ORIGINAL ARTICLE

Comparative Evaluation of Frictional Resistance Between Conventional, Self-Ligating, and Ceramic Brackets Using Different Archwire Materials: An In Vitro Study

Saleh Alwadei[1*], Farhan H. Alwadei[1]

ABSTRACT

Background

Frictional resistance at the bracket-archwire interface is a critical determinant of force delivery during sliding mechanics. Bracket design, slot material, ligation method, and archwire alloy may modify static and kinetic friction, thereby influencing clinical efficiency during alignment and space closure.

Methods

This in vitro experimental study compared frictional resistance among three 0.022-inch slot bracket systems: conventional stainless steel brackets with elastomeric ligation, passive self-ligating stainless steel brackets, and polycrystalline ceramic brackets with elastomeric ligation. Three archwire materials were tested: 0.019 x 0.025-inch stainless steel, nickel-titanium, and beta-titanium. Ninety bracket-archwire assemblies were prepared, with 10 specimens per bracket-wire combination. Testing was performed using a universal testing machine at a crosshead speed of 5 mm/min under artificial saliva lubrication at 37 degrees C. Static frictional resistance and kinetic frictional resistance were recorded in Newtons. Data were analysed using two-way ANOVA and Tukey post hoc tests.

Results

Mean static friction differed significantly by bracket type and wire material ($p<0.001$). Self-ligating brackets showed the lowest overall static friction (1.42 +/- 0.32 N), followed by conventional stainless steel brackets (2.37 +/- 0.46 N), whereas ceramic brackets showed the highest values (3.29 +/- 0.58 N). Stainless steel archwires produced the lowest mean static friction (1.67 +/- 0.48 N), nickel-titanium produced intermediate values (2.33 +/- 0.67 N), and beta-titanium produced the highest values (3.08 +/- 0.79 N). The highest friction was observed with ceramic brackets and beta-titanium wires (4.12 +/- 0.39 N), while the lowest was recorded with self-ligating brackets and stainless steel wires (0.98 +/- 0.18 N). Conclusion: Frictional resistance was significantly influenced by both bracket system and archwire material. Passive self-ligating brackets combined with stainless steel archwires offered the most favourable low-friction combination, whereas ceramic brackets with beta-titanium archwires generated the highest resistance.

Keywords

archwire; brackets; ceramic brackets; frictional resistance; orthodontics; self-ligating brackets; sliding mechanics.

INTRODUCTION

Sliding mechanics is widely used during orthodontic space closure, canine retraction, alignment, and controlled tooth movement. During these procedures, the bracket moves along the archwire or the archwire slides through the bracket slot, and part of the applied orthodontic force is lost as friction, binding, or notching. The biological response of the periodontal ligament depends not only on the magnitude of the applied force but also on the proportion of force effectively transmitted to the tooth. Excessive resistance to sliding may reduce treatment efficiency, demand heavier applied forces, and increase anchorage strain, whereas very low resistance may improve mechanical efficiency when the clinical objective requires sliding movement [1].

Frictional resistance is a multifactorial phenomenon. It is influenced by bracket material, slot dimension, ligation method, archwire alloy, wire cross-section, surface roughness, saliva, angulation, torque, interbracket distance, and manufacturing tolerance. Experimental studies have shown that the coefficient of friction is not

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1 Saleh Alwadei, Department of Pediatric Dentistry, College of Dentistry, Prince Sattam Bin Abdulaziz University, AlKharj 11942, Saudi Arabia. Email: s.alwadei@psau.edu.sa

2. Farhan H. Alwadei, Department of Pediatric Dentistry, College of Dentistry, Prince Sattam Bin Abdulaziz University, AlKharj 11942, Saudi Arabia.

Correspondence:

Department of Pediatric Dentistry, College of Dentistry, Prince Sattam Bin Abdulaziz University, AlKharj 11942, Saudi Arabia. Email: s.alwadei@psau.edu.sa

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a fixed property of a single material but a response of the bracket-wire couple under defined environmental and mechanical conditions. Stainless steel couples often demonstrate comparatively stable and low friction, while beta-titanium wires may exhibit greater frictional variability due to surface characteristics and oxide layer behaviour [2].

The distinction between classical friction and resistance to sliding is clinically important. In an ideally aligned bracket-wire system with negligible angulation, friction may dominate the resistance encountered during movement. However, when second-order angulation or torque develops, binding and notching become increasingly relevant. Articolo and colleagues demonstrated that resistance to sliding rises markedly with bracket-wire angulation, indicating that frictional assessment under zero-angulation conditions alone may underestimate clinical resistance [3].

Archwire material is a major determinant of bracket-wire interaction. Stainless steel wires generally show low surface roughness and high stiffness, which are favourable for sliding mechanics. Nickel-titanium wires are commonly used during alignment because of elasticity and shape memory, but their frictional behaviour may vary by surface finish and cross-section. Beta-titanium wires are useful for finishing and segmental mechanics due to formability and springback; however, multiple studies have reported higher frictional resistance for beta-titanium than for stainless steel and nickel-titanium in bracket slot testing [4].

Bracket design also plays a key role. Conventional stainless steel brackets are commonly tied with elastomeric modules or stainless steel ligatures. Elastomeric ligation may increase friction because the ligature actively presses the archwire against the bracket slot floor. Self-ligating brackets were developed partly to reduce ligation-related resistance by using a built-in clip or door, thereby reducing the normal force exerted on the wire. Nevertheless, the advantage of self-ligation is not absolute and may depend on wire size, slot clearance, bracket prescription, active or passive clip design, and the presence of angulation [5].

Ceramic brackets are popular because of esthetic demand, but their frictional characteristics remain a concern. Polycrystalline ceramic slots may show greater surface roughness and hardness than stainless steel slots, potentially increasing friction and causing greater wear of the archwire. Metal-insert ceramic brackets and ceramic self-ligating systems were introduced to reduce this disadvantage, but conventional ceramic brackets remain widely used in clinical practice, especially in patients prioritising esthetics [6].

Previous in vitro investigations have compared isolated bracket systems or specific wire materials, but the evidence remains heterogeneous because of differences in bracket brands, wire dimensions, test speeds, artificial saliva protocols, ligation techniques, and specimen alignment. Some systematic and laboratory evidence suggests lower friction with self-ligating brackets in ideal alignment and small round wires, whereas the difference is less predictable with large rectangular wires and in the presence of angulation or binding [7].

Because clinical space closure is commonly performed on rectangular working archwires, there is a need for controlled laboratory comparison of commonly used bracket systems with different rectangular archwire materials. The present in vitro study was designed to compare static and kinetic frictional resistance among conventional stainless steel, passive self-ligating, and ceramic brackets using stainless steel, nickel-titanium, and beta-titanium archwires. The null hypothesis was that bracket type and archwire material would not significantly affect frictional resistance.

MATERIALS AND METHODS

Study design and setting: This was an in vitro comparative experimental study performed in a dental materials and orthodontic biomechanics laboratory. The study evaluated frictional resistance generated by different bracket-archwire combinations under standardised conditions. As the investigation did not involve human participants, patient records, or biological samples, institutional ethical review was not required; however, the study protocol was reviewed by the departmental research committee before testing.

Sample size: A total of 90 bracket-archwire assemblies were tested. Sample size was calculated using pilot observations from five specimens per group, assuming a minimum detectable difference of 0.6 N in static friction among groups, standard deviation of 0.35 N, alpha error of 0.05, and power of 80%. Ten specimens were included in each of nine experimental groups, formed by combining three bracket systems with three archwire materials.

Bracket systems: Three maxillary right premolar bracket systems with 0.022 x 0.028-inch slots and MBT prescription were evaluated: Group C represented conventional stainless steel brackets tied with elastomeric modules; Group SL represented passive self-ligating stainless steel brackets; and Group CE represented polycrystalline ceramic brackets tied with elastomeric modules. All brackets were inspected under 10x magnification before testing to exclude slot defects, fractures, manufacturing irregularities, or distorted tie-wings.

Archwire materials: Three 0.019 x 0.025-inch rectangular archwire materials were evaluated: stainless steel, nickel-titanium, and beta-titanium. Wire segments measuring 10 cm were cut from straight posterior segments using a hard wire cutter. Each wire segment was cleaned with 70% isopropyl alcohol and dried with oil-free compressed air before testing. A new bracket and a new wire segment were used for each test to avoid carry-over effects caused by surface wear.

Specimen assembly: Each bracket was bonded using cyanoacrylate adhesive to an acrylic mounting block with the bracket slot aligned parallel to the direction of movement. A custom stainless steel jig was used to standardise bracket position and eliminate unwanted torque or rotation. For conventional and ceramic brackets, the archwire was ligated using fresh elastomeric modules placed with a ligature director. For self-ligating brackets, the passive door was closed according to manufacturer instructions. After assembly, specimens were stored in artificial saliva at 37 degrees C for 10 minutes before testing to simulate oral lubrication.

Friction testing procedure: Frictional resistance was measured with a calibrated universal testing machine fitted with a 50 N load cell. The acrylic block containing the bracket was fixed to the lower grip, and the archwire segment was attached to the upper movable crosshead. The wire was pulled through the bracket slot over a 10 mm distance at a crosshead speed of 5 mm/min. Static frictional resistance was defined as the initial peak force required to initiate movement. Kinetic frictional resistance was calculated as the mean force recorded during steady sliding after the initial peak. The testing environment was maintained at 37 +/- 1 degrees C with artificial saliva applied immediately before each run.

Outcome variables: The primary outcome was static frictional resistance in Newtons. Secondary outcomes included kinetic frictional resistance and percentage increase in static friction relative to the lowest-friction combination. The independent variables were bracket type and archwire material.

Statistical analysis: Data were entered into a spreadsheet and analysed using statistical software. Normality was assessed by the Shapiro-Wilk test and homogeneity of variance by Levene's test. Descriptive statistics were presented as mean +/- standard deviation. Two-way analysis of variance was used to examine the main effects of bracket type and archwire material and their interaction. Intergroup comparisons were performed using Tukey's post hoc test. A p-value <0.05 was considered statistically significant.

RESULTS

All 90 specimens completed testing without bracket debonding, wire distortion, or failure of the ligation mechanism. The data were normally distributed within groups, and variance assumptions were acceptable for parametric analysis. Static and kinetic frictional resistance varied consistently according to bracket system and archwire material.

Table 1. Static frictional resistance according to bracket type and archwire material

Bracket type	Stainless steel wire (N)	Nickel-titanium wire (N)	Beta-titanium wire (N)	Overall mean (N)
Conventional stainless steel	1.52 +/- 0.25	2.34 +/- 0.31	3.25 +/- 0.44	2.37 +/- 0.46
Passive self-ligating	0.98 +/- 0.18	1.39 +/- 0.22	1.89 +/- 0.28	1.42 +/- 0.32
Polycrystalline ceramic	2.52 +/- 0.33	3.24 +/- 0.42	4.12 +/- 0.39	3.29 +/- 0.58
Overall mean	1.67 +/- 0.48	2.33 +/- 0.67	3.08 +/- 0.79	2.36 +/- 0.84

Table 1 shows the static frictional resistance values for the nine bracket-wire combinations. The lowest static friction was observed in the self-ligating bracket with stainless steel wire group (0.98 +/- 0.18 N), whereas the highest value was observed in the ceramic bracket with beta-titanium wire group (4.12 +/- 0.39 N). Within each archwire material, self-ligating brackets produced the lowest static friction and ceramic brackets produced the highest static friction.

Bracket type	Stainless steel wire (N)	Nickel-titanium wire (N)	Beta-titanium wire (N)	Overall mean (N)
Conventional stainless steel	1.18 +/- 0.21	1.86 +/- 0.27	2.72 +/- 0.37	1.92 +/- 0.42
Passive self-ligating	0.74 +/- 0.15	1.05 +/- 0.19	1.46 +/- 0.23	1.08 +/- 0.28
Polycrystalline ceramic	2.02 +/- 0.29	2.68 +/- 0.36	3.48 +/- 0.35	2.73 +/- 0.51
Overall mean	1.31 +/- 0.42	1.86 +/- 0.64	2.55 +/- 0.77	1.91 +/- 0.76

Table 2. Kinetic frictional resistance according to bracket type and archwire material

Outcome	Factor	F value	p-value	Interpretation
Static friction	Bracket type	186.42	<0.001	Significant
Static friction	Archwire material	142.75	<0.001	Significant
Static friction	Bracket x wire interaction	9.84	<0.001	Significant
Kinetic friction	Bracket type	174.28	<0.001	Significant
Kinetic friction	Archwire material	128.36	<0.001	Significant
Kinetic friction	Bracket x wire interaction	8.21	<0.001	Significant

Across all bracket systems, stainless steel archwires generated the lowest mean static friction (1.67 +/- 0.48 N), followed by nickel-titanium (2.33 +/- 0.67 N) and beta-titanium (3.08 +/- 0.79 N). The mean static friction in the beta-titanium groups was approximately 84.4% higher than that observed with stainless steel wires.

Two-way ANOVA demonstrated significant main effects of bracket type and archwire material on both static and kinetic friction (Table 3). A significant bracket x wire interaction was also observed, indicating that the influence of archwire material differed according to bracket system. Tukey post hoc testing showed that self-ligating brackets differed significantly from conventional and ceramic brackets for all three wire materials ($p<0.001$). Ceramic brackets also differed significantly from conventional brackets for stainless steel, nickel-titanium, and beta-titanium wires ($p<0.001$).

When the lowest-friction combination was used as the reference, conventional stainless steel brackets with stainless steel wires showed a 55.1% increase in static friction, ceramic brackets with stainless steel wires showed a 157.1% increase, and ceramic brackets with beta-titanium wires showed a 320.4% increase. These findings rejected the null hypothesis and confirmed that both bracket type and archwire material significantly affected frictional resistance.

Discussion

The present in vitro study demonstrated that frictional resistance was significantly affected by both bracket system and archwire material. Passive self-ligating brackets showed the lowest static and kinetic frictional resistance, conventional stainless steel brackets showed intermediate values, and polycrystalline ceramic brackets showed the highest values. Among the archwire materials tested, stainless steel wires produced the lowest friction, nickel-titanium wires showed intermediate values, and beta-titanium wires produced the highest friction. These findings are biomechanically plausible and consistent with established concepts of bracket-wire interaction during sliding mechanics [8].

The lower friction observed with passive self-ligating brackets may be explained by the absence of active elastomeric ligation force pressing the archwire against the slot base. In conventional brackets, elastomeric modules add a normal force component that increases resistance during sliding. Hain and colleagues reported that ligation method significantly influences frictional behaviour, with elastomeric ligation generally producing greater friction than low-friction ligation alternatives [9]. In the present study, the effect of ligation was evident across all three wire materials, as self-ligating brackets consistently produced lower friction than elastomerically ligated conventional brackets.

The current findings agree with Monteiro et al., who reported lower frictional resistance for self-ligating brackets compared with conventional brackets under several bracket-archwire-angle combinations [10]. However, the magnitude of self-ligating advantage should be interpreted carefully. Systematic review evidence indicates that self-ligating brackets may reduce friction mainly in ideal alignment and with smaller wires, whereas the difference may become less predictable when large rectangular archwires, tipping, torque, or binding are present [11]. The present study used rectangular working wires under standardised alignment, and therefore the results represent controlled sliding conditions rather than the full complexity of clinical tooth movement.

Ceramic brackets produced the highest frictional resistance in this investigation. This may be attributed to the hardness, surface roughness, and ceramic slot characteristics that increase mechanical interaction with the archwire. Williams et al. reported that conventional ceramic brackets generated greater static frictional resistance than metal slot ceramic and self-ligating ceramic bracket systems, particularly when larger rectangular archwires and increased angulation were used [12]. Similarly, Cacciafesta and colleagues observed that metal-insert ceramic brackets reduced friction compared with conventional ceramic brackets, although they did not always achieve the low frictional values seen with stainless steel brackets [13]. These findings support the view that esthetic ceramic brackets may carry a biomechanical compromise unless slot design is modified.

Archwire material had a strong influence on friction. Stainless steel archwires produced the lowest mean friction in the present study, likely because of their smoother surface finish, high stiffness, and favourable interaction with metallic bracket slots. Kusy and Whitley reported that stainless steel couples often show the lowest and most consistent frictional coefficients in model orthodontic systems, whereas beta-titanium wires may show higher and more erratic frictional behaviour [2]. The comparatively low friction of stainless steel wires supports their frequent use during sliding space closure after alignment and levelling are complete.

Nickel-titanium archwires demonstrated intermediate frictional values. Although nickel-titanium wires are indispensable during initial alignment due to superelasticity and shape-memory properties, their surface characteristics and lower stiffness may influence sliding behaviour. In the present study, nickel-titanium generated greater friction than stainless steel but less than beta-titanium in all bracket systems. This suggests that nickel-titanium may be acceptable when light flexible alignment is required but may not be the most efficient option for mechanics primarily dependent on low-friction sliding.

Beta-titanium archwires produced the highest frictional resistance across all bracket groups. This finding is consistent with Cacciafesta et al., who reported higher frictional resistance for beta-titanium archwires compared with stainless steel and nickel-titanium in various bracket-archwire combinations [4]. The oxide layer, surface topography, and adhesive interaction between beta-titanium and bracket slot material may contribute to higher friction. Clinically, beta-titanium wires remain valuable for finishing bends, torque expression, and segmental force systems, but they may be less favourable when the primary objective is friction-efficient sliding.

The significant bracket x wire interaction observed in the present study indicates that bracket and wire variables should not be considered independently. Ceramic brackets combined with beta-titanium wires produced the highest frictional values, suggesting an additive or synergistic unfavourable interaction between a rougher slot surface and a higher-friction wire alloy. Conversely, self-ligating brackets with stainless steel archwires provided the most favourable low-friction combination. This interaction has practical relevance because clinical appliance selection often involves both esthetic preference and biomechanical requirement.

The difference between static and kinetic friction was also clinically meaningful. Static friction represents the force required to initiate movement, whereas kinetic friction reflects resistance during ongoing sliding. In orthodontics, tooth movement occurs intermittently rather than as continuous mechanical sliding; therefore, repeated episodes of static resistance may be relevant during activation cycles. Higher static peaks, especially in ceramic-beta-titanium combinations, may lead clinicians to apply heavier forces, potentially increasing anchorage demand or patient discomfort without necessarily improving biological efficiency [14].

The present findings should be interpreted in light of resistance-to-sliding theory. Burrow emphasised that clinical sliding mechanics is affected not only by friction but also by binding and notching, especially when brackets are not ideally aligned [1]. In this study, bracket slots were aligned with the direction of pull to isolate the effect of bracket type and wire material. While this improves internal validity, it may underestimate resistance in crowded arches or during bodily tooth movement where second-order angulation develops. Studies involving bracket angulation have shown substantial increases in resistance to sliding as angulation increases [3,15].

Artificial saliva was used to approximate oral lubrication, but the oral environment remains more complex. Temperature variation, plaque accumulation, corrosion, masticatory loading, bracket wear, and time-dependent degradation of elastomeric modules can alter frictional behaviour. Elastomeric ligatures may absorb water, lose force, and change their frictional profile over time. Similarly, wire and slot surfaces may undergo wear during clinical use. Therefore, the values reported in this study should be viewed as comparative laboratory measurements rather than direct predictors of clinical treatment duration.

Despite these limitations, the study provides useful biomechanical guidance. During space closure requiring sliding mechanics, passive self-ligating brackets with stainless steel rectangular archwires may reduce frictional losses. Conventional stainless steel brackets can also provide acceptable frictional behaviour, particularly when low-friction ligation strategies are used. Ceramic brackets should be selected with awareness of their higher resistance, especially when combined with beta-titanium wires. When esthetics are essential, ceramic brackets with metal-lined slots or ceramic self-ligating designs may be considered to reduce friction while preserving appearance [16].

The study has several limitations. Only one bracket prescription and one wire dimension were evaluated. The brackets were tested under ideal alignment without torque, tipping, rotation, or interbracket distance variation. Only immediate frictional resistance was measured; long-term wear, ligature ageing, and repeated sliding cycles were not simulated. Brand-specific manufacturing differences were not the focus of this investigation. Future studies should include dynamic oral simulation, bracket angulation, multiple wire dimensions, surface roughness assessment by profilometry, scanning electron microscopy of wear patterns, and correlation with clinical space-closure rates.

Overall, the results support the rejection of the null hypothesis. Bracket system and archwire material significantly altered frictional resistance, and the lowest-friction assembly was passive self-ligating stainless steel brackets with stainless steel archwires. The highest friction occurred with polycrystalline ceramic brackets and beta-titanium archwires. These findings reinforce the importance of selecting bracket-wire combinations according to the biomechanical phase of treatment rather than relying solely on esthetics or appliance popularity [17-22].

CONCLUSION

Within the limitations of this in vitro study, passive self-ligating brackets demonstrated significantly lower static and kinetic frictional resistance than conventional stainless steel and ceramic brackets.

Stainless steel archwires produced the least friction, nickel-titanium wires produced intermediate friction, and beta-titanium wires produced the greatest resistance across all bracket systems.

The most favourable low-friction combination was passive self-ligating brackets with stainless steel archwires, whereas ceramic brackets with beta-titanium archwires generated the highest frictional resistance.

Clinical bracket and archwire selection should consider the biomechanical requirements of sliding mechanics, esthetic expectations, and the potential frictional compromise associated with ceramic brackets and high-friction wire alloys.

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