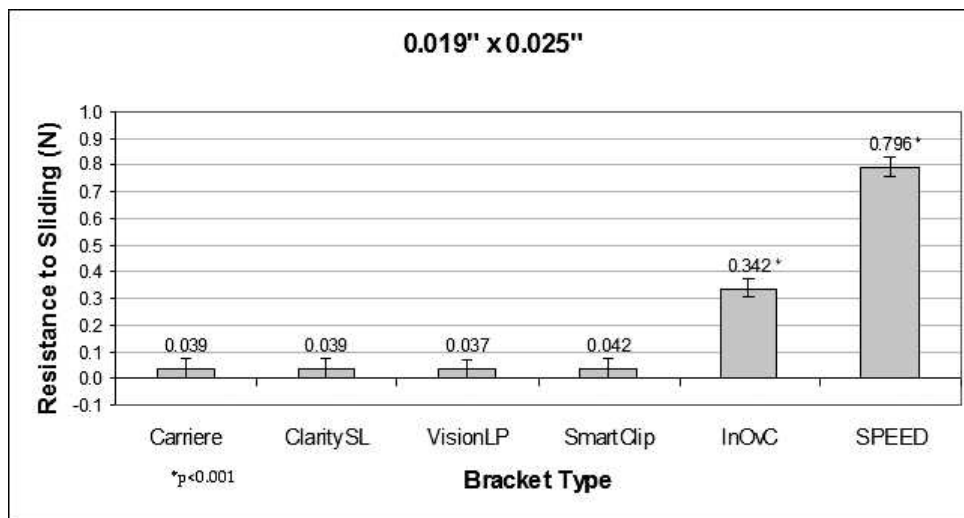

Figure 7. Mean resistance (N) for the 0.019- × 0.025- inch stainless steel wire.
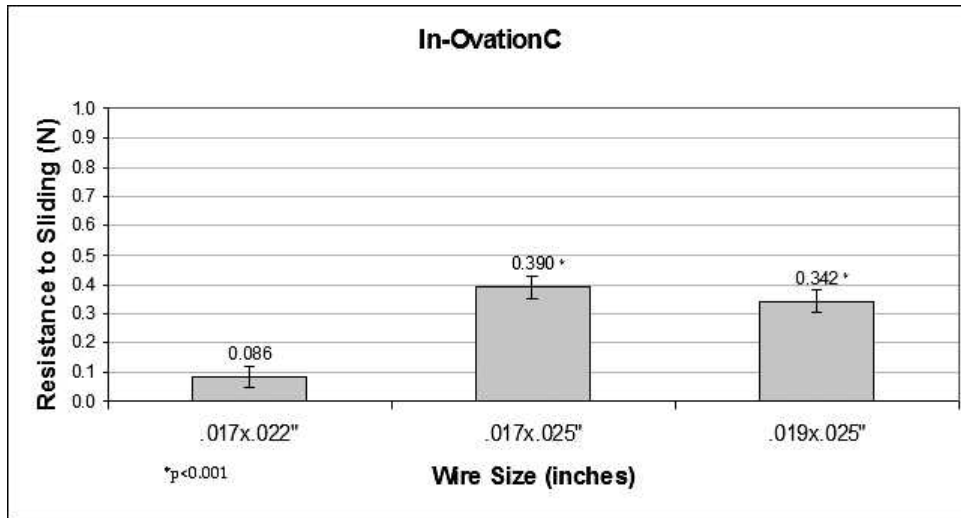
Figure 8. Mean resistance (N) for the In-Ovation C bracket.

that, for passive self-ligating brackets, width may not be of primary importance in terms of resistance to sliding.

With respect to the more actively ligated brackets (In-Ovation C and SPEED), the effect of bracket width was more difficult to determine. The SPEED bracket is considerably narrower, and it generated significantly more frictional force at all wire sizes tested ($P < .001$). Therefore, one might conclude that bracket width could have at least partially contributed to these results.

Limitations

Since this was an in vitro experiment, several limitations applied compared to the clinical situation:

- The use of a viscous fluid medium in this investigation was not an attempt to simulate the periodontal ligament and alveolar bone with respect to physical properties. The medium functioned to convert the typodont tooth from a free object to a partially embedded one, as teeth are in the mouth. Therefore, it created an appropriate center of resistance, in essence allowing the tooth to tip and rotate under the influence of the traction force in a repeatable manner.

- This investigation did not consider the effects of saliva, since no wet condition testing was undertaken. However, the role of saliva in the friction equation remains unclear at this time.

- This study did not consider the potential effects of perturbations during occlusal function due to the difficulty in simulating and standardizing such a three-dimensional and inherently haphazard phenomenon.
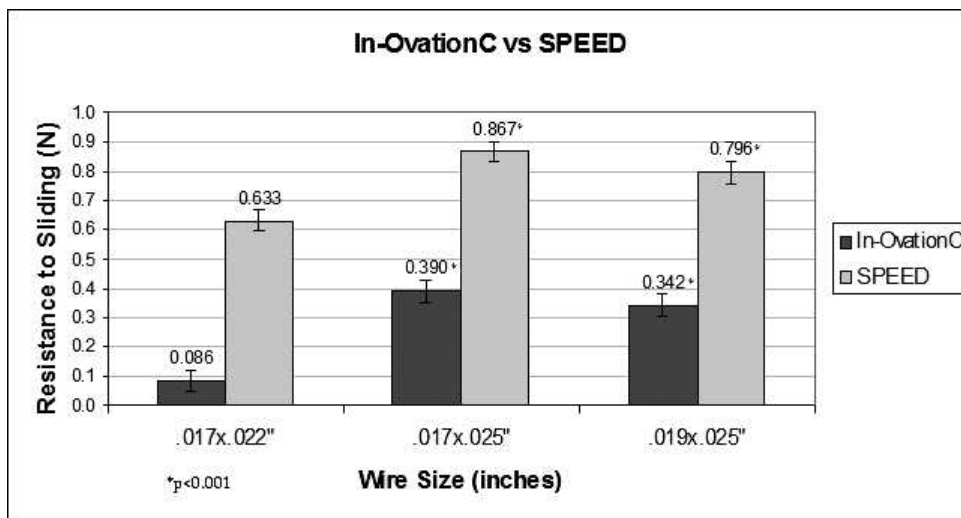

Figure 9. Comparison of mean resistance for the In-Ovation C and SPEED brackets.

CONCLUSIONS

- Passive self-ligating brackets generated extremely low frictional resistance to sliding, even with wires of large dimensions (eg, 0.019- × 0.025-inch stainless steel).
- The active SPEED bracket was consistently associated with significantly higher resistance to sliding than all other brackets tested.
- The interactive In-Ovation C bracket behaved as marketed, being passive below and active above a certain wire buccolingual dimension. This study observed a wire depth "threshold" of 0.022 inch, rather than the 0.020 inch suggested by the manufacturer.
- Wire depth played a more significant role in regulating the resistance to sliding of active or interactive brackets than wire height.

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