In vitro evaluation of frictional forces between archwires and ceramic brackets

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The aim of this study was to evaluate the frictional force between orthodontic brackets and archwires. The differences in magnitude of the frictional forces generated by ceramic brackets, ceramic brackets with metal reinforced slot, and stainless steel brackets in combination with stainless steel, nickel-titanium, and beta-titanium orthodontic archwires were investigated. Brackets and wire were tested with tip angulations of 0° and 10°. Friction testing was done with the Emic DL 10000 testing machine (São José do Rio Preto, PR, Brazil), and the wires were pulled from the slot brackets with a speed of 0.5 cm/min for 2 minutes. The ligation force between the bracket and the wire was 200 g. According to the data obtained, the brackets had frictional force values that were statistically significant in this progressive order: stainless steel bracket, ceramic bracket with a metal reinforced slot, and traditional ceramic bracket with a ceramic slot. The beta-titanium wire showed the highest statistically significant frictional force value, followed by the nickel-titanium and the stainless steel archwires, in decreasing order. The frictional force values were directly proportional to the angulation increase between the bracket and the wire. (Am J Orthod Dentofacial Orthop 2004;125:56-64)

Ceramic brackets were introduced in orthodontics to meet increasing esthetic demands,1,2 but their incorrect use or their wrong indication can lead to several problems, such as the high friction coefficient between the bracket and the archwire; this can interfere in the orthodontic treatment.3-6

Friction is defined as a force that delays or resists the relative motion of 2 objects in contact, and its direction is tangential to the common interface of the 2 surfaces.5,7,8 There are 2 types of friction: kinetic (dynamic), which occurs during the motion, and static, which prevents the motion.8-11

Under normal conditions, the frictional force is proportional to the applied load, depending on the nature of the sliding surfaces,9 and independent of the contact area between the surfaces and the sliding speed (except at very low speeds).5 The friction coefficient of a given material couple is the ratio between the tangential force (frictional force) and the normal or perpendicular load applied during the relative motion.5,12

In fixed orthodontic therapy, teeth can be moved by using either retraction archwires, involving minimal friction, or sliding mechanics, in which friction is very considerable. Friction is a factor in sliding mechanics, such as during the retraction of the teeth into an extraction area, active torque, leveling, and alignment, when the archwire must slide through the bracket slots and tubes.5,8,9 During sliding mechanics, the biologic tissues respond, and tooth movement occurs only when the forces applied exceed the friction on the bracket-wire interface. High levels of frictional force could result in the debonding of the bracket, associated with either a small dental movement or no movement at all. When friction prevents the movement of the tooth to which the bracket is attached, friction can reduce the available force by almost 40%, resulting in an anchorage loss.5,6,13 Therefore, it is essential to understand the impact of friction between the bracket and the wire so that the proper force can be applied to obtain adequate dental movement and optimum biologic tissue response.5,14-17

Clinically, when stainless steel brackets are used on posterior teeth, in combination with ceramic brackets on anterior teeth, the difference in friction between the steel and the ceramic brackets can result in faster movement of the posterior teeth; this would cause an undesired anchorage loss7,10,18,19 and an increase of the overbite.4 If this occurs, posterior anchorage should be
strengthened with devices such as headgear, palatal bars, or Nance holding arches. To decrease the overbite, heavier wires or compensating moments should be used to resist this side effect.4,20 Therefore, to reduce the undesirable effects of frictional force, some authors suggest developing ceramic brackets with smoother slot surfaces to decrease any possible effects of static fatigue.4,6 Recently, a new ceramic bracket was designed with a metal-lined archwire slot,2 but the studies do not prove its efficiency in reducing frictional force in sliding mechanics.

Thus, we intended to evaluate the frictional force of ceramic brackets, ceramic brackets with metal reinforced slots, and stainless steel brackets using stainless steel, nickel-titanium, and beta-titanium orthodontic archwires, with angulations of 0° and 10° between the bracket and the wire.

**MATERIAL AND METHODS**

In this study, 30 brackets of each type were used: stainless steel brackets (Victory Series, 3M/Unitek, Monrovia, Calif), ceramic brackets with metal reinforced slot (Clarity, 3M/Unitek), and ceramic brackets (Transcend series 6000, 3M/Unitek). All brackets were .022 × .028-in, standard edgewise canines, with no built-in torque or tip (Fig 1).

Ninety archwire segments, with a 019 × .025-in dimension and 4.0 cm length, of each type were tested: stainless steel (Permachrome Resilient Archwire, 3M/Unitek), nickel-titanium (Nickel-Titanium Super-Elastic Archwire, 3M/Unitek), and beta-titanium (Beta III Titanium, 3M/Unitek).

The wires' displacement resistance was caused by the sliding frictional force produced by the contact between the bracket and the wire surfaces. Five samples of each kind of material were randomly selected to be mechanically tested (Table I).

The bracket-wire combinations were submitted to mechanical tests with the Emic testing instrument (São José do Rio Preto, PR, Brazil), with tip angulations of 0° and 10°. Each bracket and archwire were changed after 5 tests with both angulations. A testing apparatus (Fig 2) constructed of stainless steel was designed to hold the bracket during the mechanical test. Each archwire segment was fixed to a device, which was connected to a load cell of 2.0 kilogram force.
bracket bases were glued to the center of a rotary cylinder with an instantaneous glue (Super Bonder, Loctite Brasil Ltda, São Paulo, Brazil), and the wire segments were positioned perpendicularly in contact with the slot base. Two connected horizontal and parallel steel rollers, which could rotate freely on fine steel supporting rods, were positioned, 1 at each end of the bracket, to pull the archwire against the slot base. For the mechanical tests with 0° angulation, the brackets were placed vertically, so that the wire segments passively touched the bracket slot. After a 10° angulation was evaluated, angles were marked on the rotary cylinder so that the brackets could be placed to achieve an angle of 10° with the wire axle.

The ligature system of the wire to the bracket was standardized, so that the pressure force between the bracket and the wire was constant and equal to 200 gram force (Fig 3). The crosshead speed was 0.5 cm/min, and each test was carried out for 2 minutes. The load cell registered the maximum force level (gram force (Fig 3). The crosshead speed was 0.5 cm/min, and each test was carried out for 2 minutes. The frictional force value, at 0° angulation between bracket and wire.

However, when a 10° angulation between bracket and wire was used, other friction components were produced. In addition to the 2 friction resistances that occur when the wire is displaced from the bottom of the bracket, new friction arises when the wire touches the bracket edges (F3 and F4), as shown in Figure 6. Because these forces are hard to measure, this frictional coefficient is also difficult to calculate at a 10° angulation between bracket and wire.

**DISCUSSION**

Many variables can affect the magnitude of the frictional force between the bracket and the wire: (1) archwire: active torque, thickness or vertical dimension, cross-sectional shape and size, composition, intrinsic lubrication, abrasive wear resistance, surface texture, elastic properties, stiffness, and abrasive wear resistance; (2) bracket: material, width, thickness or vertical dimension, superficial texture, stiffness, and abrasive wear resistance; (3) ligation of archwire to bracket: force and ligature type; (4) intraoral variables: saliva, plaque, acquired pellicle, corrosion, mastication, bone density, tooth number, anatomic configuration, root surface area, and occlusion; (5) orthodontic appliance: bracket-wire angulation, interbracket distance, level of bracket slots between adjacent teeth, forces applied for retraction, and point of force application.

The ceramic bracket showed the highest frictional force value with statistical significance (P < .05), followed in decreasing order by the ceramic bracket with metal reinforced slot and the stainless steel bracket (Figs 4 and 5).

The stainless steel archwire had the lowest frictional force values with statistical significance (P < .05), followed in increasing order by the nickel-titanium and the beta-titanium archwires. The verified frictional force values were directly proportional to the angle increase between the bracket and the wire (Tables II to IV and Figs 4 and 5).

![Diagram of testing apparatus and different components of force over bracket and wire. Total compressed force was 200 gf, where: N1 = N2 = 100 gf; F1 = μ1N1; F TOTAL = F1 + F2; F TOTAL = μ1N1 + μ2N2; F TOTAL = μ1100 + μ2100; F TOTAL = 200μ.](image-url)

**RESULTS**

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In relation to the bracket-wire angulation, the results obtained indicated that the frictional force values were, in all combinations, directly proportional and statistically significant to the angulation increase, suggesting that this factor influences the magnitude of the friction between bracket and wire.

Before the frictional resistance test, the dimensions of 21 units of each type of bracket were measured (width, height, and slot depth) with a projector profile.
and the variations between brackets were evaluated. The slot depth does not seem to influence frictional resistance values; the ligation force between bracket and wire does not depend on this dimension. Although the ceramic brackets are esthetically more pleasing than the metal ones, they are bulkier and, therefore, can be uncomfortable to the patient.

According to these results, in all combinations, the ceramic brackets show the highest level of friction force. They are also the largest in mesiodistal dimension and the smallest in slot height. One cause for the increase of frictional force could be that the ceramic slot is slightly shorter. Although some authors state that the frictional force does not depend on the contact area between the surfaces, others believe that this interferes with the frictional force level. Larger brackets could offer more contact area between bracket and wire, and could cause small wire inclinations in the slot walls during their displacement, thus creating more attrition components and increasing the frictional force. On the other hand, slots with narrower mesiodistal dimensions could lead to a larger dental inclination, because the mesiodistal movements would be less controlled. Thus, the bracket-wire angulation would be increased, aggravating the attrition between these 2 surfaces. We could not define whether there is a relationship between slot width and frictional force. Consequently, we suggest further research.

Brackets and wires were submitted to electronic micrograph scanning to evaluate the surface morphology. In relation to the brackets, roughness increases in the following order: stainless steel, ceramic bracket with metal reinforced slot, and traditional ceramic, as can be seen in Figures 7, 8, and 9, respectively. The larger frictional force values produced by traditional ceramic brackets, in all combinations and angulations, could be attributed to some ceramic bracket characteristics, such as hardness and stiffness. Manufacturing procedure, finishing, and polishing are difficult to do; this might explain the granular and pitted surface of the ceramic brackets. The ceramic bracket with metal reinforced slot showed the intermediate values of the frictional force, probably because its slot is reinforced with metal, which prevents direct contact between ceramic and wire. The stainless steel brackets had the lowest and statistically most significant frictional force value, maybe because the characteristic of the metal allows better polishing and a smoother surface. The difference of the frictional force values between the ceramic bracket with the metal reinforced slot and
Comparison of frictional force between groups with $0^\circ$ and $10^\circ$ bracket/wire tip angulation (Bonferroni adjustment)

<table>
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<tr>
<th>Wire</th>
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<th>Mean</th>
<th>SD</th>
<th>Mean</th>
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<td>10.02</td>
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SD, Standard deviation.
SS, Stainless steel.
C-SS, Ceramic/metal slot.
C, Ceramic.

Table IV. Comparison of maximum frictional forces means (gf), between $0^\circ$ and $10^\circ$ Student t test

<table>
<thead>
<tr>
<th>Description</th>
<th>0$^\circ$</th>
<th>10$^\circ$</th>
<th>t values</th>
</tr>
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<tr>
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</table>

*Statistically significant difference, $P < .05$.
SS, Stainless steel; C-SS, ceramic/metal slot; C, ceramic.

Some authors state that the increasing thickness of the wire produces greater frictional force values, and that rectangular wire generally shows higher values than the round wires, because there is a larger contact area between slot and wire surfaces.8,9,13,18,20,22-24 Others believe that frictional force does not depend on the contact area.5 This variable could not be analyzed because we used rectangular wires in this study. However, this should be studied, because thinner wires could increase the bracket-wire angulation and, consequently, increase the frictional force.

Before the frictional force test, the thickness and the width of the wire were measured by a digital pachymeter at 3 standard points. All the samples had the same dimensions (0.019 in) between the reference points. Therefore, the frictional force values were probably influenced by the surface morphology and, later, by the thickness variation, because all wires showed homogeneity in dimension and in manufacturing quality.

With more flexible orthodontic wires, the frictional force magnitude could present a slight increase. Some authors justify this relationship based on the supposition that less rigid wires could cause a greater dental inclination and a larger contact area between bracket and wire.2,20 On the other hand, more rigid wires could cause higher friction, because the lack of flexibility could create sharper angles and increase the sliding mechanics displacement resistance. The elastic properties do not seem to explain the behavior of the beta-titanium, because this alloy is more rigid than nickel-titanium and more flexible than stainless steel, demonstrating greater friction force values in all combinations and angulations, in
accordance with the literature. Stainless steel wires, despite their lower flexibility, show the lowest friction force values. Therefore, it seems that the elastic properties of the wire are secondary, and the surface texture has more influence on frictional force.

Each bracket-wire combination was submitted 5 times to the mechanical test to evaluate material wear.
resistance. This methodology was adopted because, in clinical conditions and during sliding mechanics, the same bracket slides on the wire, or vice versa, several times in a period determined by the treatment objectives. Some authors believe that repeated use could cause wear to the bracket or wire surface, making them smoother and, consequently, decreasing the frictional force. Others believe that repeated use produces grooves and surface wear, thus the materials become rougher and the frictional force increases. Our results showed that there was no difference in the frictional force values with repeated use, suggesting that there is no correlation between these 2 factors.

The ligation between bracket and wire is another variable that could influence the frictional force level. Authors are unanimous in reporting that the force used through stainless steel ligature is subjective, varying according to the orthodontist, and it can fracture ceramic brackets. On the other hand, elastomeric ligature loses elasticity with time and can alter the frictional force values. In this study, the ligation between bracket and wire was standardized to eliminate this variable.

Ceramic brackets, mainly the polycrystalline ones, can be improved to decrease the frictional force by reducing the alumina particle dimensions to prevent the loosening of fragments, applying a glazed surface on the ceramic slot, inserting either a metal or a gold slot into the ceramic bracket, eliminating the flaws inherent to its size, and making the bracket edges smoother and rounder, not sharply rectangular. Even with ceramic bracket advancements, some clinical complications, such as enamel abrasion and ceramic stiffness, are still a challenge.

The ceramic bracket with metal reinforced slot seems to be a promising option to lessen the clinical complications of ceramic brackets. The advantages of a stainless steel slot are to minimize the superficial friction and to help strengthen the bracket to withstand routine orthodontic torque forces. Furthermore, the bracket base also incorporates a vertical slot, designed to help create a consistent bracket failure mode during debonding. Essentially, this new bracket is meant to combine the esthetic advantages of ceramic and the functional advantages of metal brackets. However, more studies are necessary to allow the orthodontist to use this accessory safely and efficiently. When this bracket was submitted to electronic micrograph scanning, a gap between the bracket and metal slot was observed (Fig 8, B). Perhaps it occurred because of the difficulty in adjusting the metal to the ceramic and the different expansion coefficients of the materials. Therefore, it is doubtful that this flaw in adaptation can influence the frictional force magnitude, or even if it can cause pigmentation between the bracket and metal slot, by either extrinsic factors or metal corrosion.

Until the use of ceramic brackets is safe and efficient, orthodontists must apply weightless and continuous forces during sliding mechanics, as close as possible to the center of resistance, to prevent dental inclination and to reduce the frictional force between bracket and wire.

Because frictional force is caused by several factors, which are usually correlated and dependent, these factors can also influence and create undesirable behavior in the frictional force values. Moreover, it is difficult to compare studies, because of different methodologies; these variables can be considered as influencing factors in data registers.

Intraoral variables such as saliva, plaque, acquired
pellicle, corrosion, chewing, bone density, tooth number, anatomic configuration, root surface area, and occlusion were not evaluated in this study, but they can influence frictional force values.

In vitro studies do not correspond to what really happens during dental movement, and, therefore, readers must be careful when evaluating the results from this research. The friction magnitude recorded is substantially different from the applied forces in clinical orthodontic movement. The values recorded should be used to compare the effects of different factors, rather than to quantify in vivo friction.

CONCLUSIONS

Under the conditions of the experiment, it can be inferred that:

1. The stainless steel bracket had the lowest statistically significant frictional force values (P < .05), followed by ceramic bracket with metal reinforced slot. The traditional ceramic bracket showed the greatest statistically significant frictional resistance values (P < .05) in all tested combinations.

2. The stainless steel archwires had the lowest statistically significant frictional force values (P < .05), followed, in increasing order, by nickel-titanium and beta-titanium archwires, in all evaluated combinations.

3. The magnitude forces (gf) to displace the wires in the brackets were directly proportional and significant to the angle increase between the bracket and the wire. The values were higher in the 10° angulation between the bracket and the wire than in the 0° angulation.

4. The ceramic bracket with metal reinforced slot had a lower frictional force value than did the traditional ceramic bracket, and it seems to be a promising alternative to solve the problem of friction.

5. The difference in frictional force values between the ceramic bracket with metal reinforced slot and the stainless steel bracket is probably caused by the lack of a perfect adjustment and a gap between the metal slot and the ceramic bracket.

6. Additional studies are necessary to improve the metal slot adjustment in the ceramic bracket, as well as its clinical performance, which influences the frictional resistance values.

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