

Comparative Frictional Resistance of Conventional, Self-Ligating, and Ceramic Orthodontic Brackets with Different Archwires: An In-Vitro Study

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ABSTRACT

Background

The bracket-archwire interface friction affects the force for orthodontic tooth movement during sliding mechanics. The material of the brackets, type of ligation, and the thickness of the archwire can vary in resistance to the sliding action of the ligature, and may thus influence the choice of the force.

Objective

This study aimed to compare static and kinetic frictional resistances of conventional stainless-steel, passive self-ligating stainless-steel and monocrystalline ceramic brackets against three clinically common archwires.

Materials and Methods

A laboratory model with 108 bracket-wire specimens was designed as a 3 × 3 factorial experiment with 12 specimens per combination. The slots were all 0.022". The archwires were 0.014-inch nickel-titanium (NiTi), 0.016 × 0.022-inch NiTi, and 0.019 × 0.025-inch stainless steel (SS). Standardized elastomeric modules were used to ligate the conventional metal and ceramic brackets, while the passive self-ligating brackets were tested with their built-in clips. Artificial saliva was used at 37 °C and the testing machine applied a force at 5 mm/min to the specimen: static friction was represented by the peak force required to initiate sliding and kinetic friction by the mean force during the continued sliding. The data were analyzed by two-way ANOVA and Tukey tests ($\alpha = 0.05$).

Results

The static friction of passive self-ligating brackets (0.64 ± 0.44 N) was lowest, followed by conventional metal brackets (1.36 ± 0.57 N) and highest for ceramic brackets (1.94 ± 0.78 N). Across bracket systems, mean static friction increased from 0.66 ± 0.39 N with 0.014-inch NiTi to 1.24 ± 0.57 N with 0.016 × 0.022-inch NiTi and 2.03 ± 0.74 N with 0.019 × 0.025-inch SS. All three bracket types, archwire types and their interactions, were statistically significant (all $p < 0.001$). Overall, the passive self-ligation decreased static friction by ~52.8% when compared to conventional metal brackets.

Conclusion

In this standard in-vitro setting, passive self-ligating brackets had the lowest resistance to sliding, the ceramic brackets had the highest resistance, and larger rectangular archwires significantly increased friction. When designing the sliding mechanics, therefore, the bracket and wiring needs should be taken into consideration.

Keywords

Orthodontic friction; self-ligating brackets; ceramic brackets; archwire; sliding mechanics; nickel-titanium; stainless steel.

INTRODUCTION

Sliding of an archwire through a bracket slot or movement of a bracket along an archwire are frequently required for orthodontic space closure, canine retraction and multiple phases of alignment. This resistance to relative motion is not a simple phenomenon: Classical friction, binding at bracket corners, and notching of wire are all possible components of the total resistance to sliding. Excessive resistance causes a portion of the force applied to the brackets to be lost at the bracket-wire interface making it more difficult to control anchorage and movement of the tooth. In-vitro studies have thus remained significant in order to compare variables of the appliances under standardized conditions.^{1,2}

Tribological behavior is largely influenced by bracket material. The properties of stainless-steel brackets are generally accepted as a reference due to their relatively smooth slot surfaces and mechanical properties. The ceramic

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brackets were introduced to enhance the esthetics but the alumina-based slot surfaces may be harder and more likely to develop surface irregularities, which increase frictional forces. In response to this limitation, the metal-lined ceramic slots were developed, but these slots still have frictional characteristics that are still dependent on the manufacturing quality, wire material, angulation and ligation.^{3,4}

Another variable that influences is ligation. Traditional brackets need an external ligature, and elastomers apply a normal force which pushes the module wire into the bracket slot. Self-ligating brackets have an integrated clip or door and are usually referred to as active or passive. Passive designs form a tube-like slot when they are closed, and in the case of undersized round wire, can diminish the normal force on the wire. Laboratory investigations have therefore showed less friction for many passive self-ligating systems, but this benefit decreases as the size of the wires, the angulation of the bracket-wires, the brackets' torque and binding are added.^{5,6}

Other factors of the archwire alter the friction. The larger the cross-section dimensions, the less clearance in the slot, the more likely there will be contact with the slot walls. Also, there are the composition of the alloy, the surface topography, stiffness and the shape of cross-sections. The studies that have employed rectangular stainless-steel, nickel-titanium, and beta-titanium wires have demonstrated that the friction may be quite different with different combinations of brackets and wires than with either wire alone. These interactions can be particularly pronounced in ceramic brackets, and both wire alloy and angulation have been demonstrated to affect the resistance of ceramic brackets to sliding.⁷⁻⁹

Controlled testing is still helpful to find combinations that might need different forces, but doesn't directly predict overall treatment time in the laboratory. Studies of self-ligating appliances have pointed out that, as is true for all appliances, reduced friction under idealized laboratory conditions should not be assumed to reflect increased efficiency in the clinical situation, since malocclusion, tipping, torque, biological response, and operator-dependent mechanics can alter the in-vivo situation. Recent experimental studies^{10,11} further show significant variations between the different bracket materials and the different ligation systems, justifying a comparative testing with clinically relevant wire sequences.¹²

The aim of the present in-vitro study was therefore to evaluate and compare the static and kinetic friction values of conventional stainless-steel brackets, passive self-ligating stainless-steel brackets and monocrystalline ceramic brackets with three archwires of early, intermediate and working stages of fixed appliance therapy. The null hypotheses were: ¹ the frictions of the various bracket systems would not differ; ² the frictions of the various archwires would not differ; and ³ there would be no interaction between the various bracket systems and archwires.

MATERIALS AND METHODS

Study design and sample size Controlled in-vitro experimental design with two factors (bracket system and archwire) was used. There are nine combinations of the three bracket systems and the three types of archwires. Each of the 12 independent specimens was set up in the various brackets and wire combinations, thus providing a total of 108 tests. A sample size was chosen to achieve sufficient precision to detect moderate to large differences in friction under standardized laboratory conditions. Since the model manuscript is based on simulated numbers, the sample-size framework stated in the manuscript should be replaced or reinforced by an a priori power calculation, if an actual experiment follows. **Orthodontic materials** All brackets were maxillary canine brackets with a 0.022×0.028 -inch slot, and a similar preadjusted edgewise prescription. The brackets were sorted into three groups: conventional stainless-steel brackets (Group CMB); passive self-ligating brackets (Group PSL); and monocrystalline ceramic brackets (Group CER). The 0.014-inch round superelastic NiTi archwire (W1), the 0.016×0.022 -inch rectangular NiTi archwire (W2), and the 0.019×0.025 -inch rectangular SS archwire (W3) were tested. Defects of any kind in the brackets opening that can be seen with the stereomicroscope were rejected, such as slotted openings, bent brackets, cracked brackets, or irregular manufacturing. Bends, scratches and surface contamination were also not included in wire segments

Specimen preparation

All brackets were attached to a rigid acrylic block placed in a specially designed jig with cyanoacrylate adhesive. The bonding position of the brackets was standardized using a 0.021×0.025 -inch stainless-steel alignment gauge, and unintended tip or torque was minimized. The gauge was stripped off after the polymerization and the

test wire was put in. The conventional metal and ceramic brackets were seated under identical conditions, with new elastomeric modules from the same manufacturing lot, and then ligated. Manufacturer's built-in clip used for passive self-ligating brackets. To minimize the wear carry-over effect, a new bracket, wire segment and elastomeric module were used for each test.

Testing procedure

The acrylic block was fastened on the lower end of a universal testing machine using a 10-N calibrated load cell. A 70-mm wire segment was mounted vertically to a top grip where the wire was not imposed upon the second order angulation. The bracket-wire assembly was soaked in artificial saliva for 5 minutes at $37 \pm 1^\circ\text{C}$ before being tested. The crosshead was then displaced through the bracket at a rate of 5 mm/min for 5 mm while the force-displacement data was recorded continuously. The frictional resistance in the static condition was taken as the peak force that occurred just before the onset of continuous sliding. The mean force value measured from 1-5 mm of displacement was used to determine kinetic frictional resistance.

The use of outcome measures and reliability data. The main measurement was the static frictional resistance in Newtons (N). Secondary outcome was kinetic frictional resistance. Before starting the series of experiments, the testing machine was calibrated following the manufacturer's time schedule. To test for repeatability of bracket placement and machine operation, a test was repeated during pilot standardization on 10 randomly selected assemblies, and was accepted if the difference between repeated measurements was less than 5%.

Statistical analysis

The data were expressed as mean $\pm$ SD. Prior to performing parametric analysis, normality and variance homogeneity were evaluated. For static friction, a 2-way analysis of variance (ANOVA) was used to determine the main effects of bracket system and archwire type and their interaction. Pairwise comparisons were planned for using Tukey's honest significant difference tests. Effect magnitude was expressed in terms of partial eta-squared (η^2). Descriptive analysis and the same factorial approach were used to examine kinetic friction. The criterion of $p < 0.05$ was used to define statistical significance. Analysis was indicated for a common statistical software (e.g., IBM SPSS Statistics or R).

Ethical considerations

The proposed laboratory model did not employ human participants, extracted teeth, human saliva, animal material, or identifiable information, so informed consent of humans was not required. All due caution should be taken with regard to institutional requirements for exemption, or notification, for bench-top materials research before carrying out the experiment itself.

RESULTS

The simulated dataset demonstrated clear differences in friction according to both bracket system and archwire. Static friction was consistently lowest with the passive self-ligating bracket and highest with the ceramic bracket for each tested wire (Table 1). Within every bracket system, friction increased as the test sequence progressed from the 0.014-inch round NiTi wire to the 0.016×0.022 -inch NiTi wire and then to the 0.019×0.025 -inch SS wire.

Table 1. Static frictional resistance (N) according to bracket and archwire combination (n = 12 per cell)

Bracket system	0.014-in NiTi	0.016 $\times$ 0.022-in NiTi	0.019 $\times$ 0.025-in SS
Conventional metal	0.75 $\pm$ 0.10	1.29 $\pm$ 0.15	2.04 $\pm$ 0.25
Passive self-ligating	0.17 $\pm$ 0.05	0.56 $\pm$ 0.14	1.19 $\pm$ 0.11
Ceramic	1.07 $\pm$ 0.12	1.88 $\pm$ 0.17	2.87 $\pm$ 0.35

Values are mean $\pm$ SD. NiTi, nickel-titanium; SS, stainless steel.

Kinetic friction showed the same rank order as static friction (Table 2). The lowest mean kinetic value was observed for passive self-ligation with 0.014-inch NiTi (0.10 ± 0.04 N), whereas the highest was observed for the ceramic bracket with 0.019×0.025 -inch SS (2.29 ± 0.25 N). This consistency indicates that the bracket-wire variables affected both the initiation and maintenance of sliding.

Table 2. Kinetic frictional resistance (N) according to bracket and archwire combination (n = 12 per cell)

Bracket system	0.014-in NiTi	0.016 $\times$ 0.022-in NiTi	0.019 $\times$ 0.025-in SS
Conventional metal	0.57 $\pm$ 0.14	1.00 $\pm$ 0.12	1.68 $\pm$ 0.15
Passive self-ligating	0.10 $\pm$ 0.04	0.38 $\pm$ 0.09	0.96 $\pm$ 0.13
Ceramic	0.78 $\pm$ 0.11	1.44 $\pm$ 0.21	2.29 $\pm$ 0.25

Values are mean $\pm$ SD. NiTi, nickel-titanium; SS, stainless steel.

When data were pooled across wires, mean static friction was 0.64 ± 0.44 N for passive self-ligating brackets, 1.36 ± 0.57 N for conventional metal brackets, and 1.94 ± 0.78 N for ceramic brackets. Thus, passive self-ligation produced approximately 52.8% less static friction than conventional metal ligation, whereas ceramic brackets produced approximately 42.7% more. Pooled across bracket types, static friction increased from 0.66 ± 0.39 N with W1 to 1.24 ± 0.57 N with W2 and 2.03 ± 0.74 N with W3. Two-way ANOVA confirmed large main effects for bracket and wire and a significant interaction (Table 3). Tukey comparisons indicated significant differences between all three bracket systems and between all three archwires ($p < 0.001$). Therefore, all three null hypotheses were rejected.

Table 3. Two-way ANOVA for static frictional resistance

Source	Sum of squares	df	F	p-value	Partial η^2
Bracket system	30.409	2	466.78	<0.001	0.904
Archwire	33.975	2	521.52	<0.001	0.913
Bracket $\times$ archwire	1.869	4	14.35	<0.001	0.367
Residual	3.225	99	—	—	—

η^2 , eta-squared effect estimate. Statistical values correspond to the simulated dataset used for this drafting model.

DISCUSSION

The present laboratory model shows that bracket design and archwire properties have a significant effect on the resistance to sliding. In all wire types, the passive self-ligating bracket had the lowest static and kinetic friction while conventional stainless-steel brackets had an intermediate value and the monocrystalline ceramic brackets had the highest value. Higher size of wire from a small round NiTi wire to rectangular NiTi wire to near-slot-filling rectangular SS wire caused increased friction in each bracket category. These results are in line with the biomechanical model which indicates that friction is not dependent on any single material property, but rather the entire bracket-wire-ligation system.

The lower friction of passive self-ligating brackets is in accordance with the proposed mechanism for passive clips. Unlike an elastomeric module, the passive door does not actively push the archwire against the floor of the slot, but rather confines the archwire in it. Ehsani

et al.¹ determined that the frictional resistance of self-ligating brackets was less with small round wires aligned optimally, but noted that it was not as predictable with larger rectangular wires or when the wires are tipping or torqued. The same has been proven by Pizzoni et al.⁶ with self-ligating systems, and Monteiro et al.⁷ showed that the frictional forces were significantly lower with self-ligating brackets under various wire and angulation conditions. In our model, the difference between passive self-ligation and conventional ligation was reduced with the 0.019×0.025 mm size SS wire, as biologically and mechanically plausible because larger wires will lessen the clearance of the slot and increase the contact with the bracket surfaces.

The highest friction was achieved with the ceramic bracket on all the archwires. This corresponds to the findings of Cacciafesta et al.³ that stainless-steel brackets have a higher friction than conventional ceramic brackets and of Williams and Khalaf⁴ who found that conventional ceramic brackets have significantly higher static friction than ceramic brackets with design features that reduce friction. Other researchers such as Guerrero et al.⁹ also found that there were significant differences between the different types of ceramic brackets and wire alloys. The hardness of alumina, manufacturing defect surface irregularity, sharper slot edges, and the tendency of binding and notching have been cited as the causes for high friction in ceramic brackets. However, it should be noted that the surface roughness alone is not enough to explain all observed friction due to the interaction between bracket geometry, slot dimensions, normal forces and material pairing.

The impact of wire progression was significant. The 0.014-inch NiTi wire had the lowest resistance, while 0.019×0.025 -inch SS wire had the highest resistance in all the bracket systems. This is a result of a reduction in clearance between the wire and the 0.022" slot and an increased chance of contact with the walls of the slot. Other laboratory research (e.g., Pillai et al.⁸) has demonstrated that combinations of brackets and wires are very varied, especially in the case of rectangular wires. In fact, while stainless steel generally has good sliding properties, it can create more friction than a small round NiTi wire, as size of the wire and the geometric configuration of the sliding surfaces outnumber the comparison.

Clinically relevant significant bracket by wire interaction. It suggests changing an archwire does

not have the same effect on all bracket systems. This is in line with the more recent tribological studies. Dragomirescu et al.¹² reported that both the material type and the type of ligation impact the friction, and that self-ligation can decrease the friction under certain circumstances. Similarly, Vartolomei et al.¹³ showed some differences between conventional system and self-ligating system's kinetic friction. In 2024, multiple in-vitro studies of various brands of monocrystalline ceramics brackets demonstrated that some measurable differences occurred at the bracket-wire interface¹⁴ and a comparative study in 2025 showed that both the bracket system and archwire choice significantly affected static frictional resistance¹⁵. These data support the idea that the label "low friction" should never be applied to a bracket without reference to the type of wire, type of ligation, angulations and stage of treatment.

In terms of clinical use, less friction can be advantageous if sliding is needed, since an increased amount of applied force may be available for tooth movement. But friction isn't all bad. Some resistance may be desirable for three-dimensional control and desirable in prevention of uncontrolled sliding during finishing. In addition, clinical tooth movement involves biological remodeling, response of the periodontal ligament, movement of the bracket, deflection of the wire, plaque and debris, saliva, masticatory loading and changes in angulation over time. Thus, it is critical to understand that a lower force reading on a straight wire in a laboratory jig does NOT mean that it's a faster treatment. Both Chen et al.¹⁰ and Fleming and Johal¹¹ reported that there was insufficient evidence to support the consistent improvement in overall treatment efficiency with the use of self-ligating appliances compared to conventional systems. The usefulness of in-vitro friction testing is therefore comparative and mechanistic and not a direct predictor of treatment time.

In the present model, to enhance clinical relevance, three wire stages and artificial saliva at body temperature were used. However, there are certain restrictions that still stand. First, the data presented is not actual data,

but only simulated and should be substituted with actual measurements before reporting. Secondly, a single prescription and a single representative design in each category does not represent the manufacturing variation between brands. Third, the wire sequence varies in size and alloy, which means that the effects of size and cross-sectional shape and alloy cannot be completely separated. Fourth, this is because 0° angulations are less likely to cause binding, clinically, tip and torque can be a significant source of resistance to sliding. Fifth, the present protocol assumes that elastomeric ligatures are fresh, while the elastomeric ligatures in general are prone to force relaxation and oral aging. A series of future lab tests should, therefore, use more angles, multiple aging cycles, SEM or profilometry, measure the slot dimensions independently and have factorial tests where wire alloy is separated from wire size. Finally, there is a need for well-designed clinical studies to identify when differences in the amount of friction in the laboratory result in clinically significant differences in anchorage requirements, space closure rate, patient experience, or treatment time.

CONCLUSION

In this in-vitro standardised model, passive SSBs were found to have the lowest values, conventional SSBs were intermediate, and monocrystalline ceramic SSBs were the highest regarding static and kinetic frictional resistance. The frictional force grew considerably with the increasing thickness of the archwire from 0.014-inch NiTi to 0.016 × 0.022-inch NiTi and 0.019 × 0.025-inch stainless steel (SS), and there was a significant interaction between bracket system and archwire. The results suggest that both bracket and archwire choice should be part of the treatment planning process for sliding mechanics, but that laboratory friction values do not necessarily correlate with the clinical treatment speed.

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