

***In vitro* Evaluation of Static Frictional Forces at the Bracket-archwire Interface**

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The aim of this research is to compare the static frictional forces generated by different bracket-archwire couples. The study group consisted of three types of ceramic brackets (polycrystalline alumina with stainless steel slot, polycrystalline alumina and monocrystalline alumina), one stainless steel bracket and two types of archwires (0.016" NiTi and 0.019x0.025" SS). Brackets corresponding to the upper right quadrant (from upper right central incisor to the upper right second premolar) were bonded on standardized maxillary models and elastomeric ligatures were used to secure the archwire to the bracket system. An in-vitro experiment was conducted using a testing machine designed to measure the compression and traction force, both in dry and wet testing conditions. The results indicated statistically significant differences between most bracket-archwire groups. According to the data obtained, stainless steel brackets produced the lowest static frictional forces, regardless of test conditions and orthodontic archwire type. Polycrystalline ceramic brackets with stainless steel slot generated higher static frictional forces than stainless steel brackets, but lower than ceramic brackets when combined with the 0.019" x 0.025" SS archwire. No significant differences were found between polycrystalline and monocrystalline ceramic brackets. Experiments performed with 0.019 x 0.025" SS archwire produced greater static frictional forces than those with 0.016" NiTi wire. Static frictional forces were not significantly influenced by the test conditions.

Keywords: static frictional force, orthodontic archwire, ceramic bracket, monocrystalline alumina, polycrystalline alumina

Fixed orthodontic therapy is based on the property of the teeth to be moved when a consistent and continuous force is applied. Fixed appliance therapy in orthodontics depends on the bonding of brackets to teeth [1]. The amount of the generated force is determined by the mechanical properties of the inserted archwires [2]. Sliding mechanics plays an important role in the orthodontic treatment with fixed appliances. This mechanics facilitates dental movement by gliding of the bracket along the orthodontic archwire. Controlled tipping or the rotation of the root only depends on the position of the bracket application on the tooth crown [3]. As this movement is subject to fundamental laws of mechanics, frictional force is present at the contact area of the orthodontic system components. Friction is defined as the resistance to motion when one solid body moves tangentially over another with which it is in contact, opposite to the direction of the movement force (fig. 1) [4,5].

By definition two types of frictional forces are considered: static and kinetic. The first is the lowest force required to initiate movement between two solid bodies,

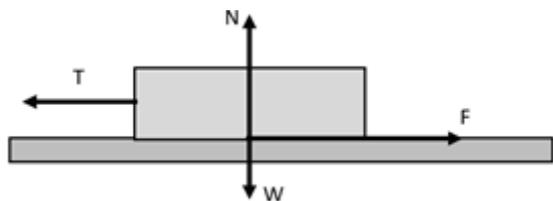


Fig. 1. Coulomb model of friction; T= tractive force, W= weight, N= normal force, F= friction [6]

while the second is the force that opposes the sliding of the two at a constant velocity. The static friction will be greater than the kinetic one because it is more difficult to modify a body from its inert state than to keep it in motion [7].

Studies have shown that between 20 and 70% of the exerted orthodontic force is lost as static frictional resistance [4,5,8]. The dental response occurs upon condition that the applied force exceeds the static frictional force. Excessive enhancement of orthodontic force in order to overcome increased frictional resistance has negative effects on orthodontic anchorage control and dental response, which can undermine the success of the orthodontic treatment. Thus, when choosing the components of a fixed orthodontic appliance it is important to evaluate the variables involved in the variation of frictional force, which can be grouped in two main categories: biological and mechanical variables.

Regarding the biological variables, it is generally accepted that saliva, through its lubricating effect, causes a decrease in friction. This entails individualization of treatment in patients with xerostomia or those receiving saliva-lowering drugs [9]. Other biological variables such as accumulation of bacterial plaque or biodegradation of orthodontic materials can contribute to the increase of frictional forces within the orthodontic system. Prolonged oral exposure (heat and humidity) can lead to elastic degradation and surface characteristic changes of

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elastomeric ligatures, implicitly reducing the frictional resistance [10].

Mechanical variables, being more easily influenced than the biological ones, have been and continue to be of great interest to the orthodontist. These mechanical variables are numerous and include: material, shape and width of bracket, slot depth, surface characteristics, archwire material and section, type and force of ligation. Among these, bracket material is the component that has undergone multiple changes and innovations in order to improve the aesthetic appearance of fixed orthodontic appliances. Nevertheless, most studies still indicate that stainless steel (SS) brackets are the *standard* in sliding mechanics because they generate lower frictional forces than esthetic brackets [4,10]. The main types of ceramic brackets are polycrystalline alumina (PCA) and monocrystalline alumina (MCA), both of which containing high-purity aluminium oxide [5]. When comparing friction of different archwires, lower values are recorded for smaller diameters and stainless steel material [11]. Regarding the ligation method, some authors consider that passive selfligating brackets are associated with the lowest frictional forces, however this aspect is not generally confirmed [12].

The purpose of this study was to compare the static frictional forces for different bracket-archwire couples.

Experimental part

Materials and methods

Working hypotheses were:

- Stainless steel brackets are associated with lower static frictional forces than ceramic brackets.
- Metal-insert ceramic brackets generate lower static frictional forces than conventional ceramic brackets.
- Monocrystalline and polycrystalline ceramic brackets produce similar static frictional forces.
- Coupling of brackets with the rectangular 0.019" × 0.025" stainless steel wire creates higher static frictional forces than with round 0.016" archwire.
- Frictional values are lower in wet testing conditions compared to dry conditions.

Experiments were performed on three types of ceramic brackets and one type of stainless steel bracket, with MBT prescription and 0.022" slot (fig. 2, table 1).

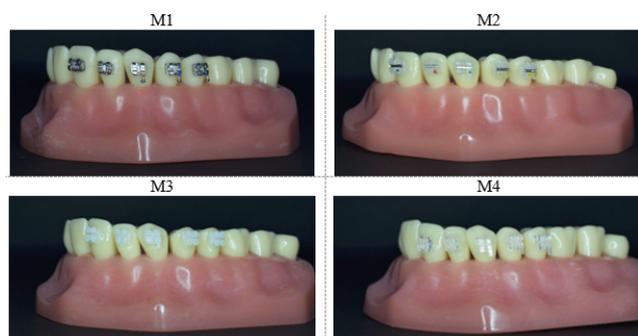


Fig. 2. Standardized models with bonded brackets

The brackets were bonded on standardized maxillary models (Spofadent Fantom Model) using a light cure adhesive for metal and ceramic appliances, with medium viscosity (Opal Bond MV, Opal Orthodontics). Brackets

Code	Bracket name	Manufacturer	Material
M1	Mini Sprint	Forestadent	stainless steel
M2	Clarity	3M Unitek	polycrystalline alumina with stainless steel slot
M3	Clarity Advanced	3M Unitek	polycrystalline alumina
M4	Radiance Plus	American Orthodontics	monocrystalline alumina

corresponding to the upper right quadrant (from upper right central incisor to the upper right second premolar) were passively aligned (bracket-wire angle=0°) using a rectangular 0.021" × 0.025" stainless steel wire (AlphaWire, Orthofocus). The brackets were tested with two ovoid archwires of different alloys (NiTi; SS), sections (round; rectangular) and sizes (0.016" and 0.019x0.025"), from the same manufacturing company (AlphaWire, Orthofocus) (fig. 3).

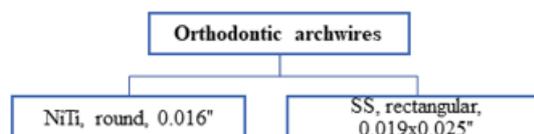


Fig. 3. Orthodontic archwires used in the study

Elastomeric ligatures (Oplaastics, Opal Orthodontics) were used to secure the archwire to the bracket system. The elastomeric ties were placed immediately before each test in order to avoid damage to the ligation force. Elastomeric ligatures rather than stainless steel ones were used because the latter exhibit greater inter- and intraoperator variability.

The experiments were conducted using a universal testing machine (Schmidt HV-500N) (fig. 4) designed to measure the compression and traction force, with a maximum capacity of 500N and a digital distance measuring system with a precision of 0.01 mm [13,14]. Reference points were traced on the model and archwire in order to accurately identify when static friction is recorded.



Fig. 4. Testig machine

The archwire engaged to the bracket system was subjected to a tractive force which progressively increased until the archwire moved from the initial point, moment corresponding to the static frictional force. The data was recorded on a computer connected to the device in the form of a graph (fig. 5), where the X axis represents the value of frictional force (N) between bracket and wire and the Y axis represents the time (s) elapsed for each experiment. After each test the testing machine was stopped, the model was removed and a new one was placed. Each bracket-archwire system was tested three times, both in dry and wet conditions (1 mL of water applied on each bracket) to simulate the oral environment.

All tests were performed under identical conditions, at a constant temperature of 22.5° ± 5°C and the models and machine were handled by a single operator in order to limit the inter-operator variability. To ensure the results are

Table 1
BRACKETS USED IN THE STUDY

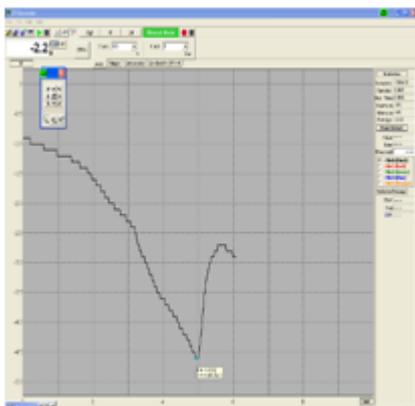


Fig. 5. Software generated graph for frictional forces

as objective as possible, during the experiment, the models had a code so that the operator of the testing machine had no knowledge regarding the type of bracket used.

Descriptive statistical analysis, including the mean and standard deviation of static frictional forces, was performed for each type of bracket-archwire combination. One-way analysis of variance (ANOVA) and Post-Hoc Tukey HSD test were used to determine whether statistically significant differences exist between the bracket-archwire couples and, if so, to accurately identify these groups.

Comparison between the values of static friction, recorded in dry and wet conditions, was realized with the Paired Samples T-Test, setting the level of statistical significance at $p < 0.05$. All statistical analyses were performed with Microsoft Office Excel 2010.

Results and discussions

Comparing the results of the first experiment (0.016" NiTi archwire), we found that, the lowest static frictional force values, both in dry (1.8N) and wet (1.5N) conditions, were recorded for the *stainless steel bracket* (M1) (table 2). *Polycrystalline ceramic brackets with stainless steel slot* (M2) generated the highest friction compared to both the metal and the ceramic brackets (M3 and M4). The frictional

forces varied in both testing environments, the maximum difference being recorded between the metal and the metal insert polycrystalline ceramic bracket (2.5N in dry condition). Analyzing the same brackets in wet condition, the difference was lower (2.3 N), and the monocrystalline ceramic bracket model (M4) generated a mean static frictional force equal to that of M2 (3.8N). Comparing the ceramic brackets, the monocrystalline ceramic type (M4) produced higher static frictional forces than the polycrystalline ceramic type (M3) in both test conditions (table 2).

Regarding the differences between the frictional forces recorded in both conditions, the T-Test did not reveal statistically significant differences, except for the polycrystalline ceramic bracket model ($p=0.034$), where the static frictional force value in dry conditions (3.2 ± 0.265) differed significantly from that in wet conditions (2.4 ± 0.264) (table 3).

For the experiment conducted with the 0.016" NiTi archwire, One-Way ANOVA (table 2) indicated significant differences ($p < 0.001$) between brackets, for both testing conditions. The Tukey HSD Post-Hoc Test revealed statistically significant differences in dry conditions (table 3) between stainless steel brackets (M1) and all ceramic brackets (M2-M4) and between polycrystalline ceramic brackets with (M2) and without (M3) stainless steel slot.

In respect of the experiment conducted in wet conditions (table 4) statistically significant differences were recorded between stainless steel brackets (M1) and the rest of the brackets (M2-M4), as well as between polycrystalline ceramic brackets (M3) and monocrystalline ceramic brackets (M4)/polycrystalline ceramic brackets with stainless steel slot (M2).

The results of the experiment carried out with the 0.019x0.025" SS archwire show that, similarly to the first experiment, stainless steel brackets generated the lowest static frictional force values, regardless of test conditions. On the other hand, *polycrystalline ceramic brackets* (M3)

Table 2
STATIC FRICTIONAL FORCE VALUES FOR THE EXPERIMENT USING THE 0.016" NiTi ARCHWIRE

Bracket type/Conditions	M1	M2	M3	M4	p*
Dry (Mean \pm SD)	1.8 \pm 0.264	4.3 \pm 0.557	3.2 \pm 0.265	3.8 \pm 0.1	<0.001
Wet (Mean \pm SD)	1.5 \pm 0.173	3.8 \pm 0.36	2.4 \pm 0.264	3.8 \pm 0.173	<0.001
p**	0.355	0.082	0.034	1.000	-

*One-Way ANOVA Test, ** Paired Samples T-Test, Bold= statistical significant differences

Table 3
TUKEY POST-HOC TEST FOR STATIC FRICTIONAL FORCES OBTAINED WITH THE 0.016" NiTi ARCHWIRE, IN DRY CONDITIONS

Models	M1 - M2	M1-M3	M1-M4	M2 - M3	M2 - M4	M3 - M4
p	0.001	0.004	0.001	0.017	0.337	0.212
	** p<0.01	** p<0.01	**p<0.01	*p<0.05	N.S.	N.S.

(N.S. = not statistically significant)

Table 4
TUKEY POST-HOC TEST FOR STATIC FRICTIONAL FORCES OBTAINED WITH THE 0.016" NiTi ARCHWIRE, IN WET CONDITIONS

Models	M1 - M2	M1-M3	M1-M4	M2 - M3	M2 - M4	M3 - M4
p	0.001	0.010	0.001	0.001	0.899	0.001
	** p<0.01	*p<0.05	**p<0.01	**p<0.01	NS	**p<0.01

(N.S. = not statistically significant)

Table 5
STATIC FRICTIONAL FORCE VALUES FOR THE EXPERIMENT USING THE 0.019X0.025" SS ARCHWIRE

Bracket type/Conditions	M1	M2	M3	M4	p*
Dry (Mean \pm SD)	3.7 \pm 0.265	4.3 \pm 0.200	9.9 \pm 0.306	9.8 \pm 0.173	<0.001
Wet (Mean \pm SD)	4 \pm 0.265	4.3 \pm 0.265	9.7 \pm 0.436	9.4 \pm 0.346	<0.001
p**	0.237	1	0.490	0.148	-

*One-Way ANOVA Test, ** Paired Samples T-Test, Bold= statistical significant differences

Table 6
TUKEY POST-HOC TEST FOR STATIC FRICTIONAL FORCES OBTAINED WITH THE 0.019X0.025" SS ARCHWIRE, IN DRY CONDITIONS

Models	M1 - M2	M1-M3	M1-M4	M2 - M3	M2 - M4	M3 - M4
<i>p</i>	0.062	0.001	0.001	0.001	0.001	0.899
	NS	** p<0.01	**p<0.01	**p<0.01	**p<0.01	NS

(N.S. = not statistically significant)

Table 7
TUKEY POST-HOC TEST FOR STATIC FRICTIONAL FORCES OBTAINED WITH THE 0.019X0.025" SS ARCHWIRE, IN WET CONDITIONS

Models	M1 - M2	M1-M3	M1-M4	M2 - M3	M2 - M4	M3 - M4
<i>p</i>	0.687	0.001	0.001	0.001	0.001	0.687
	NS	** p<0.01	**p<0.01	**p<0.01	**p<0.01	NS

(N.S. = not statistically significant)

were associated with the highest static frictional forces. Polycrystalline ceramic brackets with stainless steel slot (M2) produced static frictional forces lower than monocrytalline ceramic brackets (M4) (table 5). In the case of the rectangular archwire, the T-Test did not show any statistically significant differences between static frictional forces in wet versus dry conditions (table 5).

The One-Way ANOVA test (table 5) for the experiments conducted with the rectangular SS archwire established significant differences in static frictional force ($p < 0.001$). In both dry (table 6) and wet (table 7) conditions the Post-Hoc Tukey test indicated statistically significant differences between the following bracket couples: M1-M3, M1-M4, M2-M3 and M2-M4.

Regardless of the test conditions, stainless steel (M1) and polycrystalline ceramic brackets with stainless steel slot (M2) generated similar static frictional forces. Likewise, static frictional forces associated with monocrytalline ceramic brackets (M4) were comparable to those for polycrystalline ceramic brackets.

When comparing the two archwires used in this study, experiments in dry (fig. 6) and wet (fig. 7) conditions alike indicated higher static frictional forces for the rectangular 0.019x0.025" SS archwire.

The only exception was recorded for metal-insert polycrystalline ceramic brackets, for which the average values obtained in dry conditions were equal for both archwires. Results of the experiments indicate that introduction of the metal slot to the polycrystalline ceramic bracket effectively reduced static frictional forces, but only in case of the rectangular archwire (fig. 6,7).

Our study indicated that stainless steel brackets generated the lowest static frictional force, for both archwires used and independently of the test conditions. This is in accordance with the first working hypothesis and may be due to surface characteristics of the stainless steel bracket, which is smooth and facilitates sliding mechanics. These findings are consistent with other studies which compare ceramic and stainless steel brackets, the latter being considered the standard in terms of low frictional forces [15-17].

According to this study, for both archwires used, the static frictional forces generated by the *polycrystalline ceramic brackets with stainless steel slot* were higher than the ones generated by the stainless steel brackets. The same observation was made by Cacciafesta et al. [4], both for static and kinetic friction. Our research pointed out a reduction in frictional force for metal insert ceramic brackets in association with the rectangular archwire compared to all ceramic brackets. This result is in accordance to the second working hypothesis and partially agrees with data published by the above mentioned authors [4]. Although the insertion of a metal slot in the ceramic bracket aimed to combine the reduced frictional force generated by the stainless steel bracket with the aesthetics of ceramics, several studies showed higher frictional forces for the ceramic bracket with metal reinforced slot compared to the stainless steel type [9,10]. This difference could be due to the inaccurate fitting of the metal to the ceramic and to their different expansion coefficients [18].

Regarding the *ceramic brackets*, the results are different according to the type of the archwires used. If for the round 0.016" NiTi archwire the *monocrytalline ceramic brackets* created the greatest frictional force, for the rectangular archwire the *polycrystalline ceramic brackets* generated the most important frictional forces. With the exception of the study carried out with the 0.016" NiTi archwire in wet conditions, there were no statistically significant differences between the static frictional forces generated by *poly- and monocrytalline ceramic* brackets. This last aspect is in accordance with the third working hypothesis.

Results of studies concerning frictional forces generated by aesthetic brackets are heterogeneous. Most studies identify higher static frictional forces for

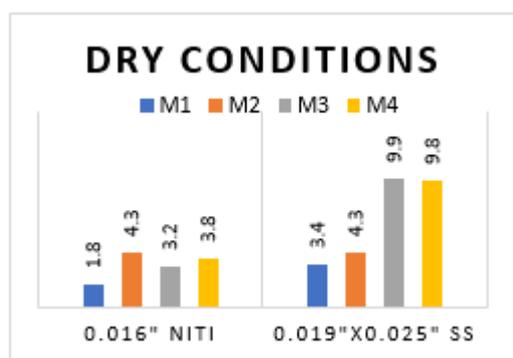


Fig. 6. Mean values of static frictional forces (N) for experiments conducted in dry conditions

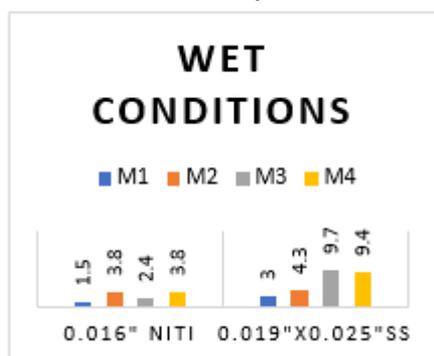


Fig. 7. Mean values of static frictional forces (N) for experiments conducted in wet conditions

monocrystalline ceramic brackets than polycrystalline ones [4,18-20], but there is also research reporting the opposite result [19,22]. Other studies did not find significant differences between the two types of ceramic brackets, both having similar surface roughness [9]. The inconsistency between studies may be attributed to the differences in methodology and materials used.

The results of our experiments are comparable to those found by Alsubaie et al. [5] in their study regarding the frictional force during the retraction of the upper canine. They recorded the lowest frictional values in the group of metal brackets, followed by the polycrystalline ceramic brackets and monocrystalline ceramic brackets, which exhibited the highest values.

Our studies indicate an increase in static frictional forces for the 0.019x0.025"SS archwire versus the 0.016" NiTi archwire. This finding confirms the fourth working hypothesis and is consistent with previous research conducted by Cacciafesta et al. [4] and Vinit Singh et al. [11], which observed that static and dynamic frictional forces are more important as the archwire diameter increases. However, it should be noted that the wires were different not only in size but also in their cross section and material. This suggests we should avoid making strong conclusions regarding the archwire diameter.

We noticed that, with one exception (the association of M3 and 0.016" archwire, $p = 0.034$), static frictional force values did not vary significantly between the two testing conditions (dry/wet).

This result is in contradiction with the fifth working hypothesis. Although some authors claim that wet conditions (saliva) reduce frictional forces [9], others [23,24] consider that saliva plays an insignificant role in orthodontic mechanics.

Conclusions

Within the limitations of this in vitro study we concluded that:

- Stainless steel brackets produce the lowest static frictional forces, regardless of the test conditions and orthodontic archwire type;
- Polycrystalline ceramic brackets with stainless steel slot generate higher static frictional forces than stainless steel brackets and lower than ceramic brackets, when combined with 0.019x0.025" SS rectangular archwire;
- Polycrystalline and monocrystalline ceramic brackets did not exhibit significant differences in terms of static frictional forces;
- Rectangular 0.019x0.025" SS archwire creates greater frictional forces compared to the round 0.016" wire;
- The association between polycrystalline brackets and rectangular archwire produces the highest frictional values, whereas stainless steel brackets coupled with round archwires produce the lowest static frictional resistance;

- Static frictional forces are not significantly influenced by the test conditions.

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