

Comparative Analysis of Sliding Resistance of Different Lingual Systems

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ABSTRACT

Objective: To analyse and compare the frictional properties of 4 lingual systems combined with two types of stainless steel archwire (0.016x0.022, 0.018x0.025) and a 0.018x0.025 TMA archwire by simulating different misalignment situations in vitro. **Material and Methods:** Five randomly chosen brackets from each system (e-Brace, Harmony, Incognito, and STb) were used for the measurements and to simulate an upper first premolar extraction case. The friction tests were performed using a material testing machine in combination with a specialized test rig. **Results:** The lowest absolute friction values were found with the 0.016x0.022 SS wire in a passive configuration. STb provided the lowest mean friction, while Harmony brackets displayed the highest friction. The TMA Beta Titanium wire showed the highest friction values, but maintained proportions similar to those of the other wires as tip and torsion increased. **Conclusion:** The type of bracket has a significant impact on friction, and there is a positive correlation between mesiodistal bracket width and resistance to sliding. The archwire sections and materials and the vertical displacement, also significantly affect the friction generated by the system.

Keywords: Orthodontics; Orthodontic Wires; Orthodontic Brackets.

Introduction

Lingual orthodontics has become more popular in recent years due to the high aesthetic demands of adult patients. Even though adult patients often have severe skeletal, articular [1], and/or periodontal problems, and/or missing teeth or prostheses [2-4], an aesthetic appliance is the only approach they will accept.

The technological evolution of lingual brackets has involved miniaturization for better patient comfort, compliance [5], and oral hygiene [6]. In addition, the reduced mesiodistal dimension of the latest generation of lingual brackets has also contributed to maintaining adequate interbracket distances – a critical biomechanical issue for lingual appliances [7].

Alongside the recent diffusion in vestibular self-ligating brackets, self-ligating lingual systems have been studied to facilitate work and reduce the amount of friction generated in the archwire-bracket interaction [8]. However, the width of the bracket is also one of the parameters that, by directly determining the critical contact angle, must be evaluated with great attention to ensure optimal efficiency of the mechanics, in particular sliding mechanics [7,9,10].

Reports in the literature regarding the bracket-archwire play show that the angle in first- and second-order bends produces binding phenomena and how this affects the phases of alignment and space closure; the passive play has been studied carefully, quantifying its relationship to different prescriptions and verifying the ability that it has to influence torque expression in vivo [11].

This study aimed to analyse the frictional properties of four lingual systems in vitro: e-Brace, Harmony, Incognito and STb.

Material and Methods

Study Design and Materials

This is an *in vitro* study. The brackets and wires used in this study are listed in Table 1. Five randomly chosen brackets out of the 10-20 of each type received were used for measurements and to simulate an upper first premolar extraction case. The archwires of the Harmony self-ligating system were engaged by closing the clip with the special tool, while in the other cases, Alastik vestibular silicone ligatures (3M Unitek Corp., Monrovia, CA, USA) were used to standardize the test (not to use this type of ligatures during orthodontic treatment). To ensure repeatability, each experiment was repeated three times using the same piece of wire, which was each time re-engaged with a new set of ligatures.

Table 1. Brackets and wires used.

Bracket	1st Wire	2nd Wire	3rd Wire
eBrace	0.016x0.022 SS	0.018x0.025 SS	0.018x0.025 TMA
Harmony	0.016x0.022 SS	0.018x0.025 SS	0.018x0.025 TMA
Incognito	0.016x0.022 SS	0.018x0.025 SS	0.018x0.025 TMA
STb	0.016x0.022 SS	0.018x0.025 SS	0.018x0.025 TMA

To simulate in vitro the sliding of the wire in the brackets, a method was chosen in which three brackets of a certain brand were fixed to a rigid support using a guide that allows them to be passively arranged thanks to a full-thickness wire (Figure 1). The support consists of a stand, three slides and three rods. A bracket is fixed to the top of each rod by laser welding.

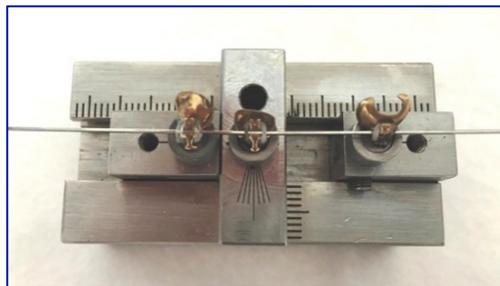


Figure 1. The rigid support with the wire engaged in a passive configuration (Incognito brackets).

The friction tests were performed at the University of Ferrara Engineering Department using an Instron 4467 dynamometer (Instron, Norwood, MA, USA), a testing machine used to analyse the mechanical properties of materials utilizing tensile or compression tests.

A full-thickness wire was engaged in the brackets to be welded and inserted into the calibrated grooves of the guide allowing the brackets to be positioned accurately on the rods for welding. In this way, after welding, the three brackets were perfectly coherent and passive with each other in the three planes of space, guaranteeing free and passive sliding of the wire in tests that reproduce the passive configuration. The three attachments were thus aligned along the pulling direction of the thread archwire. This was engaged via ligatures, which were replaced at each disassembly-reassembly of the thread [12].

This customized set-up was then fixed to the Instron plate using a threaded rod, while the wire was clamped in the jaws of the dynamometer (Figure 2). The interbracket distance can be set by moving the side slides of the device. A millimetric scale enables quantification of the displacement. The distance from the centre of the bracket on slide 3 to the centre of the bracket on slide 2 was fixed at 8 mm. The distance from the centre of the bracket on slide 2 to the centre of the bracket on slide 1 was fixed at 17 mm. This set-up simulated closure of the spaces in the arch after extraction of the first premolar, with the central bracket mimicking that on the canine, and the lateral brackets mimicking those on the lateral incisor and second premolar; as a consequence of this, we used the incisor, canine and upper second premolar brackets for each system for measurements (Figure 1).



Figure 2. The jaw pulls along an axis perpendicular to the work plane (plumb line).

The centre slide can also be moved to create linear deflection in the wires to be tested for friction. Once again, a millimetric scale enables the degree of deflection to be set (Figure 3).

The central rod can rotate around its own axis to simulate the second-order angular deflection of the archwire. A special protractor, fixed to the device, measures the second-order angle (tip) of the central bracket concerning the line uniting the two brackets, positioned on the lateral slides (Figure 4).

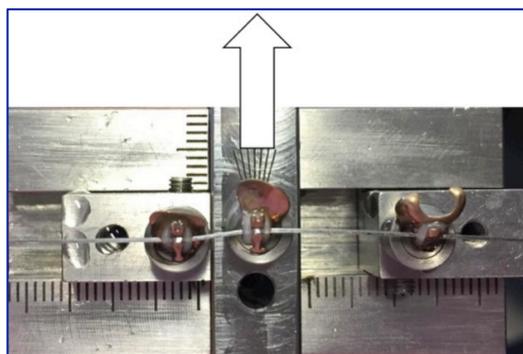


Figure 3. The vertical displacement of the central slide by 1 mm in the direction of the arrow simulates vertical displacement of the bracket.

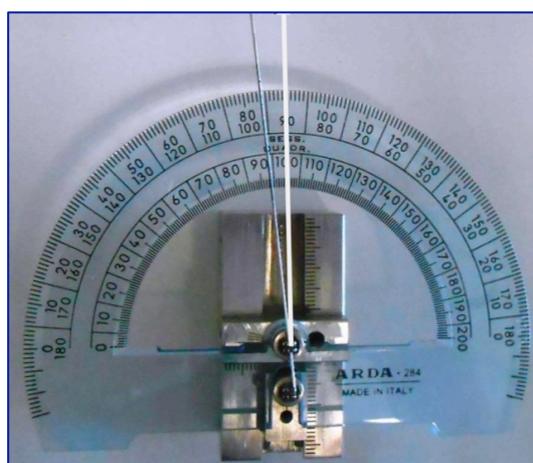


Figure 4. Measurement of the angle of the central bracket equal to 6°.

We explored three different tip angles, making the measurements with a simple angle of the central bracket set at 0, 6 and 10 degrees. We also made measurements after sliding the central tooth on the plane by a dimension Δy ; measurements were made with translation equal to 0 mm and 1 mm. All measurements were made having irrigated the wire with water using a pipette before the start of traction. Angle of tip = 0 means that the wire is in passive configuration, similar to the operating situation of Δy equal to 0. The measurements obtained in the tests with translation on the y axis were performed using a central bracket with tip equal to 0, while the central graduated rail was translated by 1 mm.

Each wire was tested three times, at room temperature, for a total of 180 measurements, all carried out by a sole operator. In addition, each wire was subjected to traction for a displacement equal to 5 mm at a 5 mm/min speed.

Statistical Analysis

Each test was acquired using Labview 5.8 Software (National Instruments, Austin, TX, USA) and then stored on an Excel spreadsheet (Microsoft Corp., Albuquerque, NM, USA). Thus 180 files were created, each describing the trend in the friction force, expressed in N, as a function of time and the position of the archwire traction for a given configuration. For each test, the maximum static friction peak value was recorded, and the average value of the developed force was calculated. Specifically, we produced a statistical analysis with means, standard deviations, and sample numbers of the variables studied. The archwire-bracket type

interaction effects were summarized and demonstrated via an ANOVA table; p-values lower than 0.05 were considered significant.

For simplicity, abbreviations have been used for the different brackets, specifically EB for eBrace, HA for Harmony, IN for Incognito, and ST for STb. Reported values are averages of those recorded in the three tests carried out on each sample.

Results

Measurement of the mean friction for the 0.016x0.022-inch SS archwire

The lowest friction values, in absolute terms, were found for the 0.016x0.022-inch SS archwire in a passive configuration: tip = 0° and translation = 0 mm (Figure 5). However, the STb (ST) system displayed the best behaviour overall, as seen in the graph comparing the averages of the maximum values (in Newton) detected in the 3 tests carried out for each system (Figure 5a). Displacement of the central slide by 1 mm on the y axis (Figure 3) produced a surge in the recorded maximum values, with the highest maximum friction being recorded for Harmony (HA) (Figure 5b).

It is evident that, as the tip angle increases, the detected friction values increase as a consequence, with a clinically relevant difference - more than 10 N - between 6 and 10 degrees of tip. In this scenario, the STb performed better in terms of friction (Figures 5c and 5d).



Figure 5. Measurement of the maximum friction values for 0.016x0.022 SS archwire.

Mean friction values measured for 0.018x0.025-inch SS archwire

An increase in thickness, and therefore also in the rigidity of the archwire, resulted in a significant increase in the maximum friction generated by all four systems. In the passive configuration, the poorest performance with a 0.018x0.025-inch SS archwire was observed for the Harmony self-ligating bracket (Figure 6a). Figure 6b shows that the behaviour was fairly homogeneous in the test with 1 mm vertical levelling of slide 2. Note the roughly tenfold increase in friction as compared to the passive configuration. The tests performed simulating different degrees of tip show that in this case, too, an increase in the thickness of the archwire produces greater friction, as did an increase in the angle of the bracket (Figures 6c and 6d).

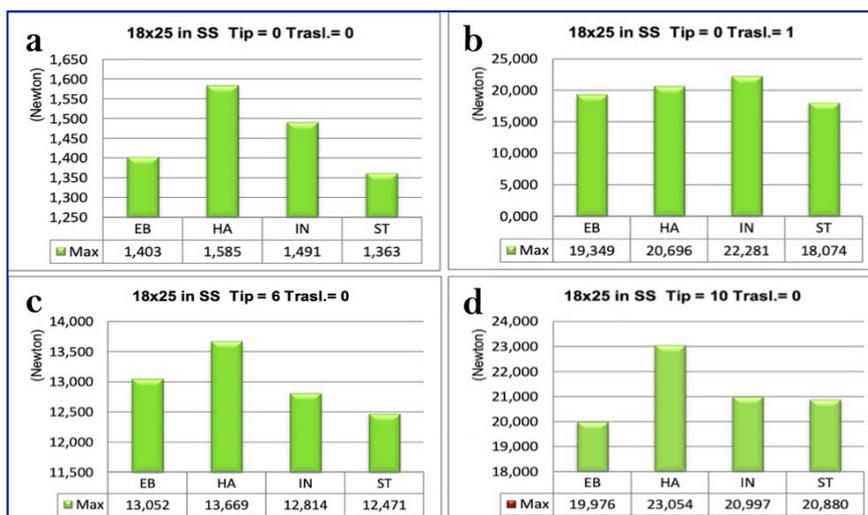


Figure 6. Measurement of the maximum friction values for 0.018x0.025 SS archwire.

Mean friction measured for 0.018x0.025-inch TMA archwire

The TMA Beta Titanium archwire displayed by far the highest friction values. However, it maintained proportions similar to the other archwires as tip and torsion increased (Figures 7a to 7d).

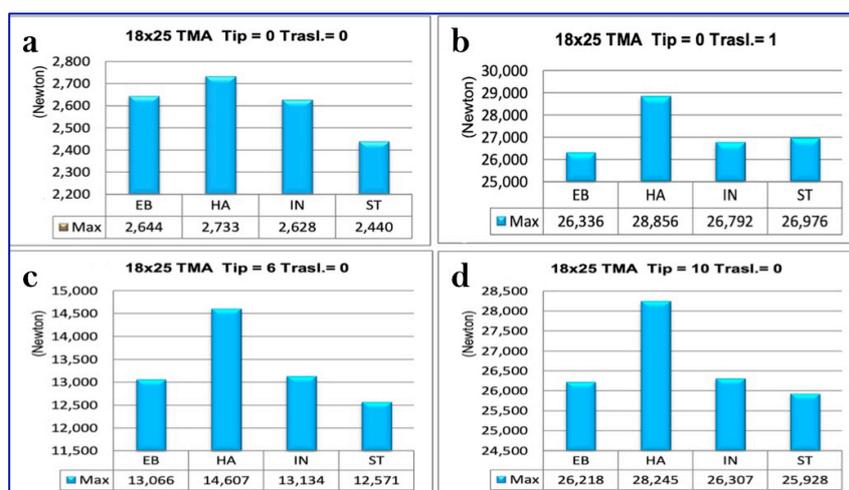


Figure 7. Measurement of the maximum friction values for 0.018x0.025 TMA archwire.

Discussion

Given the importance of friction in orthodontic treatment, we compared that generated in four lingual systems. Researchers have proposed several experimental systems designed to overcome the difficulty of simulating in vitro the response of a tooth equipped with periodontal support. These are designed to take into account rotation phenomena (due to the distance between the point of application of the force and the centre of resistance), which accentuate the complexity of the biomechanics, and the superimposition of intermittent physiological forces [13].

The Willems machine consists of a three-dimensional positioning device with a control unit that produces a rapid movement in the slot-wire interface to reproduce that dynamic phenomenon, but in a somewhat arbitrary way [14]. Drescher's method, on the other hand, simulates the resilience of the

periodontal ligament. However, it cannot accurately mimic tips that exceed the critical angle [15]. The method used by Park et al. used a tribological instrument that continuously changes the archwire-bracket angle, with a reciprocal angular velocity of $0.6^\circ/\text{s}$, 0.1 rotations per minute and a normal force of 100 g [16]. Furthermore, finite element analysis represents a valid alternative for simulating dental movements following precise forces applied in 3D, as described and widely utilized in the literature [17-19].

We opted to carry out our testing using the first method, both because it has already been successfully tested in our school, thanks to a fruitful collaboration with the Engineering Department, and because it was also used in two studies out of the total of three existing on static friction in lingual orthodontics [20-22]. Moreover, this system enables study of the behaviour of the creep at well-defined angles.

The method we used differs from that of Thorstenson and Kusy [23] due to the presence of 3 brackets instead of a single central one with lateral Teflon guides. However, we replicated the author's method of simulating the closure of spaces after extraction of the first premolar. Our study also differs from others in the literature due to the analysis method, with the fixed support for testing lingual brackets being characterized by extreme rigidity of the system. In fact, in this system, the base of the steel stand was screwed to the work surface of the Instron machine, and there was no simple counterweight on the side opposite to the traction of the wire. Furthermore, the brackets were welded to the support and not bonded with composite resin. It is also the only study to have used three brackets placed in sequence to simulate the closure of spaces in an extraction case.

The steel positioning jig employed a full-thickness 0.018x0.025-inch SS archwire to place the brackets. The same set-up has been used in other studies, except for one that used a 0.017x0.025-inch SS archwire [21]. We elected to perform the tests at a series of angles that also included high tip values (0.6 and 10 degrees) to simulate clinical reality and evaluate the consequences of improper equipment handling. The interbracket distance changes during orthodontic treatment. At the anterior teeth it is much smaller than at the posterior teeth, so a reasonable distance between the brackets cannot be established.

An interesting feature of this study is that we also tested the vertical levelling of the brackets, similar to some studies conducted on vestibular mechanics with superelastic archwires [24,25]. Note, however, that distalization of the upper canine in two stages is not recommended in the lingual technique for aesthetic and mechanical reasons (archwire interference). Therefore, distalization of the canine is performed until crowding is resolved, and the anterior group is subsequently retracted en masse [25]. The archwire used for this technique is 0.016x0.022-inch SS, which represents the best compromise between stiffness (to avoid the bowing effect) and containment of binding phenomena (to keep the range of forces low, avoiding loss of rear anchorage control, which is more difficult in lingual orthodontics due to disclusion).

At the same time, there is a need for anterior torque control, and the ideal positioning of the roots requires generating sufficient moments, even with reduced width brackets; therefore, in the final stages of the treatment, a pair of wire brackets an archwire-bracket capable of creating high friction is required. For this purpose, depending on the case, rectangular archwires with a larger cross-section come into play; these are what we tested, reproducing angles higher than Theta C, since in clinical reality the archwire is almost always in contact with the walls of the slot, and therefore subject to deformation, which generates binding. We also tested TMA 0.018x0.025-inch, a more resilient archwire than the steel widely used in the lingual technique due to the needs arising from the reduced interbracket distance.

Several studies on vestibular set-ups have involved dry friction tests [23,26-29], while other researchers have investigated the possible lubricating role of saliva in the archwire-slot relationship to

understand whether it actually behaves as a lubricating agent or rather an adhesive. The outcome of those experiments was that saliva can affect friction in one direction or another in relation not so much to its viscosity, but rather to the material used [30-32]. Others have hypothesized that in the active configuration, saliva can be expelled from the contact angles, advising that immersion tests be performed [33]. Our tests involved water irrigation using a pipette, carried out before the start of traction. We discounted the possibility of carrying out the tests with the samples completely immersed in a thermostat-controlled water bath, since the physical characteristics of steel, in particular its stiffness, do not vary with temperature (unlike nickel-titanium). In any case, Thorstenson and Kusy [23] found that the friction levels for steel wires in an active configuration are the same whether the wires are tested dry or in saliva.

The speed of traction to be used in tests is a very variable factor in literature. The literature reports a range of sliding speeds in tests performed on vestibular brackets, from 0.5 mm/min and 1 mm/min up to 10 mm/min. We followed the protocol of the last study performed at Ferrara, i.e., 5 mm/min for 5 mm of traction. Kusy and Whitley [30] found that a sliding speed tested the sliding velocity at 10 mm/min.

We tried to recreate a fairly realistic interbracket distance and performed all tests at room temperature since we did not test Ni-Ti archwires. The proportional increase recorded in the friction values with the increase in both the archwire cross-section and the archwire-bracket angle must be explained via the binding theory. This basically dictates that the response strength of the deflected archwire increases with increasing cross-section and stiffness, and due to the degree of deflection. It is clear that the Harmony bracket has a larger mesiodistal dimension; through the Kusy equation, it is possible to understand the direct influence of this parameter on the critical angle and consequently on the binding that is generated in an active configuration [30]. In contrast, the STb bracket, which has a smaller mesiodistal size, like Incognito, displayed lower friction values, with considerable statistical significance. It has been shown that in the lingual technique, the minimum width that guarantees correct tip control is 1.5 mm and that above this value, due to a direct effect on the interbracket distance, the level of force transmitted to the teeth is likely to increase very rapidly. The presence of a clip in the Harmony interactive self-ligating bracket then seems to exert a greater normal force on the archwires investigated in this study, significantly increasing the friction even in the passive configuration starting from the 0.018x0.025-inch cross-section, both steel and TMA.

Lombardo et al. [34] tested different types of vestibular and lingual brackets with superelastic Ni-Ti wires (0.012 inch and 0.014 inch) and found better friction reduction performance in brackets with smaller dimensions than larger brackets, despite the self-ligating mechanism. The authors concluded that the self-ligating design is ineffective in reducing friction. In-Ovation L generated more friction than STb in both the lower and upper arches. This finding agrees with Lalithapriya et al. [21], which found greater friction at larger brackets. After SEM analysis of the various types of slots studied, they stated, in agreement with Kusy and Whitley [30], that there was no direct influence of the surface roughness of the slot on the different friction performance of the systems studied.

Finally, in our research, the TMA wire always expressed higher or comparable friction values with respect to steel. This contrasts with the results in the literature, which featured a decrease in the friction values generated by TMA, as compared to steel, in a humid environment [32]. This partial limitation was imposed by the manufacturers, who provide closed sets with no duplicates, but it does not detract from the clinical significance of this work, since it is always the same archwire that remains in the patient's mouth for months without being replaced because of wear, unless it accidentally breaks.

Moreover, in our tests, friction values were much higher than those recorded in the majority of studies performed on the lingual technique. Specifically, the study by Ozturk Ortan et al. [20] recorded a dry average friction of 4.37 N with 0.017x0.025-inch SS archwire in a 0.018 STb slot at second-order angle of 5 degrees; on the same type of bracket and angle, but with a 0.016x0.022-inch SS archwire, Lalithapriya et al. [21] reported an average of 2.391 N. Park et al. [16], on the other hand, recorded for the same angle, dry, a value of 4.8 N with 0.016x0.022-inch SS archwire and 8 N with a 0.017x0.025-inch SS, again with STb. The values closest to ours were those of Park et al., who used 35-mm lengths of wire [16].

This study is the first to have considered a realistic interbracket distance and shows the significant influence of binding. It is, therefore, essential to prepare the archwires by completely eliminating compensation curves, to reduce any possible angle-to-bracket friction before proceeding with space closure [34]. Indeed, the application of excessive first-class forces can generate binding and compromise the rear anchorage, although it has recently been reported that a palatal miniscrew could be used to modify this clinical scenario [35,36]. However, it must be noted that all our results are from an in vitro study, and the clinical situation could be different due to the behaviour of the periodontal ligament, tongue, masticatory forces and lip pressure [37-43].

Conclusion

As the bracket-archwire angle increases beyond the critical angle, the resistance to sliding (binding) increases proportionally. A vertical displacement of 1 mm of the central bracket produces an increase in frictional forces of at least ten times greater than the passive configuration. The cross-section of the archwire significantly affects the binding, as thicker wires always produce greater resistance to sliding forces. The material significantly affects the frictional resistance, with the TMA producing significantly greater forces than steel. The type of bracket has a significant impact, with a positive correlation between mesiodistal bracket width.

Authors' Contributions

PA		https://orcid.org/0000-0002-4020-5065	Conceptualization, Methodology, Formal Analysis, Investigation, Writing - Original Draft and Writing - Review and Editing.
FF		---	Writing - Review and Editing.
MP		https://orcid.org/0000-0001-6198-3053	Conceptualization and Writing - Review and Editing.
FM		---	Writing - Review and Editing.
FC		https://orcid.org/0000-0002-4641-2196	Conceptualization and Writing - Review and Editing.

All authors declare that they contributed to critical review of intellectual content and approval of the final version to be published.

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None.

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability

The data used to support the findings of this study can be made available upon request to the corresponding author.

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