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List of Abbreviations

3D – 3-dimensional

SS – Stainless steel

NiTi – Nickel-titanium

θ_c – Critical contact angle

Ra – Roughness average

Rq – Root mean square

Rz – Mean peak to valley height of roughness profile

Θ – Contact angle

F – Frictional force

N – Normal component of applied load

μ - Coefficient of friction

Abstract

Objective: The purpose of this study is to compare, *in vitro,* the resistance to sliding generated by conventional, active self-ligating and passive self-ligating brackets with stainless steel and nickel-titanium wires and to evaluate the effect of binding upon resistance to sliding In addition to this, the influence of bracket´s slot surface characteristics on measured friction was estimated.

Materials and Methods: The following 0,022 inch slot brackets were essayed: Damon® Q™, Prodigy SL™ (Sybron Dental Specialties Ormco™, Orange, California, USA), Smart-Clip™SL3, Victory Series™ (3M Unitek Orthodontic Products, Monrovia, California, USA), Morelli® Roth Standard and Morelli® Roth SLI (Morelli Ortodontia, Sorocaba, São Paulo, Brazil). These brackets were coupled with either 0.016 x 0.022 inch stainless steel (Dentaurum GmbH, Ispringen, Germany) or nickel-titanium (DM Ceosa, Madrid, Spain) archwires. Alicona InfiniteFocus® optical 3-dimensional micro coordinate system (Alicona Imaging GmbH, Grambach/Graz, Austria) and Alicona IFM version 3.5.1.5 software (Alicona Imaging GmbH, Grambach/Graz, Austria) were used for assessing roughness average, root mean square and mean peak to valley height of roughness profile of slot surface. For Damon brackets, a slot profile analysis was executed in order to evaluate the contact areas between bracket and archwire

Results: Statistically significant higher resistance to sliding is observed in conventional brackets comparing to passive and active self-ligating brackets. No statistically significant differences were found between passive and active self-ligating brackets and between archwire materials in 0 degrees angulations. For 5 degrees angulations, stainless steel showed statistically significant higher resistance to sliding. No statistically significant differences in resistance to sliding were found between 0 and 5 degrees of bracket tipping. Higher values of roughness average and root mean square were correlated with friction forces lower than 3N while lower roughness values were associated with higher frictional forces. In Damon brackets, the embossed numbers in the slot are not likely to contact with the archwire since they are approximately 5.5µm lower than the lateral boxes.

Conclusion: Self-ligating brackets are helpful for obtaining low frictional forces. When coupled with a small rectangular archwire, slight bracket angulations or tooth tipping may not influence resistance to sliding. However, different alloys reveal dissimilar frictional behavior when angulations are present. Surface roughness seems to have an inverse correlation with frictional forces.

Key words: Friction; Bracket; Ligation; Binding; Surface roughness.

Introduction

Since the development of orthodontic fixed appliances, brackets design has undergone many modifications in order to improve treatment efficiency[1]. In the last decades, the popularity of self-ligating brackets has grown based on manufacturers claims of lower friction[2], faster ligation[2], less chair time[3], fewer appointments[2], shorter treatment time[2–4], increased comfort[3] and less pain[2]. Self-ligating brackets concept is not a novelty in orthodontics: in fact, many authors point Stolzenberg as the pioneer of self-ligation by the introduction of the “Russell attachment”, in 1935[2,3,5,6]. The term self-ligation in orthodontics implies that the bracket is able to engage itself to the archwire, by closing of the slot with a mechanical device[6], dispensing steel or elastomeric ligatures and then converting the slot into a tube, leading to the claimed primary advantage of reduced friction[7]. Self-ligating brackets can be divided in two categories, according to their mechanisms of closure: active self-ligating brackets, which have a spring clip that stores energy to press against the archwire for rotation and torque control; and passive self-ligating brackets which have a slide that can be closed and does not actively press against the wire[3,5,6].

Friction is the resistive force when one object moves tangentially to another and, therefore, opposes motion. Two types of friction are defined: static friction, which opposes any applied force and whose magnitude is exactly what it must be to prevent motion between two surfaces, up to the point at which it is overcome and movement starts; and kinetic friction which usually is less than static friction, then opposes the direction of motion of the object[8]. For practical purposes, static friction is more relevant than kinetic friction since arch-guided tooth movement consists of repeated movements of tipping and uprighting and continuous motion along an archwire rarely occurs[8].

William Proffit[1] stated that 50% of the applied force is lost to overcome friction leading to a potential delay or inhibition of tooth movement and anchorage loss due to the reactive force exerted on the molars. Therefore, the development of materials with low coefficient of friction is highly desirable since they can diminish the tension on anchorage[9].

Kusy and Whitley[10], divided resistance to sliding in three components: classical friction due to the contact between the arch and the walls of brackets slot, binding as a result of the contacts of the wire with the corners of the brackets caused by tooth tipping or flexion of the wire, and notching which take place when permanent deformation of the wire occurs at the wire-bracket corner interface.

The physical explanation of friction depends on the characteristics of the contacting areas and the force with which the surfaces are forced together[8]. Since slot and wire surfaces have asperities and, thus, are more or less irregular it is therefore accepted that friction increases with increased roughness of the wire and bracket surfaces[11]. 3-dimensional (3D) measurement of surfaces is an essential part in examination and controlling the properties and the function of materials[12]. Conventionally, 3D measurements have been performed by tactile devices even though they present many disadvantages, which can be overcame by optical measurement devices[12]. Among these devices, the new technology of focus variation exploits the small depth of focus of an optical system with vertical scanning to provide topographical and color information from the variation of focus[12].

The purpose of this study is to compare, *in vitro,* the resistance to sliding generated by conventional, active self-ligating and passive self-ligating brackets with stainless steel and nickel-titanium wires and to evaluate the effect of binding upon resistance to sliding In addition, the influence of bracket´s slot surface characteristics on measured friction was also estimated.

Material and Methods

Resistance to Sliding Tests

In this study, the following maxillary left cuspid brackets with 0,022 inch slots were essayed: Damon® Q™, Prodigy SL™ (Sybron Dental Specialties Ormco™, Orange, California, USA), Smart-Clip™SL3, Victory Series™ (3M Unitek Orthodontic Products, Monrovia, California, USA), Morelli® Roth Standard and Morelli® Roth SLI (Morelli Ortodontia, Sorocaba, São Paulo, Brazil). Used archwires were made of either 0.016 x 0.022 inch stainless steel (SS) (Dentaurum GmbH, Ispringen, Germany) or nickel-titanium (NiTi) (DM Ceosa, Madrid, Spain)

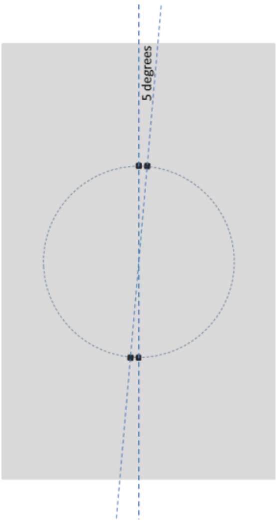


Image 1 - Illustrative diagram of the positioning holes drilled on testing apparatus.

For testing, a custom apparatus was designed and constructed. The apparatus allowed normalize the position of brackets, holding them in an appropriate position during the mechanical test. It consisted of a stainless steel base with a depth adjustable vertical plate in which four 0.022 x 0.028 inch holes were drilled, allowing simulating 5 degrees of tipping (image 1), thus creating binding of the archwire. Prior to testing, each bracket and archwire were cleaned with 70% ethanol and allowed to dry to keep them free of grease or dirt that could interfere with the results. Bracket placement was standardized by the insertion of an U-shaped stainless steel full-size 0.0215 x 0.028 inch archwire in the slots of the brackets, with elastomeric or self-ligation, with its ends fitted into holes in the plate, similarly to described by Pacheco *et al.*[13]. For each test, two brackets were bonded in the apparatus at a distance of 10mm: the upper bracket could be bonded with either 0 or 5 degrees of tipping and the lower one was parallel to the axis of the testing machine. Bracket bonding was performed using Vitrebond™ Plus light cure glass ionomer (3M ESPE™, Saint Paul, Minnesota, USA). The use of a full-size archwire in association with the glass ionomer layer effectively allowed to eliminate brackets prescription and ensured accurate and reproducible bracket placement for all specimens. After bracket bonding, the

Image 2 - Shimadzu AG-1 5kN testing instrument.

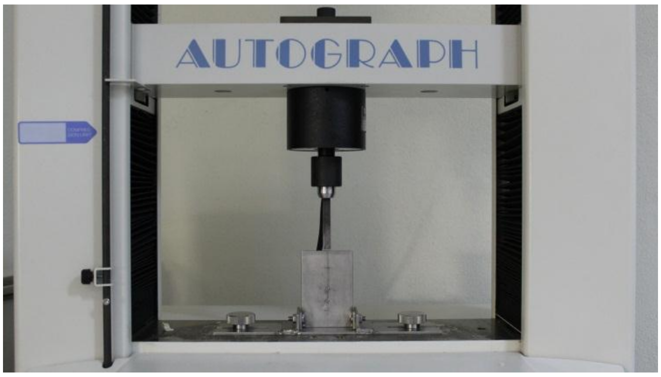


Image 3 - Testing machine with bracket-wire assembly.

positioning jig was removed and each archwire segment was fixed to a device which was connected to the load cell with glass ionomer cement. The conventional brackets were ligated with Dentalastics® Personal elastic modules (Dentaurum GmbH, Ispringen, Germany) in order to prevent individual differences in forces resulting from the ligature wires, and self-ligating slides or spring clips were closed.

Following preliminary testing to ensure the apparatus reliability, bracket-wire combinations were submitted to mechanical tests with the Shimadzu AG-1 5kN testing instrument (Shimadzu Corporation, Tokyo, Japan). Maximum registered resistance to sliding was measured throughout 5 mm translations of the archwire, at a crosshead speed of 10mm.min^{-1}. This crosshead speed was selected since Ireland *et al.*[14] found no significant differences between crosshead speeds ranging from 0.5 to 50mm.min^{-1}. Both bracket and archwire were changed after each 5 tests.

A separate series of 10 tests was carried out for each combination of bracket-SS archwire, without tipping and with elastomeric ligature to ensure a standardized ligation force. This test allowed evaluating whether there is a correlation between resistance to sliding and brackets surface roughness. Damon brackets did not allow such correlation because elastomeric ligation was impossible.

Bracket Width and Critical Contact Angle (θc) Determination

Kusy and Whitley[10] clarified that θ_c depend on archwire size (‘Size’), bracket slot size (‘Slot’) and bracket width (‘Width’). Considering those factors, these authors stated that it is possible to calculate the θ_c using the following equation:

$$\theta c = \frac{57{,}32\ \left[1 - \left(\frac{\text{Size}}{Slot}\right)\right]}{\left(\frac{Width}{Slot}\right)}$$

Accordingly, θ_c were calculated for all brackets used in this study, when coupled with 0.016 x 0.022 inch archwires. For this, mesio-distal bracket widths were measured by an analogic caliper (Kroeplin GmbH, Schlüchtern, Germany).

Table I - Combinations of brackets, tipping angulations and archwire materials tested in this study.

Bracket design	Name of bracket	Manufacturer	Tipping	Archwire size	Archwire material
Conventional ligature	Victory Series™	3M Unitek Orthodontic Products, Monrovia, California, USA	0 degrees	0.016 x 0.022-inch	Stainless steel (SS)
			5 degrees	0.016 x 0.022-inch	Stainless steel (SS)
			0 degrees	0.016 x 0.022-inch	Nickel-Titanium (NiTi)
			5 degrees	0.016 x 0.022-inch	Nickel-Titanium (NiTi)
	Morelli® Roth Standard	Morelli Ortodontia, Sorocaba, São Paulo, Brazil	0 degrees	0.016 x 0.022-inch	Stainless steel (SS)
			5 degrees	0.016 x 0.022-inch	Stainless steel (SS)
			0 degrees	0.016 x 0.022-inch	Nickel-Titanium (NiTi)
			5 degrees	0.016 x 0.022-inch	Nickel-Titanium (NiTi)
Self-ligating Passive type	Damon® Q™	Sybron Dental Specialties Ormco™, Orange, California, USA	0 degrees	0.016 x 0.022-inch	Stainless steel (SS)
			5 degrees	0.016 x 0.022-inch	Stainless steel (SS)
			0 degrees	0.016 x 0.022-inch	Nickel-Titanium (NiTi)
			5 degrees	0.016 x 0.022-inch	Nickel-Titanium (NiTi)
	Smart-Clip™SL3	3M Unitek Orthodontic Products, Monrovia, California, USA	0 degrees (elastomeric ligation)	0.016 x 0.022-inch	Stainless steel (SS)
			0 degrees	0.016 x 0.022-inch	Stainless steel (SS)
			5 degrees	0.016 x 0.022-inch	Stainless steel (SS)
			0 degrees	0.016 x 0.022-inch	Nickel-Titanium (NiTi)
			5 degrees	0.016 x 0.022-inch	Nickel-Titanium (NiTi)
Self-ligating Active type	Morelli® Roth SLI	Morelli Ortodontia, Sorocaba, São Paulo, Brazil	0 degrees (elastomeric ligation)	0.016 x 0.022-inch	Stainless steel (SS)
			0 degrees	0.016 x 0.022-inch	Stainless steel (SS)
			5 degrees	0.016 x 0.022-inch	Stainless steel (SS)
			0 degrees	0.016 x 0.022-inch	Nickel-Titanium (NiTi)
			5 degrees	0.016 x 0.022-inch	Nickel-Titanium (NiTi)
	Prodigy SL™	Sybron Dental Specialties Ormco™, Orange, California, USA	0 degrees (elastomeric ligation)	0.016 x 0.022-inch	Stainless steel (SS)
			0 degrees	0.016 x 0.022-inch	Stainless steel (SS)
			5 degrees	0.016 x 0.022-inch	Stainless steel (SS)
			0 degrees	0.016 x 0.022-inch	Nickel-Titanium (NiTi)
			5 degrees	0.016 x 0.022-inch	Nickel-Titanium (NiTi)

Surface Roughness Tests

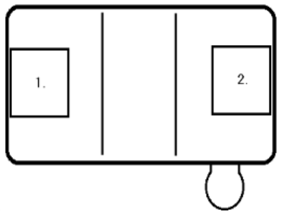


Image 4 – Selected areas for focus variation image acquisition and their relative position to the bracket.

Alicona InfiniteFocus® (Alicona Imaging GmbH, Grambach/Graz, Austria) is an optical 3D micro coordinate system for form and roughness measurement which applies the technology of focus variation. The instrument captures the spectral variation between overilluminated and under-illuminated surfaces, constructs a detailed three-dimensional model of a surface from a stack of images and incorporates software for high resolution three-dimensional analysis of the reconstructed surface calculating x, y, and z coordinates for any point within the resolution of the scan.

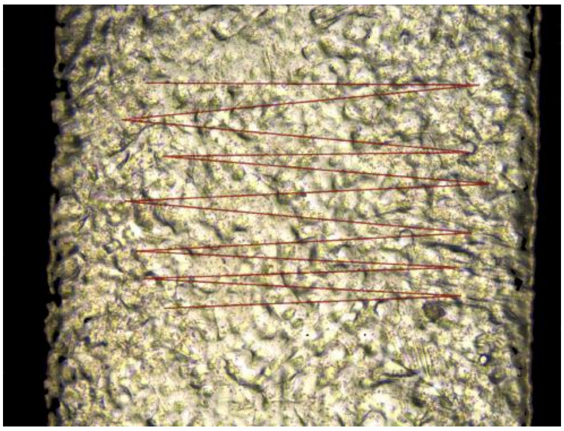


Image 5 – Example of random path traced for surface roughness analysis (20x magnification).

Bracket slot image acquisition was performed using a 20x lens in two lateral areas of potential contact between bracket and archwire, as represented in image 4. Acquired images were 712.53µm length and 540.54µm width. Measurement was archived by tracing a 5mm random path, as illustrated in image 5, which allows a random and trustworthy surface analysis.

Three parameters were selected to assess the amplitude properties of the slot surface: roughness average (Ra), root mean square (Rq) and mean peak to valley height of roughness profile (Rz). The parameters were calculated using Alicona IFM version 3.5.1.5 software (Alicona Imaging GmbH, Grambach/Graz, Austria).

For Damon bracket, a slot profile analysis was executed in order to evaluate the contact areas between bracket and archwire.

Statistical Analysis

All statistical analysis was performed using software Statistical Product and Service Solutions (SPSS®) version 20.0 (IBM®, Armonk, New York, USA).

As the Kolmogorov-Smirnov test confirmed non-normality of distribution, the Kruskal-Wallis test was performed in order to evaluate whether ligation method influences resistance to sliding. The Mann-Whitney *post-hoc* test was executed to assess the pairs of measuring methods that differed. The Mann-Whitney non-parametric test for independent samples was used to evaluate statistically significant differences between archwire material, considering tested angles, regarding resistance to sliding. The Student’s *t*-test for independent samples evaluated differences between tested angulations, independently of archwire material or bracket type. The same test was used to compare active and passive self-ligation brackets. A descriptive analysis was made for evaluating the correlation between surface roughness and friction.

Results

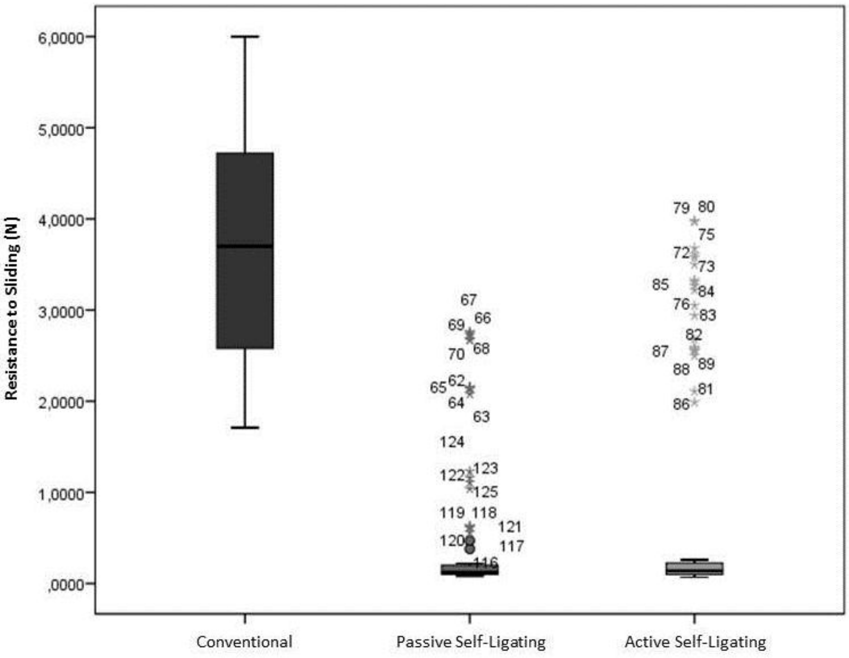
The statistics for friction tests in the studied groups are shown in table II.

Table II – Frictional forces recorded for each group of brackets according to archwire material and tipping angulation.

Archwire Material	Angulation	Conventional Brackets			Passive Self-Ligating Brackets			Active Self-Ligating Brackets		
		Mean (SD)	Minimum	Maximum	Mean (SD)	Minimum	Maximum	Mean (SD)	Minimum	Maximum
SS	0 degrees	3.85 (1.46)	2.19	6.00	0.10 (0.02)	0.08	0.14	0.11 (0.03)	0.07	0.17
	0 degrees†				2.42 (0.31)	2.08	2.76	3.05 (0.59)	1.99	3.98
	5 degrees	3.20 (1.01)	1.71	5.15	0.47 (0.39)	0.08	1.23	0.18 (0.05)	0.10	0.24
NiTi	0 degrees	4.24 (0.87)	2.83	5.28	0.11 (0.02)	0.08	0.15	0.13 (0.05)	0.08	0.26
	5 degrees	3.38 (0.90)	2.03	4.70	0.14 (0.03)	0.10	0.20	0.11 (0.02)	0.07	0.15

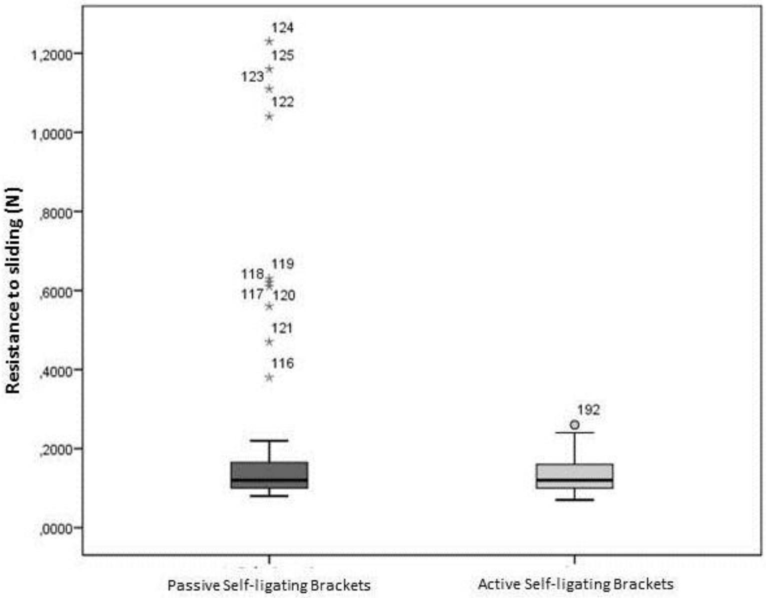
† elastomeric ligation

Taking together all data, statistically significant differences (χ(2)=161.283, p<0.001) are observed in resistance to sliding for all ligation methods. By multiple comparisons, statistically significant higher resistance to sliding is observed in conventional brackets comparing to passive self-ligating brackets (U=184.500; Z=-11.406; p<0.001). Likewise, statistically significant higher resistance to sliding was recorded in conventional brackets compared to active self-ligating brackets (U=724.500; Z=-10.449; p<0.001). No statistically significant differences were shown between active and passive self-ligating brackets. The box and whiskers plot (graphic 1) shows the distribution of resistance to sliding in tested samples.



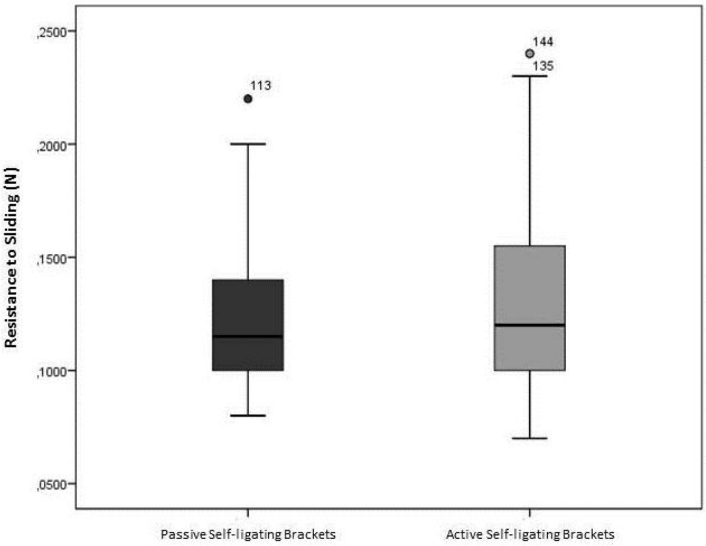
Graphic 1 – Box and whiskers plot showing the distribution of resistance to sliding registered values in conventional, passive self-ligating and active self-ligating brackets groups.

Statistically significant higher resistance to sliding (t(84.863)=2.565; p=0.012) was observed in passive self-ligating brackets comparing to active type. The graphic below (graphic 2) shoes the distribution of resistance to sliding values, according to self-ligation type.



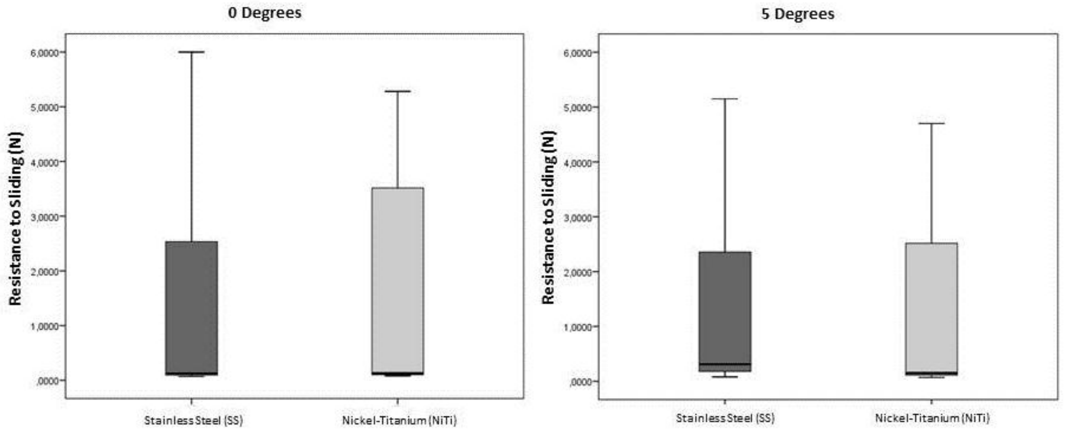
Graphic 2 - Box and whiskers plot showing the distribution of resistance to sliding registered values in passive and active self-ligating brackets groups, excluding elastomeric ligation tests.

When outlier values above 0.25N are excluded, no statistically significant differences (t(142.646)=-1.366; p=0.174) are found in resistance to sliding between passive and active self-ligating brackets. The box and whiskers plot below (graphic 3) shows the distribution of resistance to sliding in tested samples, depending on self-ligating bracket types, after outlier values exclusion.



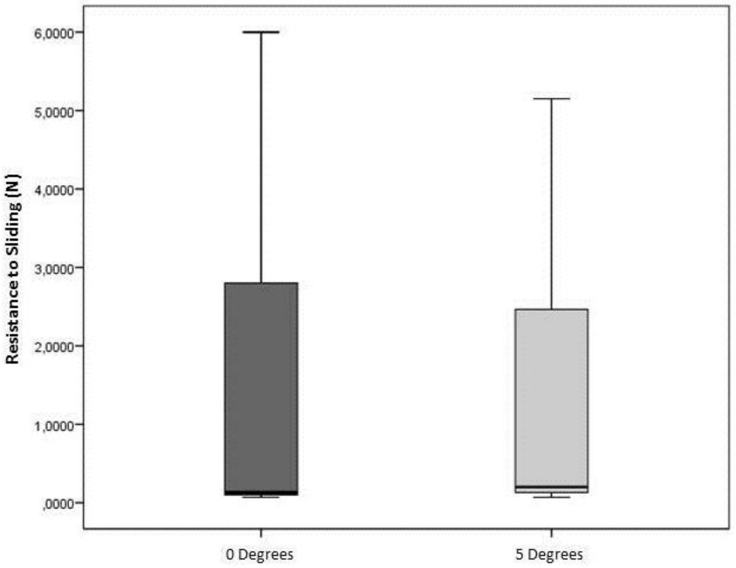
Graphic 3 - Box and whiskers plot showing the distribution of resistance to sliding registered values in passive and active self-ligating brackets groups, excluding elastomeric ligation tests (ouliers above 0,25N were excluded).

No statistically significant differences (U=1683.00; Z=-0.616; p=0.538) were found between archwire materials in 0 degrees angulations. For 5 degrees angulations, SS showed statistically significant (U=1250.00; Z=-2.889; p=0.004) higher resistance to sliding. The box and whiskers plot below (graphic 4) shows the distribution of resistance to sliding in tested samples, depending on testing angulations.



Graphic 4 - Box and whiskers plot showing the distribution of resistance to sliding registered values for SS and NiTi archwire alloys, with 0 or 5 degrees of simulated tipping.

No statistically significant differences (t(225.39)=0.779; p=0.437) in resistance to sliding were found between 0 and 5 degrees of bracket tipping, independently of bracket type and archwire material. The graphic below (graphic 5) shows the distributions of resistance to sliding values, according to bracket angulation.



Graphic 5 - Box and whiskers plot showing the distribution of resistance to sliding registered values for 0 and 5 degrees of tipping.

Critical contact angles (θ_c) for each bracket when coupled with 0.016 x 0.022 archwires are shown in table III.

Table III - Critical contact angles (θc) for tested brackets.

Bracket	Width (mm)	Size (mm)†	Slot (mm)*	Critical Angle (θ_c)
Victory Series™	3,27	0,41	0,56	2,63º
Morelli® Roth Standard	2,8	0,41	0,56	3,07º
Damon® Q™	2,81	0,41	0,56	3,06º
Smart-Clip™SL3	3,49	0,41	0,56	2,46º
Morelli® Roth SLI	3,1	0,41	0,56	2,77º
Prodigy SL™	2,8	0,41	0,56	3,07º

† Archwire size - 0.016 inch ≈ 0,41 mm

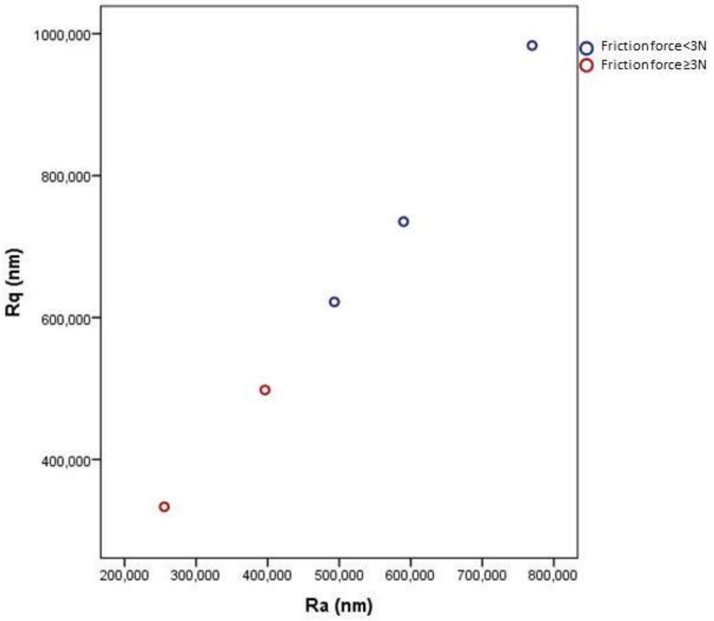
* Slot size - 0.022 inch ≈ 0,56 mm

Table IV shows the results of surface roughness tests. 3D focus variation images and roughness measurement graphics for each bracket are shown in images 7 to 12.

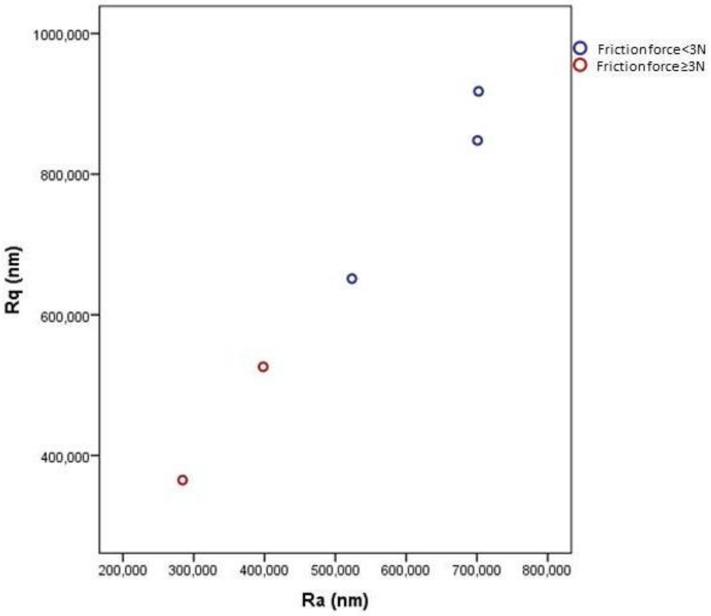
Table IV - Roughness average (Ra), root mean square (Rq) and mean peak to valley height of roughness profile (Rz) of each tested bracket, for both area 1 and 2.

	Area 1			Area 2		
Sample	Ra (nm)	Rq (nm)	Rz (µm)	Ra (nm)	Rq (nm)	Rz (µm)
Victory Series™	396.32	497,93	2,7152	398.04	526,09	3,2134
Morelli® Roth Standard	493.2	621,99	3,275	523.42	651,43	3,3342
Damon® Q™	769.64	983,28	5,4567	702.29	917,73	5,2991
Smart-Clip™SL3	698.88	939,22	5,6267	755.39	957,01	4,8894
Morelli® Roth SLI	255.54	333,28	1,9546	284.22	365,07	1,9089
Prodigy SL™	589.99	735,19	3,3024	700.82	847,87	3,6356

The following scatter plots (graphic 6 and 7) illustrate the descriptive analysis for the correlation between surface roughness and frictional forces for area 1 and 2, respectively.



Graphic 6 - Descriptive analysis for the correlation between surface roughness and frictional forces, for area 1.



Graphic 7 - Descriptive analysis for the correlation between surface roughness and frictional forces, for area 2.

As indicated in the scatter plots above, for both area 1 and 2, higher values of Ra and Rq are correlated with friction forces lower than 3N. Lower roughness values are associated with higher frictional forces. In addition, a direct correlation is observed between Ra and Rq values.

Damon bracket slot profile analysis revealed that contact between bracket and archwire occurs merely in the lateral boxes. As represented in image 6B, 6C and 6D, differences in z axis position (∆z) between red and green lines were calculated in each profile graphic, in the target area in A: for profile graphic B, ∆z=12.404µm is observed; in profile graphic C, ∆z=14.821µm is recorded; in profile graphic D, ∆z=21.753µm. Therefore it can be concluded that the embossed numbers are not likely to contact with archwire since they are approximately 5.5µm lower than the lateral boxes.

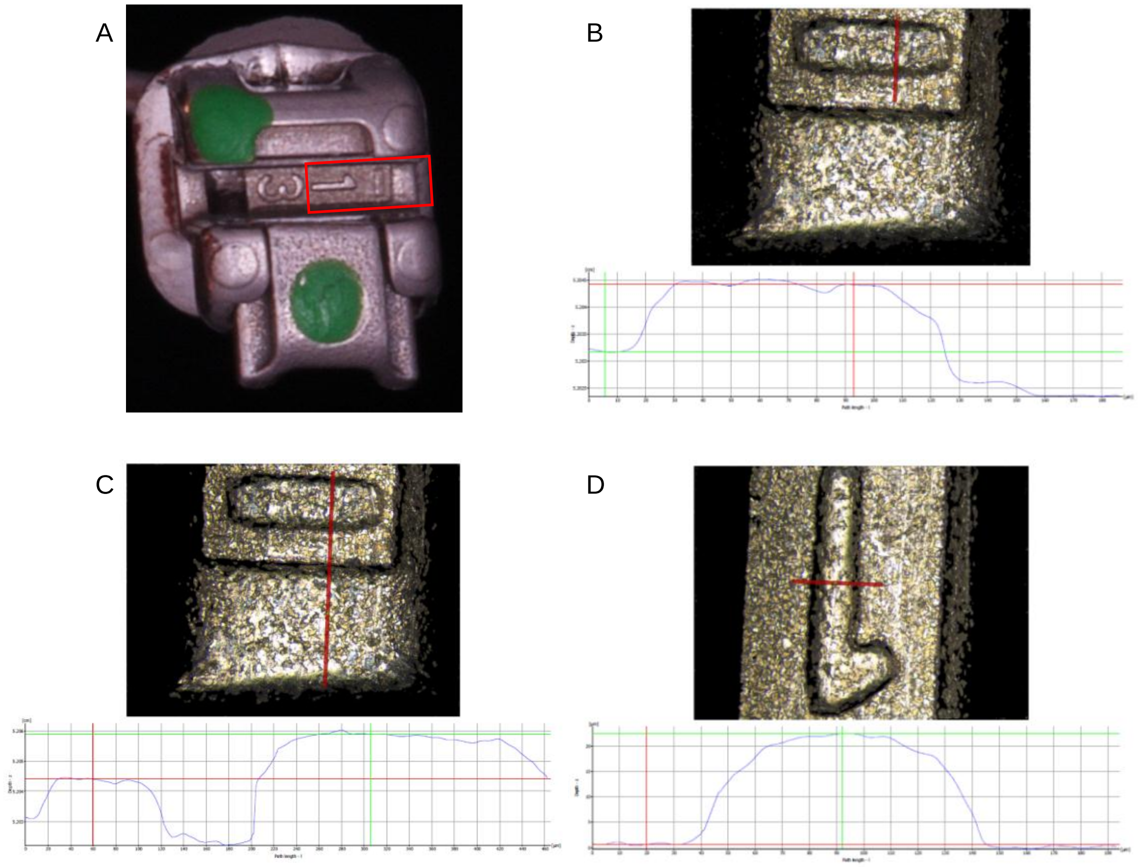


Image 6 - Slot morphology (A) and 3D focus variation images and profile analysis of the target area of Damon® Q™ bracket (B, C and D) (20x magnification).

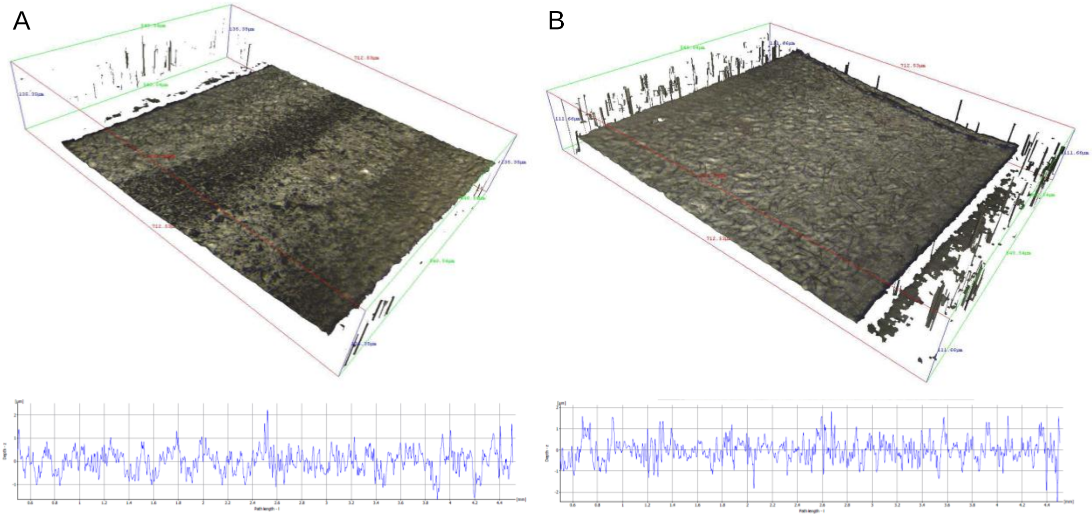


Image 7- 3D focus variation images and roughness measurement graphic of Victory Series™ brackets slot surface of both areas 1 (A) and 2 (B) (20x magnification).

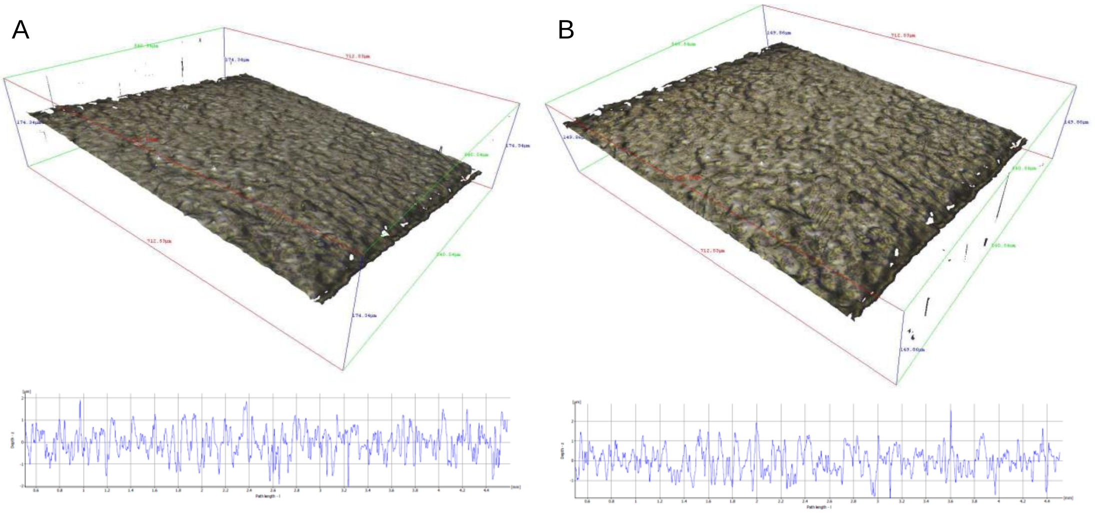


Image 8 - 3D focus variation images and roughness measurement graphic of Morelli® Roth Standard brackets slot surface of both areas 1 (A) and 2 (B) (20x magnification).

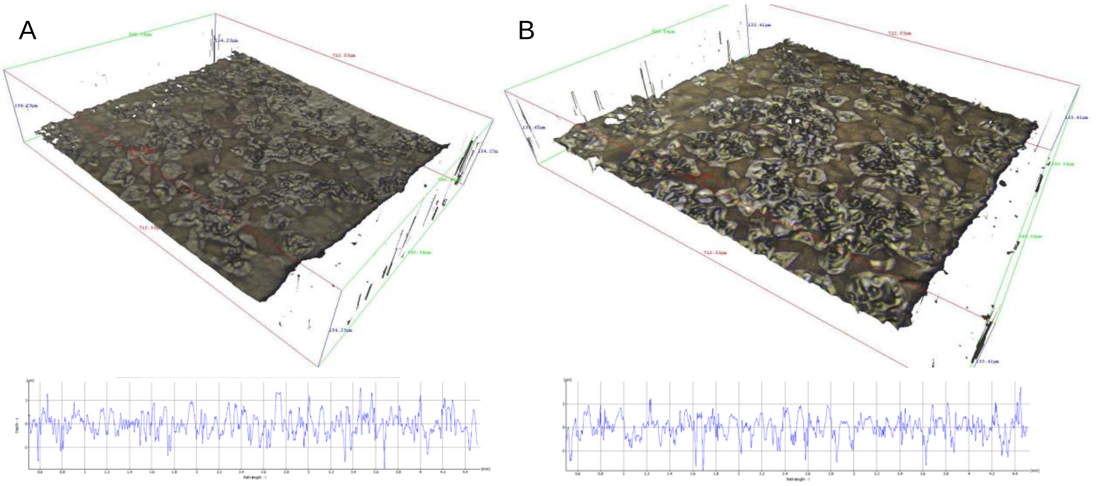


Image 9 - 3D focus variation images and roughness measurement graphic of Smart-Clip™SL3 brackets slot surface of both areas 1 (A) and 2 (B) (20x magnification).

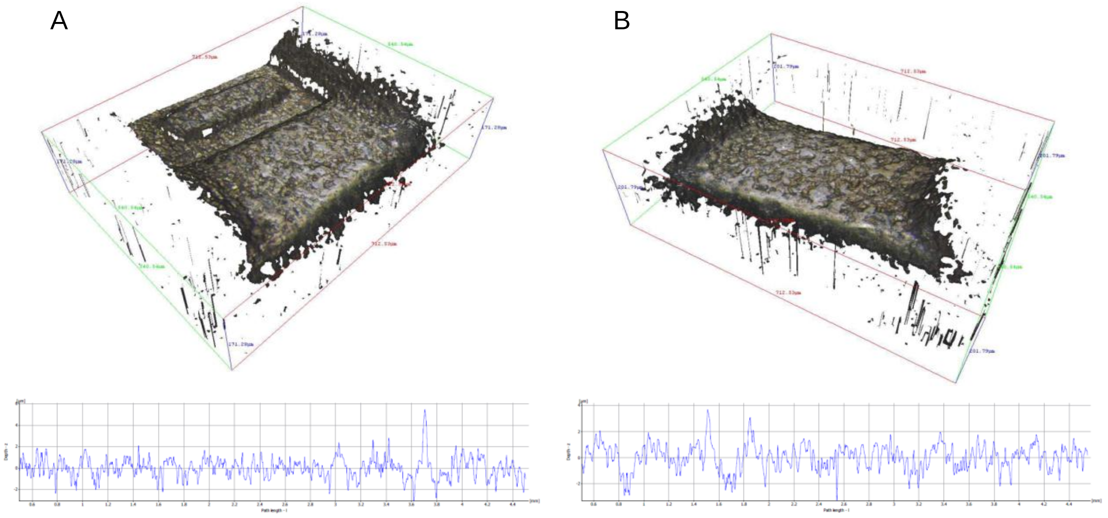


Image 10 - 3D focus variation images and roughness measurement graphic of Damon® Q™ brackets slot surface of both areas 1 (A) and 2 (B) (20x magnification).

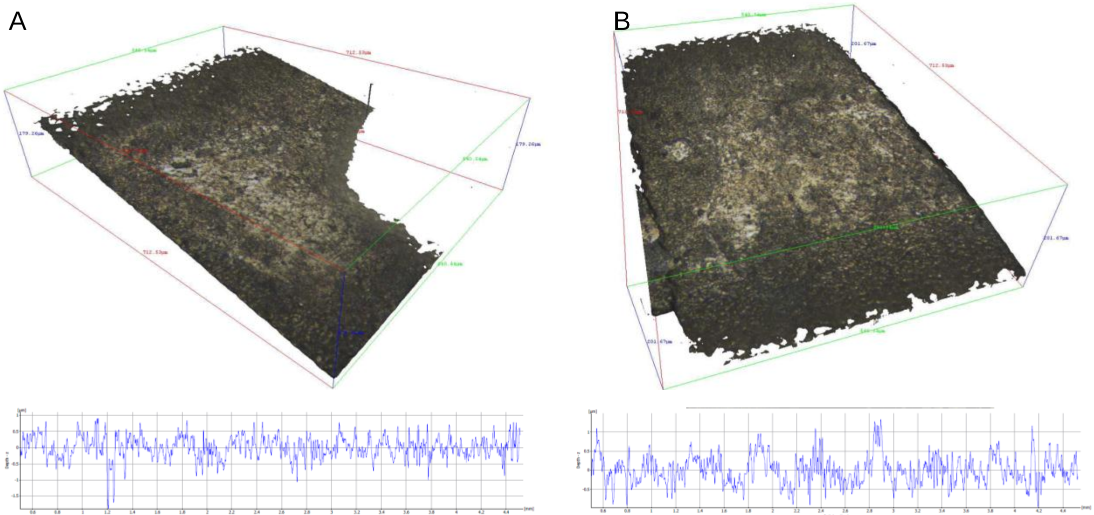


Image 11 - 3D focus variation images and roughness measurement graphic of Prodigy SL™ brackets slot surface of both areas 1 (A) and 2 (B) (20x magnification).

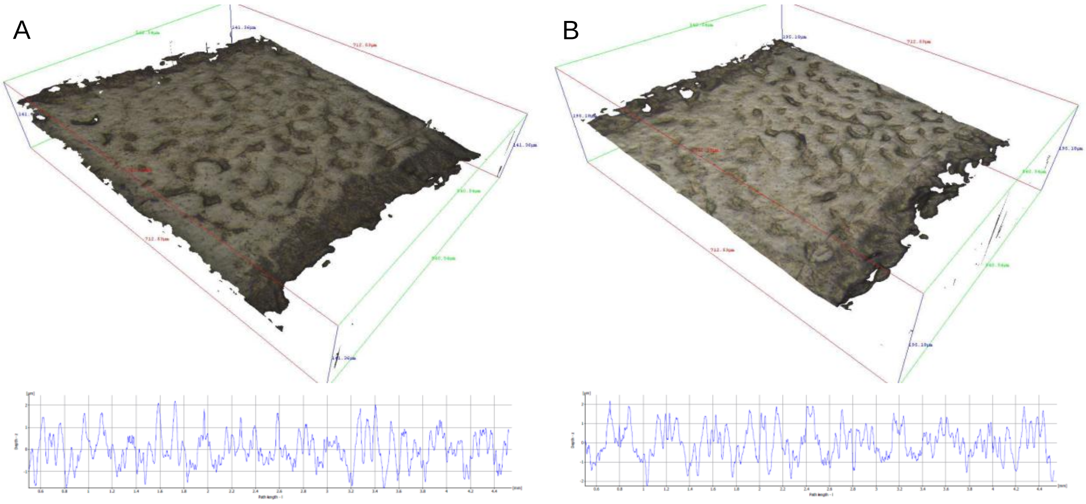


Image 12 - 3D focus variation images and roughness measurement graphic of Morelli® Roth SLI brackets slot surface of both areas 1 (A) and 2 (B) (20x magnification).

Discussion

Considering that canine teeth are frequently involved in sliding mechanics for pre-molar extraction spaces closure this research was focused on maxillary left cuspid brackets. A second bracket was bonded in the test plate to assure that binding was created in both corners of the upper bracket. A standardized ligation method was required in order to allow a correlation between surface roughness and resistance to sliding, since the force applied by self-ligating slides or spring clips is disparate, and that which is applied through stainless steel ligature differ among clinicians and among ligations. Although elastomeric ligature loses elasticity in time and can alter the frictional force values, as well as different stretching due to dissimilar bracket mesio-distal width may lead to slightly different ligation forces, it was assumed that the force delivered by each elastomeric ligature was similar and standardized for each manufacturer lot.

During the length of each run, dissimilarities in the magnitude of registered forces necessary to overcome friction were observed. Those variations are probably a consequence of different surface roughness or archwire characteristics or of third-order angulations that could exist in archwire which could not be avoided by the applied protocol. Besides, low measured forces due to an almost passive configuration of 0.016 x 0.022 inch archwire in all self-ligating brackets are easily biased by factors mentioned above. Those oscillations in measured forces hampered the interpretation of force graphics, preventing to obtaining a “classical” friction force pattern, in which static friction is higher than kinetic friction. In order to overcome this limitation, only maximum resistance to sliding forces were considered in this study.

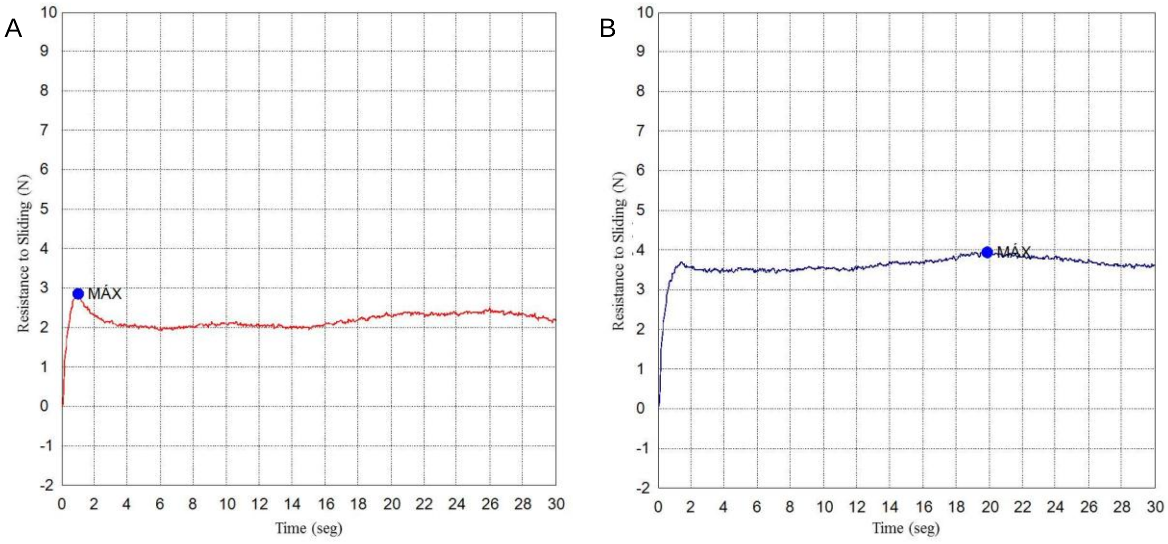


Image 13 – Representative images of the obtained resistance to sliding test graphics. In A, a “classical” friction force pattern is represented, in which static friction is higher than kinetic friction. In B, an altered graphic due to an oscillation is shown.

Classically, self-ligating brackets are classified, accordingly to their system of ligation, into passive or active, whether a spring clip presses the archwire against the slot walls. However, the term “passive” is erroneous since brackets passivity is only attained when teeth are ideally aligned in 3-dimensions and an undersized wire would not touch the walls of the bracket slot[3]. Therefore, clinically, it is almost impossible to attain complete bracket passivity because first, second or third order angulations are commonly present, leading to binding or notching, with the resultant increase of resistance to sliding.

It is generally accepted that conventional brackets offer greater resistance to motion than self-ligating brackets. Such evidence is supported by several studies which compared resistance to sliding between different designs of brackets. Shivapuja *et al.*[15] affirmed that a decrease of both static and dynamic frictional resistance is observed with self-ligating brackets, comparing to conventional brackets. Huang *et al*.[16] compared the static and kinetic frictional forces created by different designs of self-ligating brackets and concluded that passive design was associated with lower friction force than that of active or conventional brackets. Reicheneder *et al.*[17], evaluating frictional properties of aesthetic brackets, also concluded that self-ligation aesthetic brackets showed significantly lower friction than conventionally ligated ones. Our results confirm, as well, that conventional brackets showed higher values of resistance to sliding than self-ligating brackets.

Pizzoni *et al.*[18] concluded that Damon passive self-ligating brackets resulted in less friction than active Speed self-ligating brackets, when coupled with rectangular wires. Also Pacheco *et al.*[13] compared the static friction force delivered by passive and active self-ligating brackets when coupled with 0.018 inch SS and 0.017 x 0.025 inch SS archwires and concluded that self-ligating brackets showed a significant reduction in friction with round 0.018 inch archwires. Nevertheless, when coupled with rectangular archwires, active self-ligation brackets showed significantly higher friction than passive type, which presents similar results to conventional brackets. Our results are dissimilar to these conclusions: no statistically significant differences in resistance to sliding were observed between passive and active configurations when outlier values above 0.25N are excluded. The decision to their exclusion was based on the presupposition that they were the result of above-mentioned variations in the magnitude of registered forces necessary to overcome friction, due to uncontrollable variables. The absence of differences between active and passive types of self-ligation brackets might be due to the small dimensions of coupled archwire, which allowed a “free-play” passivity state in active brackets. Consequently, the lack of contact with slot walls or spring clips leads to a reduction of the resistance to motion due to absence of normal force. It is therefore plausible that coupling these brackets with larger archwires will lead to an increase of measured forces, especially in the active type.

As aforementioned, resistance to sliding (RS) can be divided in three major constituents: classical friction (FR), binding (BI) and notching (NO). Applying these components, three stages can be considered in the active phase of tooth movement and contribution of each of those components can be better understood[8,10]:

1. In the early stage of sliding mechanics, the tooth tips and contact between the archwire and bracket's corner is established. Hence, RS is the result of both FR and BI (RS=FR + BI).
2. As the contact angle between bracket and wire increases, BI increasingly restricts sliding becoming the most important source of RS (RS=BI).
3. NO of the wire occurs with the increase of the contact angle. As consequence, sliding is impossible (RS=NO).

Some previous studies evaluated the effect of bracket tipping in frictional forces. Moore *et al.*[19] measured the effects of different angles of tip and torque on static and kinetic friction when brackets were translated along 0.019 x 0.025 inch and 0.021 x 0.025 inch SS archwires. In this investigation, tip was varied from 1 to 3 degrees and torque was introduced in 2 degrees increments, from 2 to 6 degrees. The investigators concluded that small amounts of bracket tip produce rapidly increasing friction, probably due to the effects of binding between the bracket and the archwire and that friction doubled with every degree of bracket tipping. On the other hand, torque generally produced proportionately less friction than tip. Likewise, Hamdan and Rock[20] evaluated the effects of various combinations of tip and torque on the static friction between 0.019 x 0.025 inch SS archwires and 0.022 x 0.026 inch slot brackets. They concluded that every 4 degree increase in tip produced a significant increase in sliding resistance, which was predictable since critical contact angle (θ_c) was only 1 degree of tip.

As indicated, binding is considered the most important factor restricting sliding. This phenomenon is observed in the active configuration when contact angle (θ) between archwire and bracket slot is higher than critical contact angle (θ_c) in which contact between archwire and corners of the bracket occurs. In the first stage of tooth movement, when θ just equals or slightly exceeds θ_c (i.e. $\theta \geq \theta_c$), both classical friction and binding contribute to resistance to sliding. However, when θ is considerably greater than θ_c ($\theta > \theta_c$), binding becomes the main source of sliding resistance and classical friction turns out to be a negligible issue. As mentioned before, Kusy and Whitley[10] clarified that this active configuration depends on three factors: archwire size, bracket slot size and bracket width. These authors considered those factors and, theoretically, determined a practical equation to calculate the θ_c beyond which binding will increasingly obstruct sliding mechanics, which was applied in this investigation. Analyzing the results shown in table III, it is clear that θ_c values in this sample are lower than 5 degrees of tipping simulated by the protocol.

From our results, no differences were observed in resistance to sliding between 0 and 5 degrees of bracket tipping, which is not in agreement with previous studies[19,20]. However, unlike these studies, only 0.016 x 0.022 inch archwires were used for testing, instead of 0.019 x 0.025 inch. As consequence, θ_c values are higher than in those tests, being approximately 3 degrees in all tested brackets, which comes close to the 5 degrees of simulated tipping used in this protocol. Such a slight difference between θ_c and θ values might explain the absence of differences between tested angulations.

In the present study, no differences were observed in resistance to sliding between SS and NiTi archwires for 0 degrees of angulation, which is in disagreement with most previous studies: Drescher *et al.*[21] stated that wire material is the decisive factor in affecting frictional involvement and that NiTi alloys develop more frictional forces than SS. Nishio *et al.*[22] claimed that SS archwires have the lowest frictional forces values followed by NiTi. Kapila *et al.*[23] also found greater magnitude of these forces with NiTi wires than with SS wires. Vaughan *et al.*[24] found overall higher friction forces with NiTi wire alloys than with SS. Nevertheless, when analyzing the results of this experiment it is clear that for 0.022 slot Mini-Taurus bracket (one of the two 0.022 slot brackets studied) lower frictional forces were observed with 0.016 x 0.022 NiTi than SS archwires. Dissimilar results of the present investigation might be explained, in part, by the small size of tested archwire as well as the relative absence of ligation force of such undersized archwires, in self-ligating brackets. The discrepancy between archwire and bracket slot size and the absence of ligation force in self-ligating brackets lead to “free-play” and a consequent nearly lack of contact between archwire and bracket slot, therefore not allowing expressing dissimilar frictional properties of both alloys. Similar results were obtained by Tecco *et al.*[25] concluding that no statistical significant differences between SS and NiTi archwires were observed in terms of friction. Statistically significant higher resistance to sliding was observed in SS archwire for 5 degrees of angulation: this outcome might be an effect of wire stiffness: more rigid SS wires can cause higher resistance to sliding because the absence of flexibility can generate sharper angles and increase movement resistance. Kusy and Whitley[26] also concluded that wire stiffness have profound influences on binding and that stiffer wires have a greater difficulty negotiating greater angulation than do less stiff wires. Pizzoni *et al.*[18] also confirmed the importance of wire stiffness as a factor affecting resistance to sliding. Their experiment corroborate the theory that stiffer wires exhibit increased friction in all angulations probably due to the normal force, which increases at the contact point.

Although the first law of friction (F=µ x N) states that the frictional force (F) is proportional to the normal component of applied load (N) by the coefficient of friction (µ), which is depends on the material's relative roughness, this knowledge is not widely accepted in physics. In fact, laws of friction are merely phenomenological, based on Da Vinci and Coulomb experiments, and not physical fundamental laws. Moreover, this law does not consider the potential influence of contact area. Hence, some experimental results often contradict these laws: when assessing friction in orthodontics, it is likely that contact area interferes with the frictional force level. Indeed, larger brackets or wider arches could offer more contact area between bracket and wire, thus increasing the frictional force. This judgment is supported by some authors[21,22,27] and by the results of several investigations which concluded that friction intensifies with the increase of archwire diameter[17,19,21,23,24,28]. When analyzing brackets slot, it is clear that many differences exist between them. Contact area is very dissimilar as well as surface macro topography: while Morelli Standard brackets have a completely flat slot, those of Victory Series have a nearly straight slot with a slight depression in the middle. In contrast, Prodigy SL and Morelli SLI brackets have two lateral small preeminent blocks in which contact with archwire are attained. Smart-Clip brackets, notwithstanding an almost plane slot surface similar to Victory brackets, show a design different than other passive self-ligating brackets. The structure design of these brackets contains two lateral clips to hold the archwire which may contact the wire, increasing friction. In addition, Huang *et al.*[16] affirmed that those clips may create binding in archwire as the sliding occurs. Damon Q brackets, additionally to lateral prominences, have engraved on slot's base an embossed numeration which indicates corresponding tooth. If in contact with archwire, these embossed numbers could increase resistance to sliding between archwire and bracket since it can act as sharpen edge, which would be likely to increase friction. In order to evaluate if these areas could contact the archwire, a profile analysis was performed in Damon bracket images, acquired for roughness analysis (image 6). By profile analysis it was concluded that contact in these embossed numbers is not expected to happen since they are approximately 5.5µm lower than the lateral boxes. As no agreement exists, further investigations are recommended in order to evaluate whether contact area influences friction forces.

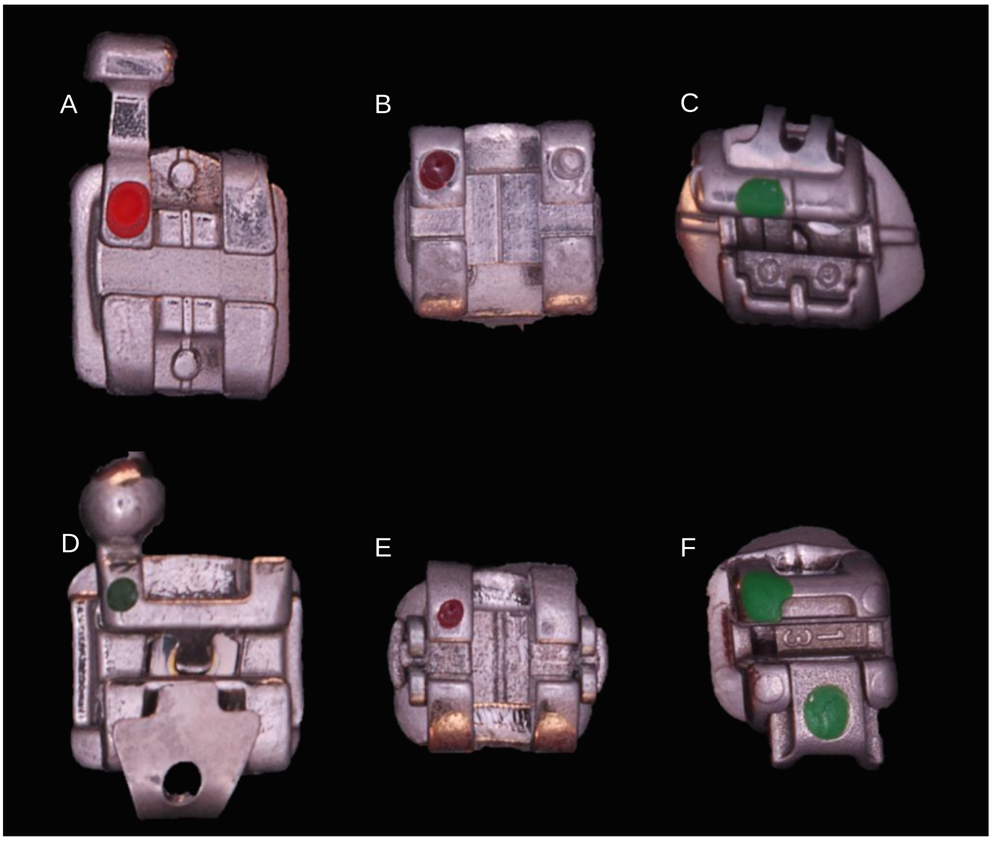


Image 14- Slot morphology of the studied brackets: Morelli® Roth Standard (A), Victory Series™ (B), Prodigy SL™ (C), Morelli® Roth SLI (D), Smart-Clip™SL3 (E) and Damon® Q™ (F).

Many investigations tried to assess the effect of wire roughness in frictional resistance but only few have been performed with the purpose of evaluating the relationship between surface roughness and the amount of frictional resistance between bracket and wire. Omana *et al.*[29] evaluated bracket slot end surfaces by scanning electron micrographs and concluded that smoothness alone cannot account for differences in bracket friction. Oppositely, Doshi *et al.*[30] evaluated this correlation of ceramic, ceramic with gold-palladium slot and stainless steel brackets and concluded that bracket slot roughness and frictional resistance showed a positive association. As slot roughness increased from ceramic with gold to SS to ceramic bracket, frictional resistance also increased. These authors also stated that no relationship was observed between wire roughness and frictional resistance. From the results of our investigation, it seems that a negative correlation exists between bracket slot roughness and friction forces. It is possible to describe a behavior pattern since rougher surfaces appeared to develop lower friction forces. Nevertheless, when considering first law of friction ($F=\mu \times N$) it is essential to take in account that surface roughness is not the only issue to influence μ. This coefficient is better categorized as a "system property" as it depends on the characteristics of both material in contact and many other variables such as wire and bracket material, temperature and velocity, which have a proven influence. As the results of the investigations concerning this topic are very dissimilar and inconsistent, further research is desirable.

Usually, 3D measurements have been executed merely by tactile devices which typically operate with a stylus tip, which is traced along a profile over the specimen surface in order to deliver roughness parameters[12]. However, these devices have some disadvantages comparing to optical instruments: firstly, measurement is much slower with tactile devices than with optical ones[12]; secondly, as they operate in a contact way damage to the surface usually occurs[12]. In addition to this, as the contact with the surface is generally attained by a stylus tip, frequently a synthetic ruby ball, a “smoothing effect” of surface profiles is observed due to the ball radius[12]. In contrast to other optical techniques, two issues should be especially addressed: first, the technology of focus variation is not limited to coaxial illumination or other special illumination techniques, which allows overcoming some limitations regarding the maximum measurable slope angle and secondly, the technology delivers true color information for each measurement point[12].

Limitations of this Study

Some wariness should be taken when analyzing the results of this study: first, an *in vitro* study cannot simulate biologic responses and the laboratory setup do not represent the clinical situation[3]. Some other factors can influence frictional resistance such as wire cross-section and dimension[31], bracket and slot width[21,23], bracket composition[22], interbracket distance[26,32] and some intraoral variables such as saliva or wet condition[26,28,32] and plaque and debris accumulation[33,34]. Corrosion, occlusion, bone density and root surface area were also not evaluated in this study, even though their influence in frictional force is stated to be possible[22]. The role of those factors in resistance to sliding might be more important that ligation system, therefore evidence about these parameters should also be analyzed and further research shall be done. Second, preformed arches used in orthodontic treatment are different from those used in this study, since all tests were performed with straight wires. As a consequence, different forces and mechanical loading at the bracket-archwire interface is created, affecting the frictional resistance. Third, the selected rate of movement (10mm.min^{-1}) is much faster than occurs clinically, and cannot take into account tooth movement due to alveolar remodeling that can occur clinically before the archwire slides through the bracket[3]. In addition to this, the effect masticatory forces and oral function, which play an important role in notching releasing[8], and thus, in orthodontic movement, cannot be evaluated in an in *vitro study.* Vibration stimulation used by some authors as a simulation of occlusal and masticatory forces is stated to lack validity[3,7]. Once evaluating the effects of roughness in friction forces, some caution is advised. In fact, as aforementioned, many other variables which are not evaluated in this investigation may influence µ and F. Moreover, the selection of elastomeric modules to standardize ligation is debatable since diverse mesio-distal widths of brackets lead to dissimilar stretching of elastomeric ligatures, which may vary ligation force, therefore biasing the results.

Some difficulties come upon the interpretation and comparison of different studies: in fact, the lack of a standardized and globally accepted protocol to assess resistance to sliding and friction makes their results incomparable, therefore being an obstacle for sustained scientific evidence about this issue.

Self-Ligating Brackets: Clinical State of the Art

In the last years, many studies were performed in order to evaluate the effect of different brackets designs in tooth movement rates by sliding mechanics. Alper Oz *et al.*[35] used a split-mouth design for bracket bonding, skeletal anchorage with mini-implant screws and closed-coil springs for canine retraction along a 0.019 x 0.025 inch SS arch wire with Smart-Clip self-ligating and Mini Uni-Twin conventional brackets. No statistical differences were found in the rate of canine distalization and angular changes between these brackets. Mezomo *et al.*[36] performed a split-mouth randomized clinical trial and used elastomeric chain for retraction of canines, without additional anchorage for posterior teeth. Better rotational control during distal movement of canines with self-ligating brackets was found, however, no differences were observed in the amount of total movement, rate of movement or anchorage loss between groups. Miles[37], in a split-mouth randomized clinical trial, compared the rates of space closure between conventional twin brackets ligated with SS ligatures and passive self-ligating Smart-Clip brackets. The authors reported median calculated rates of movement of 1.1mm per month for Smart-Clip and 1.2mm per month for conventional twin brackets, which is not a statistically significant difference. Conflicting results were found by Burrow[38]: this author measured the rate of canine retraction with retraction springs down a 0.018-inch SS wire, with Damon3, Smart-Clip and conventional Victory Series brackets. He found that the average movement per 28 days was 0,27 mm faster with the conventional brackets than with Damon bracket, a statistically significant difference. Likewise, this movement was 0.07 mm faster with conventional bracket than with the Smart-Clip bracket, also statistically significant. Burrow advocates that canine retraction by sliding the tooth along an undersized archwire tends to be faster with conventional than self-ligating brackets, probably because the narrower self-ligating brackets lead to a greater elastic binding and resistance to sliding is much more determined by this than by friction.

Two retrospective cohort studies compared total treatment time and number of visits: Eberting *et al.*[39] found a statistically significant decrease in treatment time of 6 months and 7 fewer visits. Harradine *et al.*[7] observed a 4 months reduction in total treatment time and less 4 visits. However, these authors did not mention neither the used techniques nor the controlled variables. Furthermore, prospective and randomized studies are preferable to retrospective studies as these can be potentially biased by observer bias, which can affect the outcomes: among the potentially confounding factors the enthusiasm with a new product, different archwires, wire sequences or treatment mechanics, modified appointment intervals or greater experience stand out. These variables might have played a major role in treatment time reduction. In a prospective randomized study, Fleming *et al.*[40] compared the efficiency of orthodontic treatment with Smart-Clip self-ligating and Victory conventional brackets. The results of this study demonstrated that self-ligating brackets neither improve the efficiency of treatment nor resulted in fewer treatment visits: in fact, a slight but not statistically significant difference in total treatment time was observed (21.41 months for Smart-Clip group vs. 18.32 months for Victory group) and no differences were perceived in the total number of visits. Three systematic reviews with meta-analysis reviewing the orthodontic literature have recently been published, with regard to pain levels, efficiency, effectiveness and stability of treatment with self-ligating brackets compared with conventional brackets. Chen and colleagues[5] concluded that self-ligating brackets do not appear to have a noteworthy benefit with regard to chair and treatment time or occlusal characteristics after treatment. Notwithstanding this, a statistically significant difference was found regarding mandibular incisor proclination (1.5º less proclination with self-ligating brackets). Fleming *et al.*[4] reported that “there is insufficient evidence to support the use of self-ligating fixed orthodontic appliances over conventional appliance systems or vice versa”. In addition to this, these authors also stated that “there is insufficient evidence suggesting that orthodontic treatment is more or less efficient with self-ligating brackets” and that these brackets do not provide benefit concerning subjective pain experience. These results are in agreement with the meta-analysis conducted by Celar *et al.*[41] which revealed “weak and statistically not significant overall effects that failed to substantiate major advantages of self-ligating brackets over conventional brackets” regarding pain during initial therapy, number of appointments and overall treatment time.

According to the up-to-date "top of the evidence" results, it can be concluded that claimed advantages of self-ligating brackets are grounded on marketing strategies, since no scientific reliable evidence supports any worthy and clinical significant benefits comparing to conventional brackets.

Other Strategies for Friction Reduction

Recently, many investigations have been performed in order to achieve a strategy to decrease friction between the bracket and archwire. Muguruma *et al.*[42] investigated the effect of diamond-like carbon (DLC) coating on the frictional properties of orthodontic nickel-titanium and stainless steel wires and concluded that this process reduces the frictional force for these wires in brackets. Redlich *et al.*[43] proved that a substantial reduction in the static friction could be attained by coating the wire with nickel-phosphorus (Ni-P) electroless film impregnated with inorganic fullerene-like tungsten disulfide (IF-WS_2). Farronato *et al.*[44] evaluated the influence of Teflon coating on the resistance to sliding of orthodontic archwires and concluded that for all bracket-archwire combinations, Teflon-coated archwires resulted lower friction than the corresponding uncoated archwires. Wichelhaus *et al.*[9] investigated the effect of ion implantation on frictional forces before and after clinical use. They concluded that surface treated archwires demonstrated less friction that non-treated wires before treatment. However, all wires showed an increase in friction when exposed to oral environment, therefore becoming doubtful the benefits of ion implantation for frictional properties. Likewise, Braga *et al.*[45] demonstrated in *in vitro* simulations that ion implantation treated NiTi wires showed significantly less friction force than untreated wires. Some studies[27,46,47] evaluated the effect of low-friction ligatures on frictional resistance but their results are dissimilar and inconsistent.

All these investigations demonstrate the current demand of scientific efforts in order to achieve low friction levels for sliding mechanics in orthodontics. Although resistance to sliding is a complex issue and depends, as stated, on several variables, many strategies and techniques were evaluated with some promising outcomes. Further investigations are recommended so that reliable and scientifically founded methods, products or techniques can be applied to enhance brackets or archwires proprieties, with clinically relevant results, therefore improving treatment efficiency.

Conclusions

Under the conditions of this experiment, it may be concluded that self-ligating brackets appear to have an advantage regarding low frictional forces, when comparing to conventional brackets. On the other hand, no differences are observed between active and passive types. When coupled with a small rectangular archwire, slight bracket angulations or tooth tipping may not have a significant influence on resistance to sliding. However, different alloys may exhibit dissimilar frictional behavior when angulations occur. Surface roughness appears to have an inverse correlation with frictional forces.

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