Original Article

Friction of Conventional and Silica-Insert Ceramic Brackets in Various Bracket-Wire Combinations

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ABSTRACT

Objective: To compare the level of friction resistance (FR) of conventional and silica-insert ceramic brackets using various bracket-wire combinations and angulations.

Materials and Methods: Four types of ceramic brackets were examined: (1) polycrystalline alumina bracket (PCA-C), (2) polycrystalline alumina bracket with a stainless steel (SS) slot (PCA-M), (3) polycrystalline alumina bracket with a silica layer (PCA-S), and (4) monocrystalline sapphire bracket (MCS). A conventional SS bracket was used as the control. The static and kinetic FR in four bracket-wire angulations (0°, 5°, 10°, and 15°) was examined using SS and β-titanium (β-Ti) orthodontic wires, 0.019 × 0.025 inches in size, under elastic ligature in the dry state.

Results: The FR generated by the PCA-S bracket was significantly lower than that generated with the other ceramic brackets, and was similar to that of the SS bracket. The PCA-S bracket showed the lowest FR with both the SS and the β-Ti wires at zero bracket angulation. The FR to sliding increased rapidly and nonlinearly when the bracket wire angulation was $>5°$. The PCS-S bracket showed the lowest FR from 5° to 15° of angulation. The MCS bracket demonstrated the highest increase in FR from 0° to 15° of angulation, showing the highest FR at 15° of angulation.

Conclusion: PCA-S showed minimal FR among the ceramic brackets, and was comparable to the conventional SS bracket. The silica layer and rounded edges of the ceramic slot lowered FR considerably.

KEY WORDS: Friction; Ceramic bracket

INTRODUCTION

Ceramic brackets are currently under development and were originally introduced because of increasing esthetic demands from orthodontic patients. However, their high coefficient of friction has limited their use.[1–6] It has been reported that the friction resistance (FR) of ceramic brackets is increased by their rough surface conditions. In addition, the chemical characteristics of alumina on a ceramic surface can cause a metal wire to adhere to the alumina surface.[7] A high FR can cause debonding of the brackets, and can reduce the orthodontic force by 12–60%, making it very difficult to apply optimal force.[8,9]

In an attempt to improve the problems associated with FR, a combination bracket, in which a metal slot was inserted into a ceramic bracket, was introduced.[10,11] The metal-insert ceramic bracket was designed to take into account the lower frictional characteristics of the metal bracket. In order to reduce FR, the polycrystalline ceramic bracket was designed with a smoothened edge and slot base.[12,13] Recently, a silica layer coating over the rough surface of a polycrystalline alumina bracket was introduced with the aim of reducing FR.

However, there have been problems and difficulties associated with mechanically simulating tooth movement along the arch wire, as well as in measuring FR in vitro. There are many factors that affect FR to sliding, such as (1) round versus rectangular arch wires,[11,14,15] (2) type and force of ligation,[15,16] (3) wet or dry environment,[17–18] (4) characteristics of relative motion at the bracket/wire interface,[19–20] and (5) bracket

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Table 1. Bracket, Archwire, and Ligature Materials Evaluated

Material	Design	Product	Nominal Dimensions (inches)	Prescription	
				Angulation (°)	Torque (°)
Bracket					
Polycrystalline alumina (PCA-S)	Silica inserted	CrystalineV[a]	0.022	0	−7
Polycrystalline alumina (PCA-M)	Metal inserted	Clarity[b]	0.022	0	−7
Polycrystalline alumina (PCA-C)	Conventional	Transcend 6000[b]	0.022	0	−7
Monocrystalline ceramic (MCS)	Conventional	Inspire[c]	0.022	0	−7
Stainless steel (SS)	Metal	Kosaka[a]	0.022	0	−7
Archwire					
Stainless steel		Rectangular[c]	0.019 × 0.025		
β-titanium		TMA[c]	0.019 × 0.025		
Ligature					
Elastic ligation		Molded O[c]	0.120		

[a] Tomy, Tokyo, Japan.
[b] 3M Unitek, Monrovia, Calif.
[c] Ormco, Glendora, Calif.

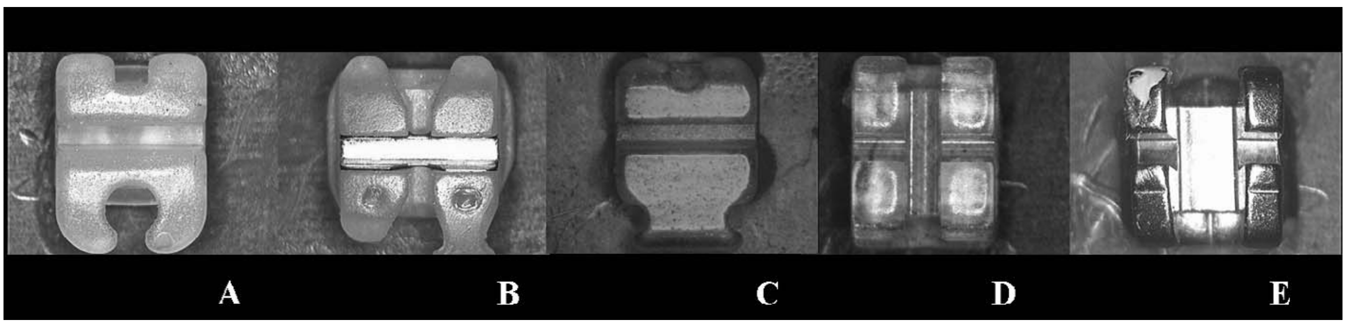

Figure 1. Tested brackets: (A) PCA-S; (B) PCA-M; (C) PCA-C; (D) MCS; (E) SS (magnification 20×).

and wire materials.[15,21] For these reasons, there have been many studies examining the FR of ceramic brackets under different experimental conditions.[1,4–12] The FR of ceramic brackets is generally measured by moving a wire parallel to the bracket slot.[2–6] However, in practice, teeth tend to move by repeatedly tipping and uprighting rather than by moving parallel to the bracket slot.[22,23]

With regard to the tipping movement of a tooth, Kusy and Whitley[19,20] measured the critical angulation (θ) which is the angle at which the space between the bracket and wire is lost and binding between the bracket and archwire begins to occur. According to a study based on index-engagement index plots, the maximum critical angle was 3.7° when wires of a minimum size of 0.016 inches were tested in a 0.022-inch slot. Hence, binding would increase abruptly, and sliding would cease at higher angulations.[20] Beyond this critical angulation (θ), FR was found to be influenced by the physical characteristics of the materials themselves, such as surface roughness, hardness, yield strength, and elastic modulus.[24] Therefore, an individual bracket-wire combination tends to demonstrate different friction levels according to the change in the bracket-wire angulation.

This study examined the recently introduced ceramic brackets with a lower FR. The FR was measured by forming specific angles between the bracket and wire under elastic ligation.

MATERIALS AND METHODS

Five different types of upper first bicuspid brackets with 0.022-inch slots and 0.019 × 0.025-inch rectangular arch wires made from two different alloys were chosen (Table 1; Figure 1). Twenty nonrepeated evaluations for each bracket-wire combination were carried out at angulations of 0°, 5°, 10°, and 15°. A total of 800 brackets were used. The same person placed all the elastomeric rings (Ormco, Glendora, Calif) immediately before each test in order to avoid ligature force decay. Prior to the evaluation, each wire and bracket was cleaned with 95% ethanol and dried with compressed air. All the tests were carried out in the dry state, in prevailing air, and at an ambient oral temperature of 34°C.

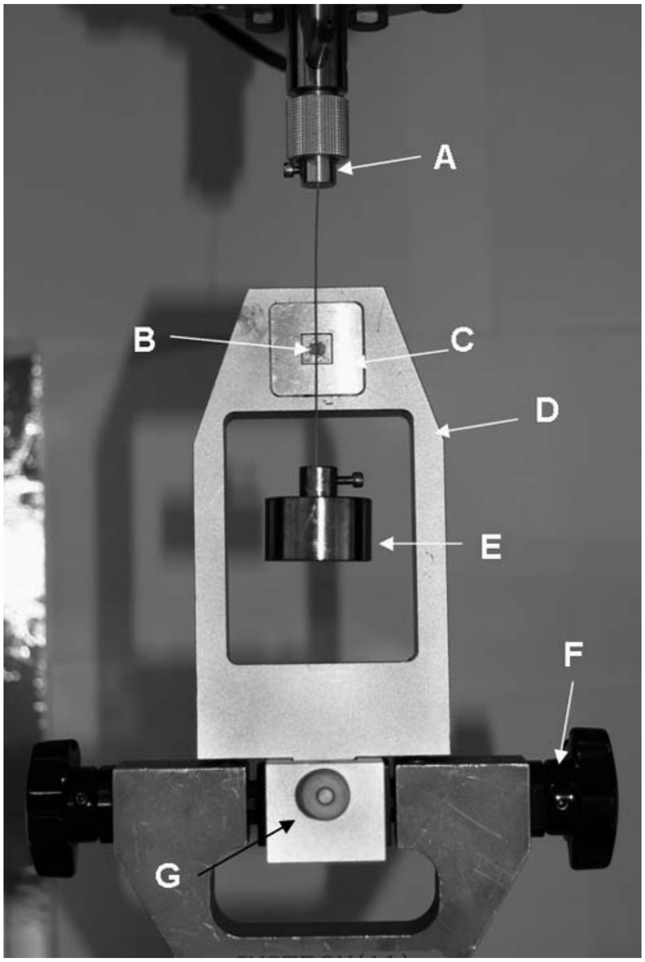

Figure 2. Testing machine, bracket-wire assembly, and force measuring equipment. (a) Rotation fixture. (b) Inner aluminum block. (c) Outer aluminum block. (d) Anterior-posterior adjustable block. (e) Weight (150 g). (f) Horizontal adjustable joint. (g) Anterior-posterior adjusting handle.

The precise angles between the bracket and the experimental wire were formed using a sight modification of the method reported by Redlich et al.[25] The four outer blocks were specially designed to fit in accordance to each alumina block with different angulations (0°, 5°, 10°, and 15°). These blocks were combined and inserted into the adjustable table, which was connected to a Universal Testing Machine (Instron 6002, Canton, Mass; Figure 2). A 10-cm wire was tied to the bracket by elastic ligation. The upper end of the wire was connected to the tension-loading cell of a Universal Testing Machine, and the lower end was fixed to a 150-g weight. A rotating fixture, which was connected to the upper end of the wire, was used to help insert the wire in the bracket slot without producing any torque.

The experimental wire was connected to a load cell with a range of up to 500 KgN and was pulled through 10 mm with a crosshead speed of 5 mm/min. The static frictional force was recorded by measuring the maximum force at the initial extension, and the kinetic frictional force was calculated by averaging the frictional force after reaching the static friction peak. Scanning electron microscopy (SEM; Hitachi-800, Hitachi, Tokyo, Japan) was used to evaluate the morphology of the different brackets. Using a vapor-deposition process, all the ceramic brackets were coated with gold-palladium in order to improve their conductivity. Each bracket was examined at 10 kV in secondary electron mode.

The mean and the standard deviation of the FR were calculated. The effect of three variables (bracket, wire, and angulation) on the FR was analyzed initially using a two-way analysis of variance and a Tukey's test with a 5% level of significance. A Student's *t*-test was used to examine the differences between static and kinetic friction, as well as between the stainless steel (SS) and β-titanium (β-Ti) wires.

RESULTS

Analysis of the Levels of Static and Kinetic FR With the Different Types of Bracket-Wire Combination (No Bracket-Wire Angulation)

All the bracket-wire combinations showed a significantly higher static FR than kinetic FR ($P < .05$). With the exception of the polycrystalline alumina (PCA-C) bracket, the β-Ti wire generated significantly higher FR levels than the SS wire ($P < .05$) (Table 2). The polycrystalline alumina bracket with a silica layer (PCA-S bracket) showed the lowest static and kinetic FR with the SS wire. The PCA-C bracket produced the largest friction, showing a static and kinetic friction of 260.6 and 236.3 g, respectively. For the β-Ti wire, the PCA-S bracket produced the lowest FR in kinetic friction together with the SS bracket. The monocrystalline sapphire (MCS) bracket produced the highest FR.

Analysis of the Levels of Static and Kinetic FR With Different Bracket-Wire Angulations

SS wire-bracket combination. PCA-S showed the lowest FR at every degree of angulation. The polycrystalline alumina bracket with a stainless steel (SS) slot (PCA-M bracket) showed the lowest increase in kinetic FR, by 2.1-fold (179.2 g at 0°, 382.1 g at 15°). The PCA-C and MCS brackets showed the highest increase in kinetic FR, by 1.7-fold, from 0° to 5°, and by 2.1-fold, from 5° to 10° of angulation, respectively, thus showing the highest FR from 10° to 15° of angulation. The MCS bracket demonstrated the highest increase in kinetic and static FR, by 3.7-fold (199.8 g at 0° and 739.8 g at 15°) and 3.3-fold (248.8 g at 0° and 835.0 g at 15°), respectively. (Table 2; Figures 3 and 4).

Table 2. Kinetic and Static Frictional Forces (g) of Groups for Each Wire and Angulation; Tukey Tests of the Five Brackets Are Also Shown

Wire	FR Type	Bracket	Angulation				
			0°	5°	10°	15°	Tukey test
SS	Kinetic	PCA-S (V)	120.2 ± 16.5	162.4 ± 27.5	215.6 ± 28.9	311.7 ± 34.4	0 < 5 < 10 < 15
		PCA-M (C)	179.2 ± 30.3	233.0 ± 39.7	315.9 ± 51.6	382.1 ± 54.1	0 < 5 < 10 < 15
		PCA-C (T)	236.3 ± 29.1	392.7 ± 50.8	446.1 ± 45.3	636.1 ± 102.2	0 < 5 < 10 < 15
		MCS (I)	199.7 ± 43.9	243.5 ± 60.2	513.0 ± 100.3	739.8 ± 111.9	0, 5 < 10 < 15
		SS (K)	149.5 ± 29.8	168.0 ± 31.5	304.8 ± 57.9	494.1 ± 54.2	0, 5 < 10 < 15
		Tukey test	V < K < C, I < T	K, V < C, I < T	V < C, K, < I, T	V < C < K < I, T	
	Static	PCA-S (V)	159.5 ± 46.1	187.8 ± 57.0	269.1 ± 41.2	361.8 ± 47.7	0, 5 < 10 < 15
		PCA-M (C)	239.6 ± 49.4	304.2 ± 49.4	401.9 ± 57.4	441.2 ± 51.8	0 < 5 < 10, 15
		PCA-C (T)	260.6 ± 36.5	437.9 ± 41.4	515.8 ± 45.1	726.3 ± 69.1	0 < 5, 10 < 15
		MCS (I)	248.8 ± 42.3	272.4 ± 47.3	559.6 ± 155.6	835.0 ± 281.1	0, 5 < 10 < 15
		SS (K)	176.8 ± 71.3	200.2 ± 35.5	330.0 ± 58.8	458.7 ± 174.9	0, 5 < 10 < 15
		Tukey test	V < K < I, C, T	V, K < C, I < T	V, K < K, C < I, T	V, C < C, K < T, I	
β-Ti	Kinetic	PCA-S (V)	189.7 ± 45.0	169.1 ± 33.5	273.7 ± 54.7	536.3 ± 63.0	0, 5, 10 < 15
		PCA-M (C)	247.0 ± 53.3	280.5 ± 63.0	612.4 ± 67.3	660.1 ± 63.5	0, 5 < 10, 15
		PCA-C (T)	215.4 ± 9.2	475.1 ± 49.3	573.1 ± 87.8	650.0 ± 62.1	0 < 5 < 10 < 15
		MCS (I)	371.0 ± 75.8	245.9 ± 74.6	588.2 ± 74.9	867.6 ± 108.8	0 < 5 < 10 < 15
		SS (K)	568.2 ± 67.7	285.5 ± 48.9	568.2 ± 67.7	1028.3 ± 177.4	0, 5 < 10 < 15
		Tukey test	V, K < K, C, T < 1	V < I, C, K < T	V < C, I, K T	V < C, T < I < K	
	Static	PCA-S (V)	237.1 ± 57.9	209.8 ± 42.7	404.5 ± 56.5	693.2 ± 104.6	0, 5 < 10 < 15
		PCA-M (C)	281.4 ± 56.3	320.4 ± 54.4	701.1 ± 75.4	764.6 ± 87.6	0, 5 < 10, 15
		PCA-C (T)	283.5 ± 23.3	623.2 ± 45.4	667.3 ± 86.6	766.8 ± 35.1	0 < 5, 10 < 15
		MCS (I)	481.9 ± 57.1	294.2 ± 94.0	708.8 ± 113.2	1036.6 ± 169.4	0 < 5 < 10 < 15
		SS (K)	293.4 ± 61.8	369.6 ± 81.9	698.9 ± 85.6	1187.9 ± 168.6	0, 5 < 10 < 15
		Tukey test	V, C, T < C, T, K < I	V < C, I < C, K < T	V < C, I, K, T	V, C, T < I, K	

[a] Friction force data are presented as mean ± SD. $\alpha = 0.05$. FR indicates friction resistance; SS, stainless steel; PCA-S, polycrystalline alumina with a silica layer; V, CrystalineV; PCA-M, polycrystalline alumina with an SS slot; C, Clarity; PCA-C, polycrystalline alumina; T, Transcend 6000; MCS, monocrystalline sapphire bracket; I, Inspire; K, Kosaka; β-Ti, β-titanium.

β-ti wire—bracket combination. The PCA-S bracket had the lowest FR for every degree of angulation. However, the PCA-M bracket showed the highest increase in FR, by 2.1-fold, from 5° to 10° of angulation. The PCA-C and MCS brackets produced the highest increase in kinetic FR, by 2.2-fold, from 0° to 5°, and by 2.4-fold, from 5° to 10° of angulation, respectively, and the MCS bracket generated the highest FR among the ceramic brackets at 15° of angulation. The SS brackets showed a significant increase in FR at all degrees of angulation, showing the highest FR among the groups of 15° of angulation. (Table 2; Figures 3 and 4).

Slot Surface Topography

The slot layer of the PCA-C bracket had porous and plucked-out surfaces (Figure 5). In contrast, the PCA-S and MCS brackets were devoid of these pockmarks and facets. Although the MCS bracket had a smoother surface than the PCA-S bracket, the MCS edges were sharply demarcated. The edge of the SS bracket slots was also well rounded compared with the sharp edges of the slots with the PCA-M bracket slot.

DISCUSSION

Among the factors that can influence FR, only four bracket-wire angulations (0°, 5°, 10°, and 15°) and brackets as well as 2 wire types were examined in this study. Therefore, experimental critical angulation (θ) could not be determined because continuous change in bracket-wire angulation was not simulated in this model. Factors such as minute movements that can be generated during mastication or swallowing were also not examined under the steady condition.

The PCA-S bracket (Crystaline V) had a similar FR to the SS bracket (Kosaka), but had a lower FR than the PCA-M (Clarity) bracket. Earlier studies revealed that the ceramic bracket generated a higher FR than the metal bracket on account of the chemical adhesion and surface roughness.[2–6] Even though metal-slot–insert ceramic brackets have been successful in reducing FR compared with monocrystalline ceramic brackets, they still exhibited a higher FR than the metal brackets.[11]

Interestingly, the polycrystalline ceramic bracket with the silica insert (PCA-V) produced significantly lower FR than the conventional metal brackets. SEM showed that the silica layer of the PCA-S brackets had a nonporous surface and slot borders with rounded margins. The PCA-S brackets appeared to greatly reduce the FR of the ceramic brackets. However, laser specular reflection experiments will be needed in order to obtain further information of the quantitative magnitude of the surface roughness.

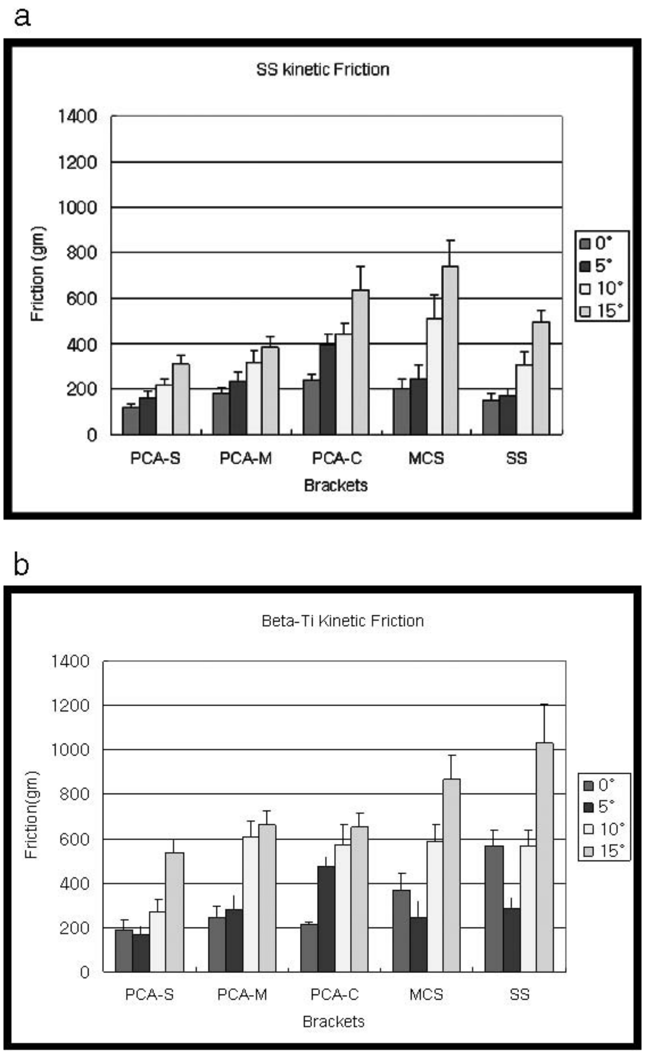

Figure 3. Kinetic mean friction between the four angles (0°, 5°,10°, and 15°). Note graph showing the increase in friction with increased tipping angle. (A) Kinetic mean friction between SS wire/bracket combinations (B) Kinetic mean friction between β-Ti wire/bracket combinations.

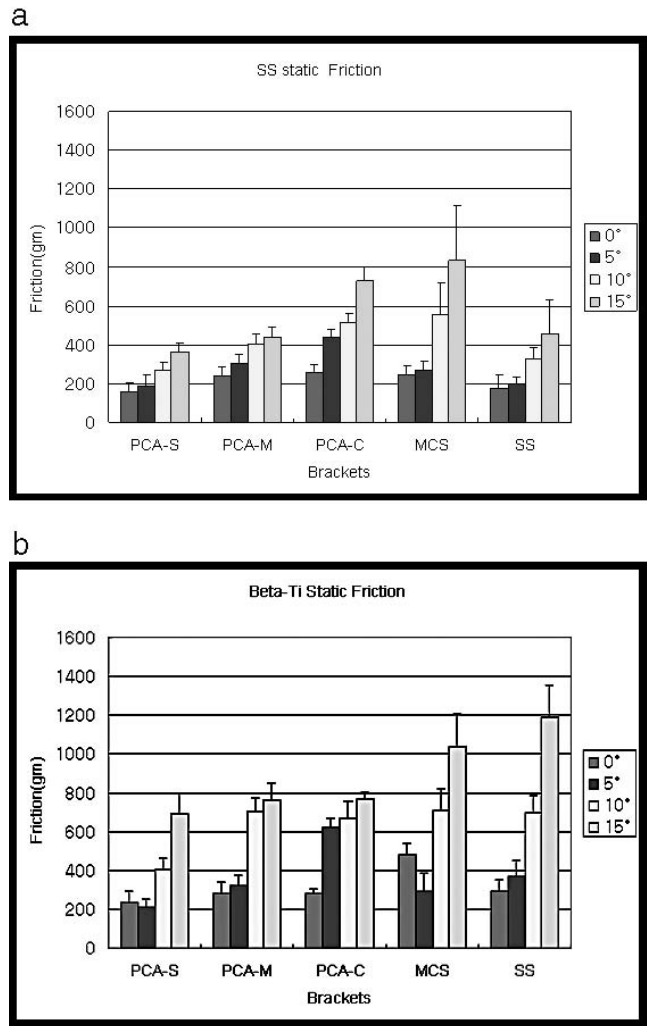

Figure 4. Static mean friction between at the four angles (0°, 5°,10° and 15°). Note graph showing the increase in friction with increased tipping angle. (A) Static mean friction between SS wire/bracket combinations. (B) Static mean friction between β-Ti wire/bracket combinations.

The FR for all groups increased slowly up to 5° and abruptly when the angulation was over 10°. This pattern was significant in the bracket–β-Ti wire combination. The increase in FR was different between the groups, and was not correlated with the FR value at 0° angulation. The MCS bracket–β-Ti wire combination showed the lowest increase in FR by 2.3-fold (from 370.9 at 0° to 867.6 at 15°), and the highest FR of 199.8 ± 43.9 g at 0° angulation. Accordingly, some bracket-wire combinations showed a reversal in the order of FR with increasing angulation.

The PCV-M brackets had a higher kinetic resistance (233.0 ± 39.7 g) than the metal brackets (168.0 ± 31.5 g) at 5° of angulation, as reported in other studies.[11,17,21] However, they had a lower kinetic resistance (382.1 ± 54.1 g) than the metal brackets (494.1 ± 54.2 g) at 15° angulation with both the SS and the β-Ti wires. This result at 15° angulation was unexpected, but previous studies did not test angulations >10°. Nishio et al[21] observed a gap between the bracket and the metal slot using SEM. He suggested that this gap might occur as a result of the difficulty in adjusting the metal to the ceramic and to their different expansion coefficients. Therefore, it is possible for a metal slot to be distorted because of excessive bracket-wire angulations >10°, which can affect the decrease in friction between the bracket and wire. Further research will be needed to determine the possible distortion in the bracket slots.

It was interesting that the PCA-C and MCS brackets showed significant increases in FR at different levels of angulation. However, although the PCA-C bracket demonstrated a significant increase in FR from 0° to

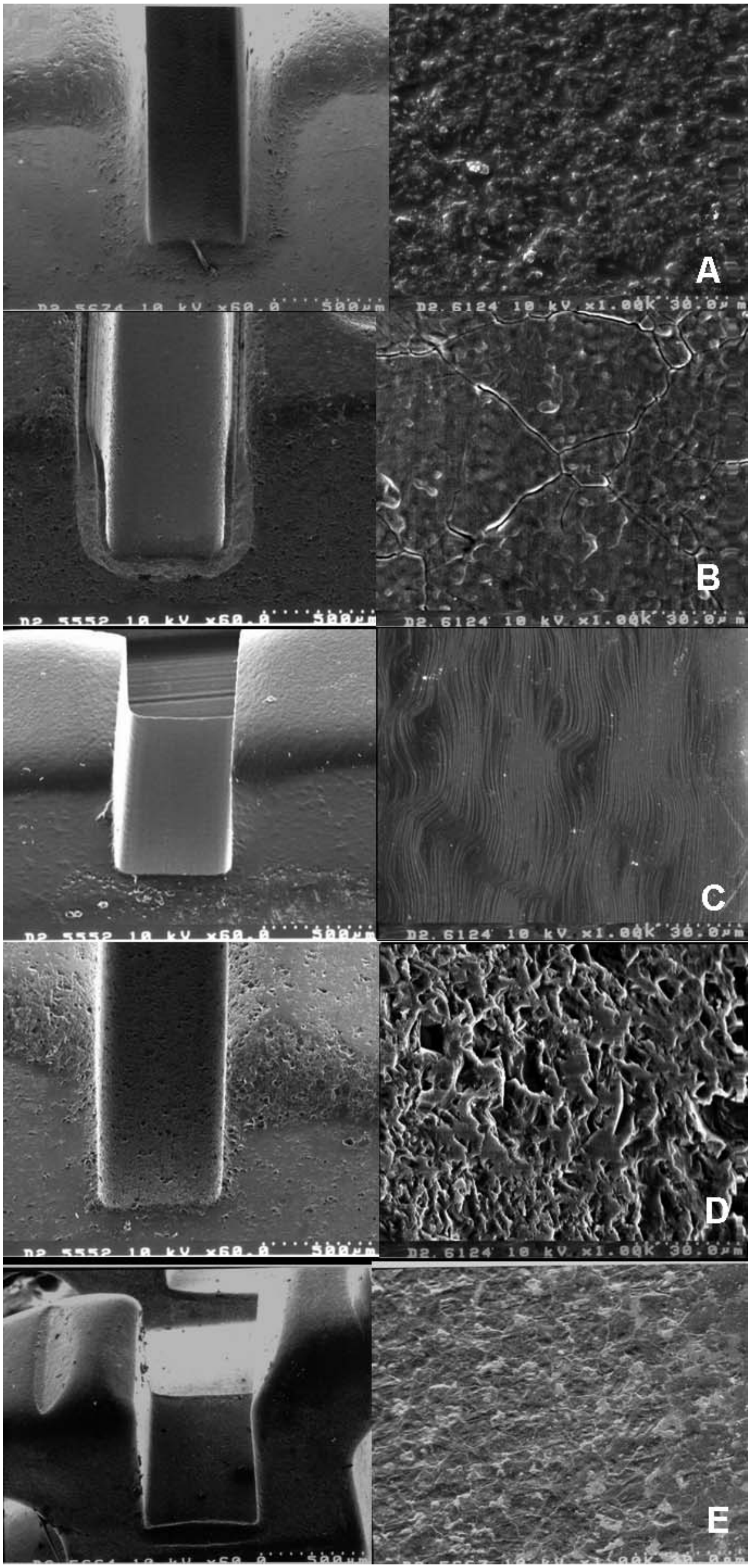

Figure 5. Scanning electron micrographs of brackets at 60× and 1000× magnification. (A) PCA-S; (B) PCA-M; (C) MCS; (D) PCA-C; (E) SS.

5° of angulation, the MCS showed the highest increase in FR from 5° to 10° of angulation for both the β-Ti and SS wires. This difference is clinically important, considering that it can generate an undesirable increase in FR depending on the bracket types at a certain point of bracket-wire angulation. Therefore, understanding the FR for specific bracket-wire combinations can provide important clinical information on the efficient tooth movement. The data from Articolo and Kusy[24] showed that the coefficients of kinetic friction for a combination of ceramic brackets and SS wires were directly affected by the change in angulation. They reported that, depending on bracket types, the increase in FR as well as the increase in the coefficient values can mainly be attributed to the binding.

This study also demonstrated that β-Ti generated higher friction than SS for all bracket-wire combinations. These findings confirm those of previous studies.[11,15,21,26] Tests with β-Ti wire, which is known for its high FR, have shown it to be less consistent than SS wire.[24,27] However, the increase in FR between the wire types differed among the brackets. For example, the MCS bracket with the SS combination demonstrated a higher increase in FR by 3.7-fold (199.8 g at 0° and 739.8 g at 15°) compared with the 2.7-fold increase obtained using the β-Ti wire (371.0 g at 0° and 867.6 g at 15°). On the other hand, the PCA-C and PCA-S brackets showed a higher increases in FR with the β-Ti wire than with the SS wire. This result for the MCS couples supports the previous hypothesis that couples consisting of SS wires are less efficient when sliding at these higher levels of angulation compared with couples consisting of Ti (β-Ti) wires. However, this is limited to specific couples because other properties such as roughness and bracket design also influence the FR values.[10,21,24]

In conclusion, the newly introduced silica-insert ceramic brackets exhibited a lower FR than the other ceramic brackets, showing an FR similar to that of SS brackets. However, the FR of ceramic brackets was examined under dry conditions with only one wire size. The influences of the oral environment, such as the components of the saliva or vibrations that can occur during mastication, were not considered. Hence, additional experiments will be needed to determine the effects of these conditions.

CONCLUSIONS

- The newly-introduced silica-insert ceramic brackets exhibited a lower FR than the other ceramic brackets.
- The PCA-S showed the lowest FR with both the SS and β-Ti wires at zero bracket angulation.
- The FR for all groups increased slowly at up to 5° of angulation and increased abruptly when angulation was >10°. The PCS-S bracket showed the lowest FR from 5° to 15° of angulation.
- Among the ceramic groups, the MCS bracket demonstrated the highest increase in FR from 0° to 15° of angulation, showing the highest FR at 15° of angulation.
- The silica layer and rounded edges of the PCA-S bracket lowered FR considerably.

REFERENCES

1. Pratten DH, Popli K, Germane N, Gunsolley JC. Frictional resistance of ceramic and stainless steel orthodontic brackets. *Am J Orthod Dentofacial Orthop.* 1990;98:398–403.
2. Bednar JR, Gruendeman GW, Sandrik JL. A comparative study of frictional forces between orthodontic brackets and arch wires. *Am J Orthod Dentofacial Orthop.* 1991;100:513–522.
3. Ireland AJ, Sherriff M, McDonald F. Effect of bracket and wire composition on frictional forces. *Eur J Orthod.* 1991; 13:322–328.
4. Kusy RP, Whitley JQ. Coefficients of friction for arch wires in stainless steel and polycrystalline alumina bracket slots, I: the dry state. *Am J Orthod Dentofacial Orthop.* 1990;98: 300–312.
5. Springate SD, Winchester LJ. An evaluation of zirconium oxide brackets: a preliminary laboratory and clinical report. *Br J Orthod.* 1991;18:203–209.
6. Tanne K, Matsubara S, Shibaguchi T, Sakuda M. Wire friction from ceramic brackets during simulated canine retraction. *Angle Orthod.* 1991;61:285–290.
7. Saunders CR, Kusy RP. Surface modification methodologies for polycrystalline alumina: effects on morphology and frictional coefficients. *J Mater Sci Mater Med.* 1993;4:422–430.
8. Kusy RP, Keith O, Whitley JQ, Saunders CR. Coefficient of friction characterization of surface-modified polycrystalline alumina. *J Am Ceramic Soc.* 1993;76:336–342.
9. Kusy RP, Whitley JQ. Friction between different wire-bracket configurations and materials. *Semin Orthod.* 1997;3:166–177.
10. Dickson J, Jones S. Frictional characteristics of a modified ceramic bracket. *J Clin Orthod.* 1996;30:516–518.
11. 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;124:403–409.
12. Kapur Wadhwa R, Kwon HK, Close JM. Frictional resistances of different bracket-wire combinations. *Aust Orthod J.* 2004;20:25–30.
13. Ghosh J, Nanda RS, Duncanson MG Jr, Currier GF. Ceramic bracket design: an analysis using the finite element method. *Am J Orthod Dentofacial Orthop.* 1995;108:575–582.
14. Vaughan JL, Duncanson MG Jr, Nanda RS, Currier GF. Relative kinetic frictional forces between sintered stainless steel brackets and orthodontic wires. *Am J Orthod Dentofacial Orthop.* 1995;107:20–27.
15. Bazakidou E, Nanda RS, Duncanson MG Jr, Sinha P. Evaluation of frictional resistance in esthetic brackets. *Am J Orthod Dentofacial Orthop.* 1997;112:138–144.
16. Keith O, Jones SP, Davies EH. The influence of bracket

material, ligation force and wear on frictional resistance of orthodontic brackets. *Br J Orthod.* 1993;20:109–115.
17. Thorstenson G, Kusy R. Influence of stainless steel inserts on the resistance to sliding of esthetic brackets with second-order angulation in the dry and wet states. *Angle Orthod.* 2003;73:167–175.
18. 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;120:361–370.
19. Kusy RP, Whitley JQ. Assessment of second-order clearances between orthodontic archwires and bracket slots via the critical contact angle for binding. *Angle Orthod.* 1999;69:71–80.
20. Kusy RP, Whitley JQ. Influence of archwire and bracket dimensions on sliding mechanics: derivations and determinations of the critical contact angles for binding. *Eur J Orthod.* 1999;21:199–208.
21. 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;125:56–64.
22. Tanne K, Matsubara S, Hotei Y, et al. Frictional forces and surface topography of a new ceramic bracket. *Am J Orthod Dentofacial Orthop.* 1994;106:273–278.
23. Tanne K, Matsubara S, Shibaguchi T, Sakuda M. Wire friction from ceramic brackets during simulated canine retraction. *Angle Orthod.* 1991;61:285–290; discussion 291–292.
24. Articolo LC, Kusy RP. Influence of angulation on the resistance to sliding in fixed appliances. *Am J Orthod Dentofacial Orthop.* 1999;115:39–51.
25. Redlich M, Mayer Y, Harari D, Lewinstein I. In vitro study of frictional forces during sliding mechanics of ''reduced-friction'' brackets. *Am J Orthod Dentofacial Orthop.* 2003;124:69–73.
26. Kapur R, Sinha PK, Nanda RS. Comparison of frictional resistance in titanium and stainless steel brackets. *Am J Orthod Dentofacial Orthop.* 1999;116:271–274.
27. Kusy RP, Whitley JQ. Effects of surface roughness on the coefficients of friction in model orthodontic systems. *J Biomech.* 1990;23:913–925.