ORIGINAL ARTICLE

Evaluation of frictional forces during dental alignment: An experimental model with 3 nonleveled brackets

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Introduction: The aim of this in-vitro study was to evaluate the frictional forces generated by various combinations of brackets and orthodontic wires by using an experimental model with 3 nonleveled brackets to gain a better understanding of the resistance to sliding during dental alignment and leveling. **Methods:** Two kinds of orthodontic brackets were tested: passive self-ligating brackets and conventional twin stainless steel brackets. The following wires were tested: 3 nickel-titanium (.014, .016, and .016 × .022 in), 2 stainless steel (multistranded .0155 and .016 in), and 1 beta-titanium alloy (.016 in). The ligatures used with conventional brackets were elastomeric modules (power 'O' 110) and preformed stainless steel ligature wire (.010). Each of the 10 bracket-archwire combinations was tested 10 times. Kinetic frictional forces were measured on a specially designed testing machine. The wires tested were pulled through a set of multiple nonleveled brackets at a speed of 4 mm per minute over a distance of 5 mm. All data were statistically analyzed. **Results:** The sliding of the wire in the 3-bracket nonaligned system was significantly influenced by wire cross-section dimension (P <0.001), wire material (P <0.001), number of wire strands (P <0.001), and type of ligation (P <0.001). **Conclusions:** Frictional forces can be reduced during alignment by using self-ligating brackets, small dimensions, and less stiff wires, thereby inducing the wire to slide in the slots. Under such conditions, the force required by the orthodontic wire to overcome resistance to sliding is reduced. This allows the wire to exploit its mechanical characteristics more efficiently. (Am J Orthod Dentofacial Orthop 2008;133:708-15)

When straight-wire mechanics are used in orthodontics, the resistance to sliding (RS) generated at the wire/bracket interface greatly influences the character of the force transmitted to teeth.[1]

Friction is defined as the force (F_{FR}) that opposes a movement when an object moves tangentially against another.[2] It is proportional to normal force (F_N), which acts perpendicularly to the direction of the movement on the contact surface. The coefficient of friction (μ) of a specific material is a constant; its value varies according to the surface characteristics of the interfacing materials. Friction is the product of multiplying the coefficient of friction by normal force: $F_{FR} = \mu \, F_N$. Usually, the force needed to slide an object over another is greater than the force necessary to keep it moving. These 2 aspects of friction are called static and kinetic friction.[2] Sliding between bracket and wire in the oral cavity occurs at low velocity as a sequence of short steps rather than as a continuous motion.[1] In such conditions, the distinction between static and kinetic frictional resistance is arbitrary because these 2 forms of friction are dynamically related.[3] Many variables influence the frictional forces between bracket and orthodontic wire. The method by which the archwire is ligated to the bracket can significantly affect RS.[4-7] All types of conventional ligatures, both elastomeric and stainless steel, apply a force that pushes the archwire against the base of the slot, and this ligation force is responsible for the increase in frictional forces.[8] Several studies have shown that self-ligating brackets produce a significant reduction in the amount of friction between bracket and wire compared with twin edgewise brackets and conventional ligatures.[9-12] Kusy and Whitley[13] demonstrated how the size and shape of the

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Table I. Study design

Wire alloy	Wire section (in)	Observations (n)		
		Damon SL2	Conventional with EM	Conventional with SS ligature
Ni-Ti	.014	10	10	
Ni-Ti	.016	10	10	10
Ni-Ti	.016 × .022	10	10	
SS	.0155 (coaxial)	10		
SS	.016	10		
TMA	.016	10		

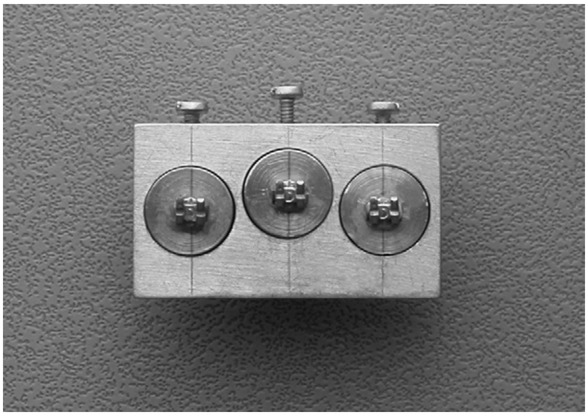

Fig 1. SS support to assemble 3 vertically nonaligned brackets.

bracket and the archwire significantly affect friction. Many studies have shown that ceramic brackets produce greater friction than stainless steel (SS) brackets.[14-18] Drescher at al[19] ranked wire alloys on the basis of friction produced as follows: SS, cobalt-chromium, nickel-titanium (Ni-Ti), and β-titanium (TMA). To improve the surface characteristics of some materials, manufacturers have treated highly frictional materials, such as TMA, with ion implantation.[20] In these studies, temperature also has an important effect on all Ni-Ti archwires, including austenitic stabilized ones.[21,22] Saliva provides hydrodynamic lubrication between brackets and archwire, and it also reacts chemically with frictional surfaces.[3] When saliva is present, frictional forces and coefficients can increase, decrease, or not change; this depends on the physical and chemical characteristics of the materials tested.[23]

Great efforts have been made recently to make experimental conditions as close as possible to clinical situations to obtain data that are clinically useful. During space closure, the sliding of the bracket along the wire is preceded by tipping of the crown[1] with consequent formation of second-order angulation between bracket slot and wire (active configuration).[13,24] This has led many researchers to include this point as a variable in their studies.[1,25-30] Under such conditions, phenomena such as elastic binding (BI) and notching (NO) contribute to RS.[31] BI occurs when the angulation between bracket slot and wire exceeds the critical contact angle; NO is the extreme manifestation of BI, resulting in plastic deformation of the orthodontic wire.[8] Overall RS at the wire-bracket interface can be expressed as:

$$RS = FR + BI + NO$$

where *FR* is classical friction and occurs as a result of the ligation force mentioned earlier.[31]

To date, few studies have dealt with the RS of wires and nonleveled brackets to give clinicians useful clinical data about the frictional forces during the first phase of any straight-wire treatment, ie, dental alignment.

The aim of this in-vitro study was to evaluate the friction generated by various combinations of brackets and orthodontic wires in an experimental model with 3 nonleveled brackets to gain a better understanding of the frictional forces during dental alignment and leveling.

MATERIAL AND METHODS

We used 180 self-ligating brackets (Damon SL2; SDS Ormco, Glendora, Calif) and 120 conventionally tied SS brackets (Mini Twin; SDS Ormco) in this study. Both the self-ligating and the conventional brackets were SS maxillary second premolar brackets and shared the following features: nominal slot dimension, .022 in; mesiodistal width, 2.67 mm; prescription, torque −7°; and angulation, +2°.

All wires used in this study were supplied in straight lengths. Three superelastic Ni-Ti wires, sizes .014, .016, and .016 × .022 in, were tested (G&H, Greenwood, Ind). Two SS wires (SDS Ormco), a multistranded coaxial wire of .0155 in, another of .016 in, and a .016-in TMA wire (SDS Ormco) were also tested. The ligatures used with conventional brackets were elastomeric modules (EM) (Power 'O' 110; SDS Ormco) and SS ligatures (Preformed .010; SDS Ormco). A summary of the materials used is given in Table I.

An SS support was constructed to assemble 3 vertically nonaligned brackets (Fig 1). It was designed to simulate a nonaligned dental segment that included 2 premolars and the canines. The SS support allowed the slot of the central bracket to be set in a more apical position of 2 mm compared with the other 2 bracket slots. The vertical discrepancy between the brackets was set at 2 mm because this realistically represents

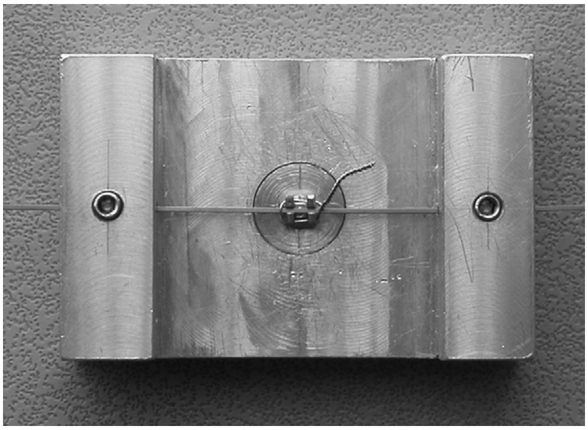

Fig 2. Jig and mounting apparatus.

nonalignment in the segment of dental arch being studied.

The interbracket distance, measured from the center of the brackets, was 11 mm. Composite resin (Enlight LV; SDS Ormco) was used to bond the test brackets onto a brass mount in a mounting apparatus (Fig 2) before incorporating it into the 3-bracket apparatus. The brass mount was cylindrical, with a hole to hold the resin, and had a line at the midline as a guide for correct positioning of the brass mount in the 3-bracket apparatus. Correct positioning of the bracket slot onto the brass mount was achieved by using a 016 .× 022-in jig in TMA, as described by Thomas et al.[12] The jig was used so that the largest cross-section size (.022 in) occupied the entire slot height. The mounting apparatus was built so that the jig was parallel to its upper edge and passed over the center of the brass mount. During bonding, a set square was used to ensure that the line drawn on the brass mount was perpendicular to the upper edge of the mounting apparatus. Correct mesiodistal positioning of the bracket slot onto the brass mount was achieved by lining up the top end of the vertical line (inscribed by the manufacturer at the mesiodistal center of the bracket) with the line engraved on the brass mount. During the bonding phase, a metal ligature was used to attach the bracket to the jig to bring the jig into contact with the base of the slot. After assembling the bracket brass mounts, they were then correctly positioned onto the 3-bracket apparatus by ensuring that the 3 vertical reference lines on the brass mount and the 3-bracket apparatus matched. By this method, the influence of the preadjusted bracket prescription on frictional forces was eliminated; moreover, the method ensured that the bracket position could be reproduced by the bracket slot in all 3 dimension.

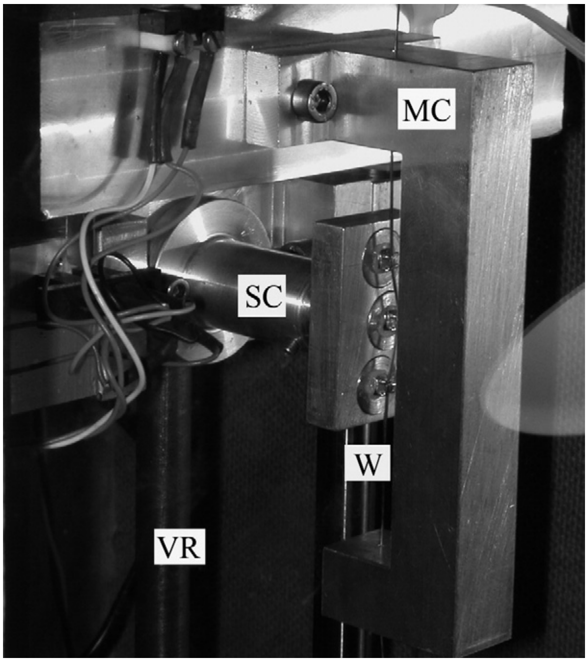

Fig 3. Testing machine: static carriage (*SC*), vertical rod (*VR*), wire (*W*), and moving carriage (*MC*).

A testing machine capable of measuring friction was designed and built by the Istituto per i Processi Chimico Fisici of the Consiglio Nazionale delle Ricerche in Messina, Italy, and used to measure levels of friction. It consisted of a static carriage bearing the test assembly, described above, that could slide along 2 vertical parallel rods by 4 smooth linear ball bearings (Fig 3). The static carriage weight was firmly fixed to a vertical rod through which it acted on a force sensor. The output from the sensor was read by a computer via a special interface. The wire, which passed through the brackets on the static carriage, was fixed to the end of a moving carriage with 2 stop screws. The moving carriage was driven by a computer-controlled stepper motor at a set speed of 4 mm per minute. The force measured by the sensor changed during motion due to the frictional coupling between the moving wire and the brackets.

Tests were carried out at a temperature of 34°C in the dry state. The machine calculated the average of kinetic frictions over about 100 data points on the first run of the wire through the set of brackets on a 5-mm piece of archwire. One test was carried out for each trio of brackets and each wire. After each test, the tested brackets and wire were removed from the machine and new ones were placed. All ligatures tested in this study were attached to the brackets with a needle holder. To standardize the ligation force exerted by the metallic

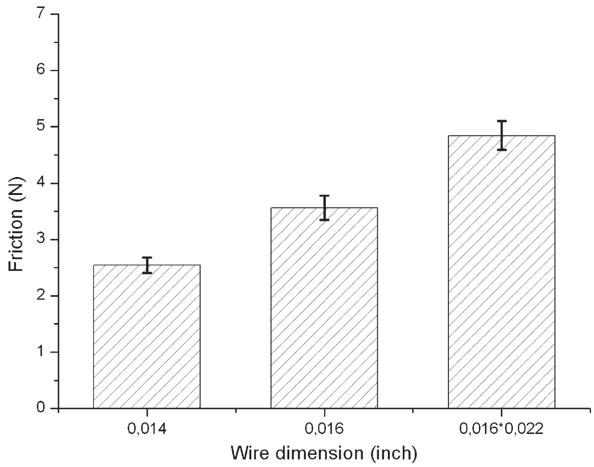

Fig 4. Frictional forces and standard deviations from testing various Ni-Ti wires coupled with conventional brackets and elastomeric ligatures (group 1).

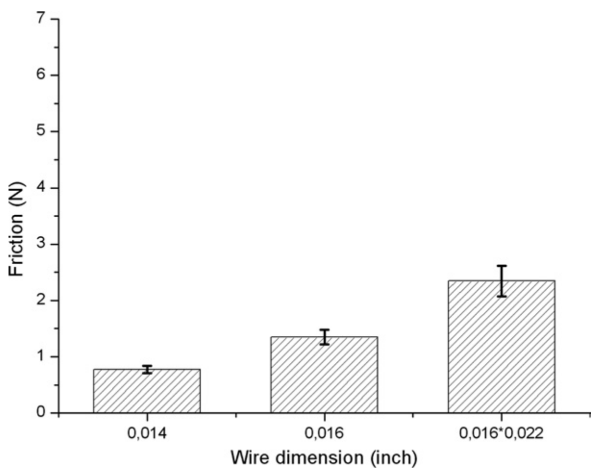

Fig 5. Frictional forces and standard deviations from testing various Ni-Ti wires coupled with self-ligating brackets (group 2).

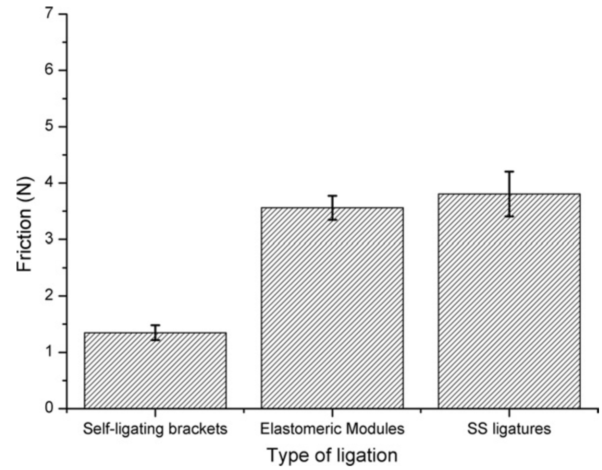

Fig 6. Frictional forces and standard deviations from testing various types of ligation coupled with .016-in Ni-Ti wires (group 3).

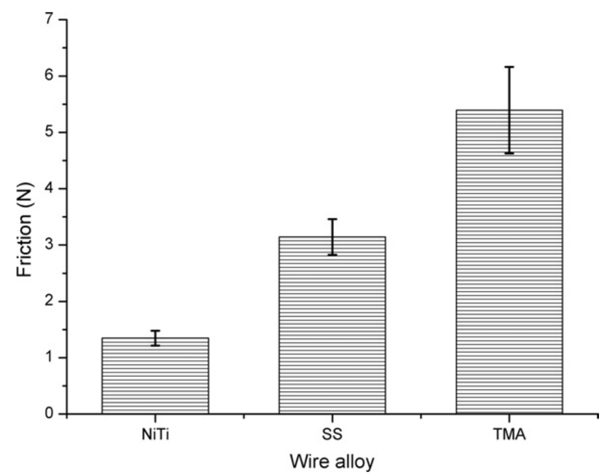

Fig 7. Frictional forces and standard deviations from testing various alloys of .016-in wires coupled with self-ligating brackets (group 4).

ligatures, we used a method that was previously described.[6] Every SS ligature, once it had been correctly positioned onto the bracket, was twisted 7 times with the needle holder. Before twisting the short ligatures, a right-angled bend was made where the portion of pretwisted ligature split into 2 SS wires. This was done to prevent sliding between the needle holder and the ligature during tightening. Ten trials were performed for each bracket/archwire combination. The bracket, archwire, and ligature wires were cleaned with ethanol to remove surface debris before testing.

All data were displayed and recorded by a software program especially designed for this study. Descriptive statistics were calculated including mean, standard deviation, median, minimum, and maximum values. The data were put into groups to account for the unbalanced study design and were then used to evaluate the effects of the independent variables on the frictional forces by using inferential statistical tests. A graph was produced for each group (Figs 4-8), and the homogeneity of variance was evaluated by using the Bartlett's test. Nonparametric analyses were carried out when a significant difference of variance was observed in any group. Parametric analyses were used in all other cases, as shown in Table II. The level of significance for all tests was set at $P < 0.05$.

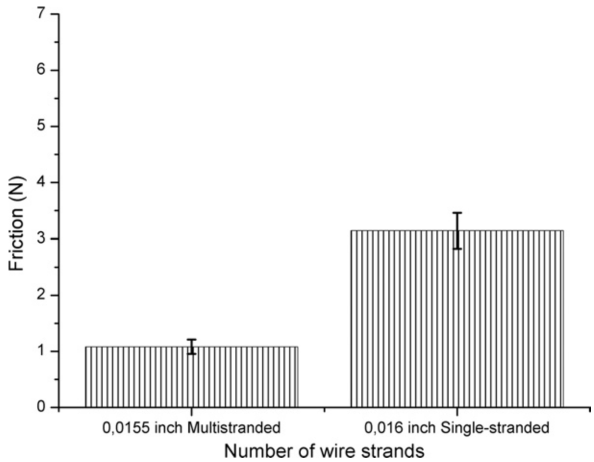

Fig 8. Frictional forces and standard deviations from testing various types of SS wires (multistranded and single-stranded) coupled with self-ligating brackets (group 5).

Table II. Inferential statistics

Inferential statistics	*Significance and statistical analysis*
Wire dimensions and conventional bracket	† (a)
.014 vs .016	* (b)
.014 vs .016 × .022	* (b)
.016 vs .016 × .022	* (b)
Wire dimensions and self-ligating bracket	† (c)
.014 vs .016	* (d)
.014 vs .016 × .022	* (d)
.016 vs .016 × .022	* (d)
Type of ligation	† (a)
Self-ligation vs EM	* (b)
Self-ligation vs SS ligature	* (b)
EM vs SS ligature	Not significant (b)
Wire alloy	† (a)
Ni-Ti vs SS	* (b)
Ni-Ti vs TMA	* (b)
SS vs TMA	* (b)
Number of strands of SS wire (.0155 multistranded vs .016 single-stranded)	† (b)

*$P < 0.05$; †$P < 0.001$.

[a]Kruskal-Wallis analysis; [b]Mann-Whitney test with Bonferroni adjustment; [c]ANOVA; [d]Scheffé test.

RESULTS

Descriptive statistics of kinetic friction are reported in Table III for all bracket/wire combinations. Inferential statistics are reported in Table II. Wire dimension significantly influenced the sliding of the wire in the 3-bracket nonaligned system for both conventional ($P < 0.001$) and passive self-ligating brackets ($P < 0.001$). The .016 × .022-in wire generated the highest friction levels for both the conventional and the self-ligating brackets. Next came the .016-in wire and then .014-in wire. Significant differences for frictional forces were found for all wire dimensions tested, both for conventional and self-ligating brackets ($P < 0.05$). The method by which the wire was held in the slot significantly influenced the sliding of the wire itself in the bracket system ($P < 0.001$). Passive self-ligating brackets produced significantly lower friction than conventional brackets with EM ($P < 0.05$) and SS ligatures ($P < 0.05$). No significant differences were found between EM and SS ligatures. The wire material was a variable that significantly influenced friction ($P < 0.001$). Ni-Ti was the least frictional alloy of those tested ($P < 0.05$) followed by SS ($P < 0.05$) and TMA ($P < 0.05$). The number of strands (multistranded or single-stranded) of the SS wire was also a variable that significantly affected frictional forces ($P < 0.001$).

DISCUSSION

This is the first study to assess the impact of nonleveled bracket slots on the frictional forces generated during the dental alignment process. Henao and Kusy[32] evaluated the friction generated between an archwire and a set of brackets mounted on a typodont. However, they assessed the malocclusion in overall terms and did not evaluate the impact of each dental variable that contributed to increased RS (degree of nonalignment, tipping, torque, and dental rotation).

In many clinical situations, the alignment of the dental arch involves sliding the orthodontic wire toward the distal portions of the arch. Clinical evidence of this process shows that the wire progressively protrudes from the last distal molar tube during the alignment phase. This occurs when the trajectory of the orthodontic wire just after bonding is longer than that of the wire after the alignment phase.

The experimental 3-bracket model in this study simulates a middle segment of the dental arch including the 2 premolars and the canine. This is because sliding between wire and brackets occurs mainly in this area during dental alignment and leveling.

The frictional forces in the sliding of orthodontic wire during alignment influence the amount of force delivered to the periodontal ligament of the teeth. If the friction level is high, part of the force generated by the orthodontic wire is needed to overcome the frictional force and is thereby lost. Consequently, only the remaining part of the force can be transferred to the teeth and cause their movement. Lower levels of friction will therefore reduce the force lost.

In light of this, it appears that the significant reduction of friction we found when testing self-

Table III. Descriptive statistics of kinetic frictional forces (Newtons)

Variables								
Wire alloys	*Wire dimension (in)*	*Ligation*	*Observations*	*Mean*	*SD*	*Minimum*	*Median*	*Maximum*
Ni-Ti	.014	Self-ligation	10	0.78	0.06	0.69	0.77	0.91
Ni-Ti	.014	EM	10	2.54	0.13	2.26	2.57	2.71
Ni-Ti	.016	Self-ligation	10	1.35	0.13	1.05	1.36	1.48
Ni-Ti	.016	EM	10	3.56	0.21	3.15	3.62	3.78
Ni-Ti	.016	SS ligature	10	3.81	0.40	3.09	3.89	4.31
Ni-Ti	.016 × .022	Self-ligation	10	2.35	0.27	2.01	2.31	2.77
Ni-Ti	.016 × .022	EM	10	4.84	0.25	4.41	4.86	5.25
SS	.0155 coaxial	Self-ligation	10	1.08	0.13	0.88	1.10	1.25
SS	.016	Self-ligation	10	3.14	0.32	2.63	3.12	3.59
TMA	.016	Self-ligation	10	5.39	0.77	4.04	5.28	6.74

ligating brackets against conventional ones allows the mechanical characteristics of the wires to be exploited more efficiently. This suggests that, when practitioners use self-ligating brackets, these should be coupled with wires that generate lower levels of force to avoid overloading the periodontal tissues.

No significant differences were found between EM and SS ligatures in this study. Nevertheless, a point worth highlighting is the greater standard deviation of metallic ligatures compared with that for EM. The method we chose to standardize the parameter ligation force can also be used in vivo, unlike the one used by other authors (constant ligation force application).[1] This finding illustrates the difficulty of standardizing the magnitude of the ligation force exerted by a SS ligature for methods that can be used in vivo.

In this study, the wire alloy also appeared to be a factor that can significantly influence frictional forces. The friction generated when an orthodontic wire slides through nonaligned brackets is the combined result of 2 critical factors: surface characteristics and orthodontic wire stiffness.

The SS–Ni-Ti bracket-wire combination was the gold standard in our study, even though the surface characteristics of Ni-Ti wires compare unfavorably with SS ones.

The explanation for this result must lie in the reduced stiffness of Ni-Ti wires that decreased the amount of normal force exerted on the apical and coronal surfaces of the slot with nonleveled brackets. Even though TMA is less stiff than SS, we found that the SS-TMA bracket-wire combination produced more friction than the SS-SS one.[33] In such a case, the poor surface characteristics of TMA seem to be important in determining the magnitude of RS.

A factor that significantly affected the frictional forces in this study was the cross-sectional size of the wire. This influences RS by modifying wire stiffness and the critical contact angle (θ_c).[31] Thus, wires with larger cross-sections increase the impact of BI and NO on RS during dental alignment.

Multistranded SS wires are still widely used in the initial leveling phases of orthodontic treatment. In our study, the RS of these wires was lower than that of single-stranded SS ones of comparable size. This result was undoubtedly related to the distinctive structure of multistranded wires that makes them less stiff.

Our findings suggest that the use of self-ligating brackets and wires that are less stiff and of small dimension not only enables frictional forces to be reduced during alignment, but also improves archwire efficiency and allows the use of lighter and more predictable forces. A reduction in the forces applied is highly desirable because this promotes direct bone resorption (and therefore assumedly faster dental movement) and prevents root resorption.

The ultimate aim of in-vitro studies on friction is to provide experimental results that can give orthodontic practitioners relevant and useful clinical information. There has been much debate about whether these studies can be relied on and whether the data obtained about frictional forces really correspond to those in vivo.

Ho and West found that the forces required to overcome friction in vivo are lower than those in vitro.[34] Loftus and Artun simulated the periodontal ligament in their experimental model and found that PDL affects significantly in vitro frictional resistance.[30] It is, therefore, difficult to be completely certain how accurately a laboratory experiment on friction can reproduce the exact situation in vivo.[35]

It is often impossible to compare the results of in-vitro studies because many variables affect friction, and there little uniformity in the variables included. However, a qualitative comparison of the variables assessed in any study is significant.

In our study, technical reasons prevented the interbracket distance of 11 mm from being reduced, even though this was found to be slightly oversized. We do, however, believe that it is more interesting for a clinician to know the differences from testing various types of material rather than focusing unduly on the precise figures for the frictional forces.

CONCLUSIONS

The use of self-ligating brackets reduces RS during alignment and leveling and thereby enhances sliding of the wire in the slots. In this case, less of the force exerted by the orthodontic wire is used to overcome frictional forces. This allows the mechanical characteristics of the wires to be exploited more efficiently and suggests that practitioners should use wires that generate lower levels of force to avoid overloading the periodontal tissues with self-ligating brackets.

No significant differences were found between EM and SS ligatures. However, the greater standard deviation of SS ligatures compared with EM is worth noting. This demonstrates how difficult it is to standardize the magnitude of ligation force generated by SS ligatures with methods that can be used in vivo.

In this experimental model with nonleveled brackets, the wire alloy influenced RS. The gold standard was the SS–Ni-Ti bracket/wire combination. This finding is certainly related to the reduced stiffness of Ni-Ti wires. Although TMA is less stiff than SS, we found that the SS-TMA bracket-wire combination produced more friction than the one in SS-SS. In this case, it seems that the poor surface characteristics of TMA play an important role in determining the amount of RS. Another factor that significantly influences RS is the cross-section dimension of the wire. This affects RS by modifying wire stiffness and the critical contact angle (θ_c). Thus, wires with larger cross-sections increase the impact of BI and NO on RS during dental alignment. Multistranded SS wires produced lower RS compared with single-stranded SS of comparable size; this result was due to the characteristic structure of these wires that makes them less stiff.

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