Received: 09th March 2015 *Accepted: 18th July 2015* *Conflicts of Interest: None*

Source of Support: Nil

Original Research

Comparison of Frictional Forces Generated by a New Ceramic Bracket with the Conventional Brackets using Unconventional and Conventional Ligation System and the Self-ligating Brackets: An *In Vitro* Study

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How to cite the article:
Pasha A, Vishwakarma S, Narayan A, Vinay K, Shetty SV, Roy PP. Comparison of frictional forces generated by a new ceramic bracket with the conventional brackets using unconventional and conventional ligation system and the self-ligating brackets: An *in vitro* study. J Int Oral Health 2015;7(9):108-113.

Abstract:
Background: Fixed orthodontic mechanotherapy is associated with friction between the bracket - wire - ligature interfaces during the sliding mechanics. A sound knowledge of the various factors affecting the magnitude of friction is of paramount importance. The present study was done to analyze and compare the frictional forces generated by a new ceramic (Clarity Advanced) bracket with the conventional, (metal and ceramic) brackets using unconventional and conventional ligation system, and the self-ligating (metal and ceramic) brackets in the dry condition.

Materials and Methods: The various bracket wire ligation combinations were tested in dry condition. The brackets used were of 0.022″ × 0.028″ nominal slot dimension of MBT prescription: Stainless steel (SS) self-ligating bracket (SLB) of (SmartClip), SS Conventional bracket (CB) (Victory series), Ceramic SLB (Clarity SL), Conventional Ceramic bracket with metal slot (Clarity Bracket), Clarity Advanced Ceramic Brackets (Clarity™ ADVANCED, 3M Unitek). These brackets were used with two types of elastomeric ligatures: Conventional Elastomeric Ligatures (CEL) (Clear medium mini modules) and Unconventional Elastomeric Ligatures (UEL) (Clear medium slide ligatures, Leone orthodontic products). The aligning and the retraction wires were used, i.e., 0.014″ nickel titanium (NiTi) wires and 0.019″ × 0.025″ SS wires, respectively. A universal strength testing machine was used to measure the friction produced between the different bracket, archwires, and ligation combination. This was done with the use of a custom-made jig being in position.

Results: Mean, standard deviation, and range were computed for the frictional values obtained. Results were subjected to statistical analysis through ANOVA. The frictional resistance observed in the new Clarity Advanced bracket with a conventional elastomeric ligature was almost similar with the Clarity metal slot bracket with a conventional elastomeric ligature. When using the UEL, the Clarity Advanced bracket produced lesser friction than the conventional metal bracket; but not less than the ceramic metal slot bracket. Ceramic SLB produced lesser friction when compared with the Clarity Advanced bracket with UEL, but the metal SLB produced the least friction among all the groups and subgroups.

Conclusion: The present study concluded that the SS SLB produced least friction among all groups. Using the archwire and ligation method, frictional forces observed in the Clarity Advanced bracket and the conventional ceramic with metal slot bracket were almost similar; but the least resistance was determined in SS CB using both the ligation (CEL and UEL) system.

Key Words: Clarity Advanced brackets, conventional elastomeric ligatures, friction, self-ligating brackets, sliding mechanics, unconventional elastomeric ligatures

Introduction

Friction is defined as a force tangential to the common boundary of two bodies in contact that resists the motion or tendency to the motion of one relative to the other.[1,2] The magnitude of the frictional force varies with the normal force that pushes the two surfaces together.

Tooth movement takes place as a series of short steps rather than a smooth continuous motion. Initially, static friction between the archwire and the bracket must be overcome to initiate tooth movement. While the tooth is moving, kinetic friction occurs as the crown of the tooth tips in the direction of applied force.[3]

The concept of friction or "tribology" has an important role in day to day orthodontic practice. It is considered "the evil of all motions" as far as orthodontics is concerned. Orthodontic tooth movement involves two types of mechanics:

1. Friction mechanics or sliding mechanics and
2. Frictionless mechanics or sectional/loop mechanics.[4]

The success of orthodontic tooth movement with preadjusted appliances depends to a large extent on the ability of the orthodontic archwire to slide through brackets and tubes. The major disadvantage with the use of sliding mechanics is the friction that is generated between the bracket and the archwire during orthodontic tooth movement.[5]

When a bracket is sliding along an archwire, these laws imply that friction arises from the force normally acting on the points of contact. Possible components of this force are:

1. Engagement of the archwire in brackets that are out of alignment
2. Ligatures pressing the archwire actively against the base of the slot
3. Active torque in the rectangular wire
4. Two-point contact between the bracket and archwire resists tipping, causing bodily tooth movement.

Hence, for appropriate tooth movement and for the success in reducing treatment time, there has to be minimal friction between the bracket - archwire - ligature interface.

The Clarity™ ADVANCED Ceramic Bracket made using fine-grained ceramic material, is one of the newest entrants in the esthetic bracket segment and is designed for patient comfort. It has rounded corners to minimize binding and notching. There is generous under the tie wing area to accommodate easy ligation. This design of the Clarity Advanced Bracket helps to reduce the friction resistance. Till date, no studies have been published regarding frictional forces generated by this bracket.

Therefore, this study was undertaken to compare the frictional forces generated by the Clarity Advanced ceramic bracket with the conventional brackets (CB) (metal and ceramic) using both the conventional and Unconventional Elastomeric Ligatures (UEL) (Slide, Leone Orthodontic product) and with the self-ligating bracket (SLB) (metal and ceramic) in dry state.

The aim of this *in vitro* study was to determine the frictional forces generated by the new Clarity Advanced Bracket using conventional and UEL. Furthermore, to compare these forces with that generated by CB (both metal and ceramic) using both conventional and UEL and by SLB (both metal and ceramic).

Materials and Methods

In this *in vitro* study, maxillary premolar brackets were used to perform the experiment in the dry state. The MBT prescription brackets of 0.022″ × 0.028″ nominal slot dimension manufactured by 3M Unitek™, Monrovia, Calif were used. Totally, 40 brackets each of stainless steel (SS) CB (Victory series), Conventional Ceramic bracket with metal slot (Clarity Bracket), and New Ceramic bracket (Clarity™ ADVANCED Ceramic Brackets) were used. Totally, 20 of each bracket of SS SLB (SmartClip) and Ceramic SLB (Clarity SL) were used.

Two types of Orthodontic wires used were manufactured by 3M Unitek™, Monrovia, and Calif, each with a cross-section of: 0.014″ nickel titanium (NiTi) wire and 0.019″ × 0.025″ SS wire.

Wires were ligated into the bracket slots using the Conventional Elastomeric Ligatures (CEL) (Clear medium mini-modules, 3M Unitek™, Monrovia, Calif) and UEL (Clear medium Slide Ligatures, Leone Orthodontic Products).

A 0.014″ NiTi archwire was used to simulate the clinical alignment and leveling stage, whereas the 0.019″ × 0.025″ SS archwire was used to simulate the clinical stage of retraction during the friction mechanics.

The experimental model comprised a jig, so that the bracket-wire-ligature assembled on it moved vertically, to measure axial tensile force by Instron load. The wire was moved with the speed of 6 mm in 20 s and peak force variation was displayed onto the computer screen. The experiment was conducted in dry condition.

Each of the six bracket-wire-ligation combinations was tested 10 times, with new elastomeric ligature on each trial, to minimize the influence of elastic deformation.

In this study, Kusy's frictional test design was simulated to evaluate the coefficient of friction in the dry state for SS and NiTi wires against SS brackets.[6] A constant 100 g force was suspended from the power arm to simulate single load acting at the center of resistance; this load was kept constant for all tests.

Results

The present study was performed in Department of Orthodontics and Dentofacial Orthopedics, MR Ambedkar Dental College and Hospital, Bangalore in association with Innovation Center, Electronic City, 3M India, Bangalore.

The materials used for the study included different commercial orthodontic brackets and ligatures and the friction generated by different combinations of these materials was tested and compared. The orthodontic archwires used were 0.014″ NiTi and 0.019″ × 0.025″ SS, and the friction between the different bracket - archwire - ligature combinations was measured by using a universal strength testing machine.

The study comprised of 8 groups and each group was further divided into 2 subgroups (Table 1). The results were subjected to statistical analysis. The mean and standard deviation for 8 groups tested were established.

Discussion

Friction refers to a force that appears whenever two objects rub against each other. When surfaces of two bodies are in contact, the interactive force may have components both perpendicular and tangent to the surface. The perpendicular component is the applied force, and the tangential component is the frictional force. If there is relative sliding at the surface, the frictional force acts in two opposite directions of this motion. This ratio of the tangential force to applied force during sliding is called the coefficient of friction and depends upon the nature of two surfaces in contact.[7]

Fixed appliances used for orthodontic therapy are always associated with the generation of friction between the bracket - wire - ligature interface. During retraction phase, anterior teeth are retracted by sliding the archwire through the brackets in the posterior segments. As a result of this, the frictional forces are generated. This force resists the movement of the archwire through the posterior segment, and may transmit excessive force to the posterior anchor teeth leading to loss of posterior anchorage. It has been proven in previous studies that the material properties of the bracket, wire, and the ligature play an important role in the amount of friction generated and tooth movement can occur only when applied forces adequately overcome the frictional force.[6]

As the tooth movement occurs, a part of the applied force is split as frictional force and the remainder is distributed to the biological structures. Therefore, the force applied should be optimal, but greater than that which will be dissipated as a frictional force. This helps in decreasing the retraction phase and improvise biological tissue response.[7] Hence, there has to be negligible friction between the bracket - archwire - ligature for optimizing the tooth movement and minimizing the treatment time.

Whenever the orthodontic force is applied, crown movement precedes root displacement. Because of the width and compressibility of the periodontal ligament, the teeth will tip. Tipping occurs until two-point contacts are established between the archwire and the bracket diagonally. These movements will occur immediately on force application and before sliding of the teeth along the archwire. This in turn increases the friction from binding between archwire and bracket restricting the movement of the intact tooth.[3,8,9]

As the number of adults seeking orthodontic care increased, orthodontists felt the need to provide their patients with more esthetically "appealing" appliances. This perceived need motivated manufacturers to provide acceptable esthetic brackets including the ceramic brackets. Ceramic brackets are known to cause nicks in the arch wires, resulting in more friction between the bracket and the archwire, which can decrease the efficiency of tooth movement.[10] Polycrystalline brackets have rougher and more porous surface, hence resulting in a higher co-efficient of friction than monocrystalline brackets. However, certain studies did not find any significant advantage of monocrystalline brackets over polycrystalline ceramic brackets with regard to their frictional characteristics.[11-13] Later, the metal reinforced ceramic bracket was introduced to reduce the friction resistance during the sliding mechanics.[14]

Table 1: Grouping of samples for the study.
Group I: Conventional metal bracket with CEL
Group II: Conventional metal bracket with UEL
Group III: Metal SLB
Group IV: Conventional ceramic bracket (metal slot) with CEL
Group V: Conventional ceramic bracket (metal slot) with UEL
Group VI: Ceramic SLB
Group VII: Clarity Advanced bracket with CEL
Group VIII: Clarity Advanced bracket with UEL
CEL: Conventional elastomeric ligation, UEL: Unconventional elastomeric ligation, SLB: Self-ligating bracket

Recently, a new type of ceramic bracket, Clarity Advanced bracket (3M Unitek) has been introduced. It has rounded edges that the manufacturers claim, contributes to less friction. Hence in the present study, this bracket (Clarity Advanced) was compared with conventional SS bracket, SS SLB, Clarity with metal slot bracket, and Clarity SLB for friction.

The method of archwire ligation would appear to be an important determinant in the generation of friction.[4] They exert a force against the archwire, pressing the wire against the bracket. Elastomeric ligatures are believed to exert 50-150 g of force at the time of seating, thereby contributing to the friction. To reduce the frictional force from ligation, various ligation methods have evolved to the extent of incorporation of ligation in bracket systems; these are known as SLB. The present *in vitro* study, evaluated the friction produced by elastomeric ligatures with different design and dimension. The elastomeric ligatures used were CEL, also called the O-ring; and the slide ligatures which are coated polyurethane making it more flexible, soft, and elastic.

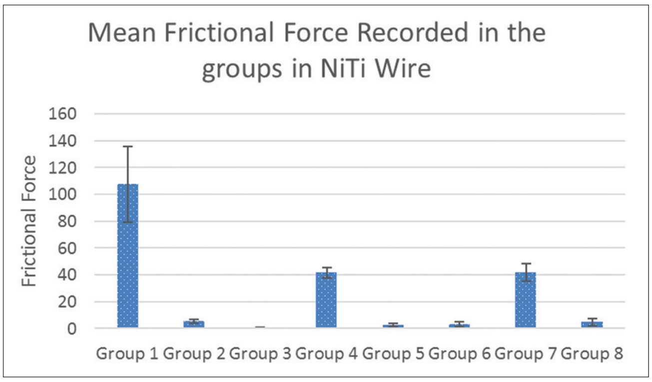
Among the 3 stages of the fixed orthodontic mechanotherapy, friction is mainly produced during the aligning and leveling stage; and the retraction stage (individual canine retraction or the en masse retraction). The kinetic coefficient of friction depends on the materials of the archwire-bracket couple.[15] In the present study, 0.014″ NiTi and 0.019″ × 0.025″SS archwire was used. During the initial stages of treatment when the teeth may be severely misaligned relative to each other, small flexible archwires like the 0.014″ NiTi archwire provide low resistance to sliding, which allows a greater portion of the applied force to be available for "unraveling" the teeth. Hence, the 0.014″ NiTi wire was used in the present study, to simulate the aligning and leveling stage of fixed mechanotherapy. A 0.019″ × 0.025″ SS wire was used in 0.022″ × 0.028″ slot dimension of MBT prescription, in order to simulate the clinical condition of the retraction stage of fixed mechanotherapy. Several studies have demonstrated a significant decrease in friction for SLB compared with CB design. The present study was performed to evaluate the friction produced by three types of ligation system (conventional elastomeric ligation, UEL, and the self-ligation system) on the various bracket and archwire combination.

MBT brackets (0.022″ × 0.025″ slot) with the 0.014″ NiTi and 0.019″ × 0.025″ SS archwire and CEL showed increased frictional resistance when compared with both the SLB and the MBT brackets with UEL. These findings were in accordance with those reported in previous studies.[16]

When comparing the NiTi wire group with various bracket and ligation combinations, the frictional resistance was observed highest in the conventional metal bracket with CEL and least with the metal SLBs. One explanation for the increase in friction with NiTi wire might be the adherence of the wire material to the material of the slot. These results fully agree with those of previous studies.[2,4,6,15,16] The significant differences between SLB and CEL on Conventional metal bracket in the current study are very similar to those reported by other studies,[4,17] where the single bracket experimental model was used. The Clarity metal slot bracket with UEL showed lesser frictional resistance than the Clarity SLBs. This result was in accordance with previous studies[8,12,18] (Table 2 and Graph 1).

Using the CEL, there was no significant difference in frictional resistance in the Clarity metal slot bracket and the new Clarity Advanced bracket. When using the UEL, the least friction was observed in the Clarity metal slot bracket when compared with the conventional metal bracket. As the morphologies of the ceramic bracket were improvised by adding metal insert, it not only improves the esthetics, but also reduces friction coefficient.[18-20] However, in the present study, there was no significant difference being observed in the conventional metal bracket and the Clarity Advanced bracket.

When comparing the frictional forces in the SS archwire among the various bracket and ligation systems, the maximum frictional resistance was observed in the conventional metal



Graph 1: Mean fictional force recorded in the groups in nickel-titanium wire.

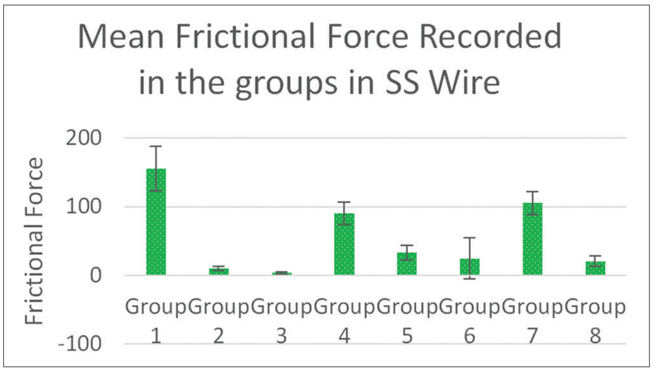
Table 2: ANOVA.					
Source of variation	**Df**	**Sum of squares**	**Mean sum of squares**	***F***	***P*-value**
Between groups	7	97180	13882.86	127.3537	<0.001*
Within groups	72	7848.736	109.0102	-	-
Total	79	105028.7	-	-	-

*Denotes the significant difference. When comparing the groups, the higher mean frictional force was recorded in Group 1 followed by Group 4, Group 7, Group 2, Group 8, Group 6, Group 5, and Group 3, respectively. The difference in mean frictional force among the groups was found to be statistically significant (*P*<0.001). In order to find out among which pair of groups there exist a significant difference, we carry out multiple comparisons using Bonferroni method. SS: Sum of squares

bracket with CEL and the least in the Metal SLB. These results fully agree with the results of the previous studies.[2,3,6,8,15] Based on the results of the present study, there was a significant difference recorded in the frictional forces in the conventional metal bracket, the Clarity Advanced bracket, and the Clarity metal slot bracket; in the descending order using both the CELs and the UELs (Table 2 and Graph 2).

Furthermore, in both the archwire groups, the metal SLBs produced lesser friction in comparison to the Clarity SLBs.

When considering the individual group of bracket-ligation combination with the two types of archwire wire alloy, in the present study, there was a significantly lower friction level for the NiTi archwire group when compared to the SS archwire group (Tables 4-11). On the other hand, no significant differences were found between NiTi and SS archwires in other studies.[8,19] However, other studies comparing the frictional resistance of these two alloys have shown conflicting results: Some studies found higher frictional forces with SS wires,[6,15] and others with NiTi wires.[12] This variability is probably due



Graph 2: Mean frictional force recorded in the groups in stainless steel wire.

Table 3: ANOVA.					
Source of variation	**Df**	**Sum of squares**	**Mean sum of squares**	***F***	***P*-value**
Between groups	7	217676.813	31096.688	137.991	<0.001*
Within groups	72	16225.471	225.354	-	-
Total	79	233902.285	-	-	-

*Denotes the significant difference. The Higher mean frictional force was recorded in Group 1 followed by Group 7, Group 4, Group 5, Group 8, Group 6, Group 2, and Group 3, respectively. The difference in mean frictional force among the groups was found to be statistically significant (*P*<0.001). In order to find out among which pair of groups there exist a significant difference, we carry out multiple comparisons using Bonferroni method

Table 4: Comparison of mean frictional force between the two wires in Group 1 (*t*-test).						
Wire	**Mean**	**SD**	**SEM**	**Mean difference**	***t***	***P*-value**
0.014" NiTi Archwire	107.710	28.257	8.936	−47.540	−3.482	0.003*
0.019"×0.025" SS Archwire	155.250	32.644	10.323			

*Denotes the significant difference. SD: Standard deviation, SEM: Standard error of mean, SS: Stainless steel, NiTi: Nickel titanium

Table 5: Comparison of mean frictional force between the two wires in Group 2 (*t*-test).

Wire	Mean	SD	SEM	Mean difference	*t*	*P*-value
0.014" NiTi Archwire	5.380	1.535	0.486	−4.920	−4.629	<0.001*
0.019"×0.025" SS Archwire	10.300	2.990	0.946			

*Denotes the significant difference. SD: Standard deviation, SEM: Standard error of mean, SS: Stainless steel, NiTi: Nickel titanium

Table 6: Comparison of mean frictional force between the two wires in Group 3 (*t*-test).

Wire	Mean	SD	SEM	Mean difference	*t*	*P*-value
0.014" NiTi Archwire	0.927	0.195	0.062	−2.590	−7.282	<0.001*
0.019"×0.025" SS Archwire	3.517	1.108	0.350			

*Denotes the significant difference. SD: Standard deviation, SEM: Standard error of mean, SS: Stainless steel, NiTi: Nickel titanium

Table 7: Comparison of mean frictional force between the two wires in Group 4 (*t*-test).

Wire	Mean	SD	SEM	Mean difference	*t*	*P*-value
0.014" NiTi Archwire	41.640	3.885	1.229	−48.790	−9.237	<0.001*
0.019"×0.025" SS Archwire	90.430	16.244	5.137			

*Denotes the significant difference. SD: Standard deviation, SEM: Standard error of mean, SS: Stainless steel, NiTi: Nickel titanium

Table 8: Comparison of mean frictional force between the two wires in Group 5 (*t*-test).

Wire	Mean	SD	SEM	Mean difference	*t*	*P*-value
0.014" NiTi Archwire	2.814	1.084	0.343	−30.225	−8.818	<0.001*
0.019"×0.025" SS Archwire	33.039	10.785	3.410			

*Denotes the significant difference. SD: Standard deviation, SEM: Standard error of mean, SS: Stainless steel, NiTi: Nickel titanium

Table 9: Comparison of mean frictional force between the two wires in Group 6 (*t*-test).

Wire	Mean	SD	SEM	Mean difference	*t*	*P*-value
0.014" NiTi Archwire	3.390	1.622	0.513	−11.374	−8.541	<0.001*
0.019"×0.025" SS Archwire	14.764	3.886	1.229			

*Denotes the significant difference. SD: Standard deviation, SEM: Standard error of mean, SS: Stainless steel, NiTi: Nickel titanium

to the differences in experimental settings and acquisition systems,[2] the different points of force application, and the different angulation between bracket and wire that in many studies is not zero. Therefore, a direct comparison of the various studies on this topic is complex.

Table 10: Comparison of mean frictional force between the two wires in Group 7 (*t*-test).

Wire	Mean	SD	SEM	Mean difference	*t*	*P*-value
0.014" NiTi Archwire	41.890	6.711	2.122	−63.316	−11.221	<0.001*
0.019"×0.025" SS Archwire	105.206	16.533	5.228			

*Denotes the significant difference. SD: Standard deviation, SEM: Standard error of mean, SS: Stainless steel, NiTi: Nickel titanium

Table 11: Comparison of mean frictional force between the two wires in Group 8 (*t*-test).

Wire	Mean	SD	SEM	Mean difference	*t*	*P*-value
0.014" NiTi Archwire	4.981	2.695	0.852	−15.404	−6.010	<0.001*
0.019"×0.025" SS Archwire	20.385	7.645	2.417			

*Denotes the significant difference. SD: Standard deviation, SEM: Standard error of mean, SS: Stainless steel, NiTi: Nickel titanium

Contemporary orthodontics relies on various bonded attachments, archwires, and other devices to achieve tooth movement. These components are composed of varying materials with their own distinctive physical and mechanical properties. The demands made on them are complex because they are placed under many stresses in the oral environment. These include immersion in saliva and ingested fluids, temperature fluctuations, and masticatory and appliance loading.

Since this study, was conducted in the dry field, the frictional force obtained may not be similar to the frictional force found in the oral environment as biological factors such as saliva and acquired pellicle also contribute to frictional resistance. Among the wet state studies, soaking elastomeric ligatures in saliva led to a reduction in friction, regardless of the bracket system,[4] but there are also studies,[3,21-23] confirming that the frictional force significantly increases in the presence of saliva. The problem in comparing these studies is the difference in lubricants used, with some using human saliva and others artificial saliva. However, Kusy[24] stated that experiments conducted in artificial saliva were invalid because it is no substitute for human saliva.

Conclusion

The present study was performed, to evaluate the friction produced by three types of ligation method (conventional elastomeric ligation, UEL, and the selfligation system) on the various brackets of 0.022″ × 0.028″ slot MBT prescription and the two archwires (0.014″ NiTi and 0.019″ × 0.025″ SS) combinations.

The inference of the results of the study:

1. The frictional resistance observed in the new Clarity Advanced bracket with conventional elastomeric ligature was almost similar to the Clarity metal slot bracket with a

conventional elastomeric ligature.
2. When using the UEL, the Clarity Advanced bracket produced lesser friction than the conventional metal bracket; but not less than the ceramic metal slot bracket.
3. UEL produced lesser friction when compared with CEL during alignment with 0.014″ NiTi wire and sliding mechanics with 0.019″ × 0.025″ SS wire, but was not significantly different with the friction produced by the SLB.
4. Ceramic SLB produced lesser friction when compared with the Clarity Advanced bracket with UEL, but the metal SLB produced the least friction among all the groups and subgroups.

References

1. Rossouw EP. Friction: An overview. Semin Orthod 2003;9(4):218-22.
2. Drescher D, Bourauel C, Schumacher HA. Frictional forces between bracket and archwire. Am J Orthod Dentofacial Orthop 1989;96(5):397-404.
3. Bednar JR, Gruendeman GW, Sandrik JL. A comparative study of frictional forces between orthodontic brackets and arch wires. Am J Orthod Dentofacial Orthop 1991;100(6):513-22.
4. Hain M, Dhopatkar A, Rock P. The effect of ligation method on friction in sliding mechanics. Am J Orthod Dentofacial Orthop 2003;123(4):416-22.
5. Kaur G, Goyal S, Rajpal S, Gera A. Comparative evaluation of frictional forces of conventional and self-ligating bracket systems: An *in vitro* study. J Indian Orthod Soc 2013;47(4):211-6.
6. Kapila S, Angolkar PV, Duncanson MG Jr, Nanda RS. Evaluation of friction between edgewise stainless steel brackets and orthodontic wires of four alloys. Am J Orthod Dentofacial Orthop 1990;98(2):117-26.
7. Huffman DJ, Way DC. A clinical evaluation of tooth movement along arch wires of two different sizes. Am J Orthod 1983;83(6):453-9.
8. Loftus BP, Artun J, Nicholls JI, Alonzo TA, Stoner JA. Evaluation of friction during sliding tooth movement in various bracket-arch wire combinations. Am J Orthod Dentofacial Orthop 1999;116(3):336-45.
9. Frank CA, Nikolai RJ. A comparative study of frictional resistances between orthodontic bracket and arch wire. Am J Orthod 1980;78(6):593-609.
10. Bishara SE, Fehr DE. Ceramic brackets: Something old, something new, a review. Semin Orthod 1997;3(3):178-88.
11. Kusy RP. Morphology of polycrystalline alumina brackets and its relationship to fracture toughness and strength. Angle Orthod 1988;58(3):197-203.
12. Karamouzos A, Athanasiou AE, Papadopoulos MA. Clinical characteristics and properties of ceramic brackets: A comprehensive review. Am J Orthod Dentofacial Orthop 1997;112(1):34-40.
13. Chen SS, Greenlee GM, Kim JE, Smith CL, Huang GJ. Systematic review of self-ligating brackets. Am J Orthod Dentofacial Orthop 2010;137(6):726.e1-726.e18.
14. Eliades T, Brantley W. Orthodontic Materials: Scientific and Clinical Aspects. International ed. Geneva, Switzerland: International Organization for Standardization; 2007. p. 151-2.
15. Kusy RP, Whitley JQ, Prewitt MJ. Comparison of the frictional coefficients for selected archwire-bracket slot combinations in the dry and wet states. Angle Orthod 1991;61(4):293-302.
16. Gandini P, Orsi L, Bertoncini C, Massironi S, Franchi L. *In vitro* frictional forces generated by three different ligation methods. Angle Orthod 2008;78(5):917-21.
17. Thomas S, Sherriff M, Birnie D. A comparative *in vitro* study of the frictional characteristics of two types of self-ligating brackets and two types of pre-adjusted edgewise brackets tied with elastomeric ligatures. Eur J Orthod 1998;20(5):589-96.
18. Kusy RP, Whitley JQ. Frictional resistances of metal-lined ceramic brackets versus conventional stainless steel brackets and development of 3-D friction maps. Angle Orthod 2001;71(5):364-74.
19. Cacciafesta V, Sfondrini MF, Scribante A, Klersy C, Auricchio F. Evaluation of friction of conventional and metal-insert ceramic brackets in various bracket-archwire combinations. Am J Orthod Dentofacial Orthop 2003;124(4):403-9.
20. Nishio C, da Motta AF, Elias CN, Mucha JN. *In vitro* evaluation of frictional forces between archwires and ceramic brackets. Am J Orthod Dentofacial Orthop 2004;125(1):56-64.
21. Thorstenson GA, Kusy RP. Resistance to sliding of self-ligating brackets versus conventional stainless steel twin brackets with second-order angulation in the dry and wet (saliva) states. Am J Orthod Dentofacial Orthop 2001;120(4):361-70.
22. Thorstenson GA, Kusy RP. Effects of ligation type and method on the resistance to sliding of novel orthodontic brackets with second-order angulation in the dry and wet states. Angle Orthod 2003;73(4):418-30.
23. Chang CJ, Lee TM, Liu JK. Effect of bracket bevel design and oral environmental factors on frictional resistance. Angle Orthod 2013;83(6):956-65.
24. Kusy RP. Materials and appliances in orthodontics: Brackets, arch wires, and friction. Curr Opin Dent 1991;1(5):634-44.