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An *in vitro* comparison of the frictional forces between archwires and self-ligating brackets of passive and active types

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SUMMARY The aim of this study was to compare the static and kinetic frictional forces generated by various contemporary designs of self-ligating brackets (SLBs) and different wire alloys. In total, six different brackets (four passive type SLB, one active SLB, and one conventional bracket) were investigated using stainless steel, nickel–titanium, and titanium–molybdenum alloy archwires of several sizes. The friction forces were measured by sliding on a bracket–wire combination system in an EZ instron testing machine. A scanning electron microscope (SEM) was used to examine the wear effects of the wall surfaces of bracket slots. Energy-dispersive spectroscopy (EDS) was used to identify the elemental compositions of the bracket surfaces. The data were collected and statistically analysed using analysis of variance. The results of static and kinetic frictional forces were lower in passive type SLBs ($P < 0.05$), except in the Smart Clip bracket. The wire materials or wire dimensions in the present study showed similar friction forces with no statistical differences ($P > 0.05$). The wearing effects were not obviously found in bracket slots under SEM observation. Only conventional brackets and mini-Clippy SLB revealed nickel ions via EDS analysis. This study shows that passive SLBs are associated with lower static or kinetic friction forces than those of active SLBs or conventional brackets. Wear on the bracket slots was not observed in the present study.

Introduction

Friction is described as an opposing and parallel force when one surface moves against another (Bhushan, 1999). There are two types of friction: static and kinetic. The static frictional force is defined as the smallest force needed to start a motion between two solid surfaces. The kinetic friction force is defined as the force needed to resist the sliding motion of one solid object over another at constant speed (Dowlig *et al.*, 1998; Redlich *et al.*, 2003).

In orthodontic tooth movement, friction (static or kinetic) results from the interaction between an archwire and the sides of an orthodontic bracket or a ligature. Friction is a small part of the resistance to overall movement that results when a bracket slides along an archwire. The force of resistance to the sliding movement is by 1. friction, which comes from the contact of a wire with the bracket surface; 2. binding, which involves the tipping of the tooth tips when the flexing of the wire contact between the wire and the corners of the bracket; and 3. notching, which involves the permanent deformation of the wire at the wire–bracket corner interface (Kusy and Whitley, 1999). The outcome of the frictional/sliding resistance is accompanied by damages to the contacting surfaces, which is mostly manifested by the wearing off of the surfaces.

For many years, the problem of friction has been studied by researchers, identified by orthodontists, and recognized by suppliers of orthodontic products who modified bracket designs accordingly in some cases. Conventional ligated edgewise brackets increased levels of frictional resistance via the elastomeric attachment between the bracket and the archwire (Pizzoni *et al.*, 1998; Schumacher *et al.*, 1999; Michelberger *et al.*, 2000). To reduce unwanted friction, various self-ligating bracket (SLB) systems have been developed. The new bracket shapes currently on the market must be subjected to scientific investigation as the clinical practitioner expects to be informed of their friction characteristics (Schumacher *et al.*, 1999).

Self-ligation eliminates the requirement for an elastomeric attachment and is associated with considerably reduced friction when used with different archwires (Read-Ward *et al.*, 1997; Thorstenson and Kusy, 2001; Henao and Kusy, 2004; Khambay *et al.*, 2004). According to bracket structures, SLBs are classified as an active type, interactive type, or passive type. The benefits of SLBs are that they may offer more archwire engagement, which requires less chair-side assistance and enables faster archwire removal and ligation (Harradine, 2001; Turnbull and Birnie, 2007). There is some debate, however, as some studies report that an overall reduction in treatment time is associated with these appliances (Chen *et al.*, 2010), while others do not support such findings. Current evidence suggests that SLBs only clinical benefits are in the reduction of chair time and the enhanced control of mandibular incisor angulation (Pandis *et al.*, 2007; Chen *et al.*, 2010; Fleming and Johal, 2010).

Only a few reports have comparatively evaluated the frictional forces of SLB designs combined with different archwire alloys. The purpose of the present study was to compare the static and kinetic frictional forces generated by various contemporary designs of SLBs and different wire alloys.

Materials and methods

The following maxillary right and left first bicuspid SLBs were used in the study: Tenbrook SLB T1 (Axis; OrthoClassic, McMinnville, Oregon, USA), Damon SL III MX (Sybron Dental Specialties Ormco, Orange, California, USA), mini-Clippy (TOMY International, Toyko, Japan), Smart Clip (2nd generation; 3 M Unitek, Monrovia, California, USA), Carriere LX (OrthoOrganizer, Carlsbad, California, USA), and OPA-K (TOMY International). All the brackets used had 0.022 inch slots (Table 1).

The passive type SLB used in this study were Tenbrook SLB T1, Damon SL III MX, Carriere LX, and Smart Clip. The active type SLB used in this study was Clippy. OPA-K was a conventional stainless steel pre-adjusted bracket, which was used as the control.

The following three types of straight orthodontic archwire alloys were evaluated: stainless steel (SS), nickel–titanium (NiTi), and titanium–molybdenum alloy (TMA; Sybron Dental Specialties Ormco Co.). The sizes of the SS wires were 0.016 × 0.022, 0.017 × 0.025, and 0.018 × 0.025 inches (3M Unitek). The sizes of NiTi wires were 0.018 × 0.025 inches low hysteresis (LH; TOMY International) and 0.019 × 0.025 inches heat activated (HA; 3M Unitek). The size of the TMA wire

Table 1 The bracket and archwire applied in study.

Bracket design	Name of bracket	Manufacturer	Archwire size		Archwire materials
Self-ligating					
Passive type	Axis (Tenbrook	Orthoclassic, Mcminnville,	0.016 × 0.022		Stainless steel (SS)
	self-ligating	Oregon, USA	0.017 × 0.025	0.018 × 0.025	Stainless steel (SS)
	bracket)		0.018 × 0.025		Stainless steel (SS)
			0.019 × 0.025		LH [titanium–nickel (TiNi)]
			0.017 × 0.025		HA (heat active NiTi)
					Titanium–molybdenum alloy (TMA)
	Damon SL III MX	Sybron Dental Specialties	0.016 × 0.022		Stainless steel (SS)
		Ormco, Orange , USA	0.017 × 0.025	0.018 × 0.025	Stainless steel (SS)
			0.018 × 0.025		Stainless steel (SS)
			0.019 × 0.025		LH [titanium–nickel(TiNi)]
			0.017 × 0.025		HA (heat active NiTi)
					Titanium–molybdenum alloy (TMA)
	Carriere LX	OrthoOrganizer, Carlsbad,	0.016 × 0.022		Stainless steel (SS)
		California, USA	0.017 × 0.025	0.018 × 0.025	Stainless steel (SS)
			0.018 × 0.025		Stainless steel (SS)
			0.019 × 0.025		LH [titanium–nickel(TiNi)]
			0.017 × 0.025		HA (heat active NiTi)
					Titanium–molybdenum alloy (TMA)
	Smart Clip	3M Unitek, Monrovia,	0.016 × 0.022		Stxinless steel (SS)
		California, USA	0.017 × 0.025	0.018 × 0.025	Stainless steel (SS)
			0.018 × 0.025		Stainless steel (SS)
			0.019 × 0.025		LH [titanium–nickel (TiNi)]
			0.017 × 0.025		HA (heat active NiTi)
					Titanium–molybdenum alloy (TMA)
Active type	Mini-Clippy	Tomy International,	0.016 × 0.022		Stainless steel (SS)
		Toyko, Japan	0.017 × 0.025	0.018 × 0.025	Stainless steel (SS)
			0.018 × 0.025		Stainless steel (SS)
			0.019 × 0.025		LH [titanium–nickel (TiNi)]
			0.017 × 0.025		HA (heat active NiTi)
					Titanium–molybdenum alloy (TMA)
Conventional ligature					
	OPA-K	Tomy International	0.016 × 0.022		Stainless steel (SS)
			0.017 × 0.025	0.018 × 0.025	Stainless steel (SS)
			0.018 × 0.025		Stainless steel (SS)
			0.019 × 0.025		LH [titanium–nickel (TiNi)]
			0.017 × 0.025		HA (heat active NiTi)
					Titanium–molybdenum alloy (TMA)

was 0.017 × 0.025 inches (Sybron Dental Specialties Ormco).

For each bracket–archwire combination, 10 observations were made. Each archwire sample was drawn only once through a bracket. In total, 720 bracket–archwire readings were made in this study. The frictional evaluation was performed according to the test protocol described by our previous study (Kao *et al.*, 2006). Testing was performed on an EZ test machine (Shimadazu, Tokyo, Japan) with a crosshead speed of 10 mm/minute over a 5 mm stretch of archwire. A plumb line was hung to ensure that the bracket mount was parallel to the vertical line scribed on the steel bar base of the bracket mount assembly. A 5 N load cell was calibrated to be between 0 and 5 N, and the archwire was drawn through the bracket as the crosshead moved inferiorly at 10 mm/minute (Figure 1). This crosshead speed was selected because a previous study found no significant differences between crosshead speeds ranging from 0.5 to 50 mm/minute. The experimental conditions were performed in room temperature 22–25°C, and the humidity condition was 50–60 per cent (Cengiz and Ucar, 2006).

Emphasis was placed on aligning the archwires so that the samples were parallel to the vertical framework of the machine. The brackets were pulled vertically by a loop of 0.018 inch stainless steel wire. The forces required to initiate and maintain the movement of the brackets over the 5 mm test distance were measured. The programme was set to highlight the maximum frictional force at initial movement, which was taken to represent the peak static frictional resistance. For each bracket–wire combination, a new wire and bracket were used.

Morphology observation and energy-dispersive spectroscopy analysis

The morphologies of the tested brackets were observed by scanning electron microscopy (SEM). SEM evaluation focused on the wearing effects and the base material. Brackets were embedded in an epoxy resin in a horizontal direction. After the setting of the resin, the embedded brackets were ground with silicon carbide (SiC) papers (600, 800, 1000, 1200, and 2000 grid) under continuous water cooling until the floors of the bracket slots were exposed. Energy-dispersive spectroscopy (EDS) was used to identify the elemental compositions of the bracket surfaces.

Statistical analysis

The load cell registered the force levels needed to move the wires through the brackets, and these values were stored on a computer hard disk. The data were then analysed using a statistical package (Primer; McGraw-Hill, New York, USA). A completely randomized one-way analysis of variance was used to test for significant differences among the bracket wire types. This was followed by a Student–Newman–Keuls multiple comparison of means at $P < 0.05$ to determine differences among the groups.

Results

Static friction force

The result illustrated in Figure 2 represents the active and passive types of SLB and the associated static and kinetic friction forces. In measuring static friction force, the right

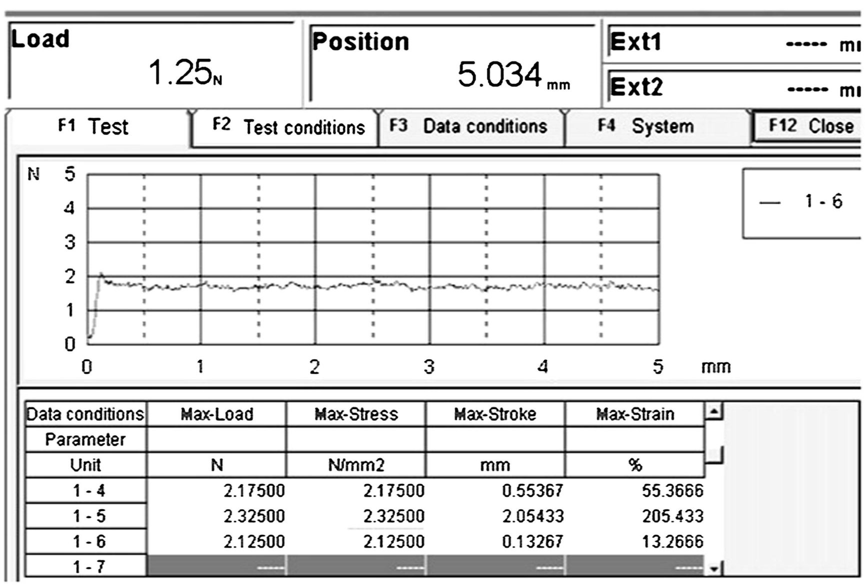

Figure 1 Representative graphic curve of the resistance force versus displacement output.

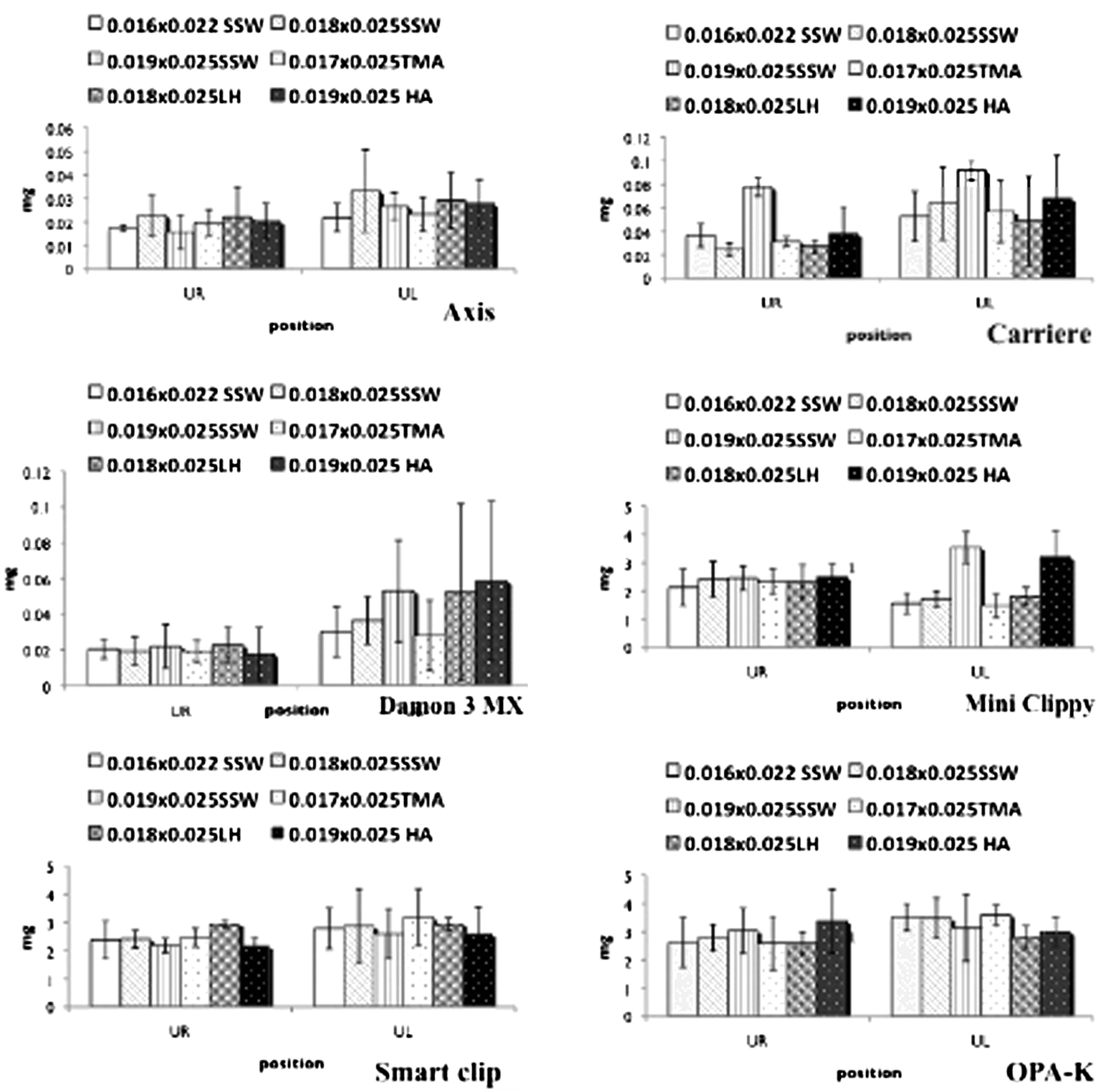

Figure 2 The static friction force of various self-ligating metal brackets with various archwires. UR: upper right side first bicuspid self ligation bracket, UL: upper left side first bicuspid self ligation bracket . The data are mean ± standard deviation.

and left first bicuspids showed no statistical differences ($P > 0.05$). The passive type SLB (Axis, Damon SL III MX, and Carriere LX) showed a lower static friction force than the active SLB (mini-Clippy) and the control bracket ($P < 0.05$), except for the Smart Clip SLB.

The bracket–SS archwire combination groups showed higher static friction forces in the Smart Clip, mini-Clippy, and control (OPA-K) groups ($P < 0.05$). There was a tendency for SLB static friction to increase as the size of the SS archwire increased. A similar static friction force was seen in the same SLB bracket combined with SS, TMA, LH, and HA archwires ($P > 0.05$).

Kinetic friction force

In measuring kinetic friction forces (Figure 3), the right and left first bicuspid showed no statistical differences ($P > 0.05$). The active type SLB or control bracket showed higher kinetic friction than passive type SLB, except for the Smart Clip SLB ($P < 0.05$). The Smart Clip SLB showed the highest kinetic friction forces among the passive type

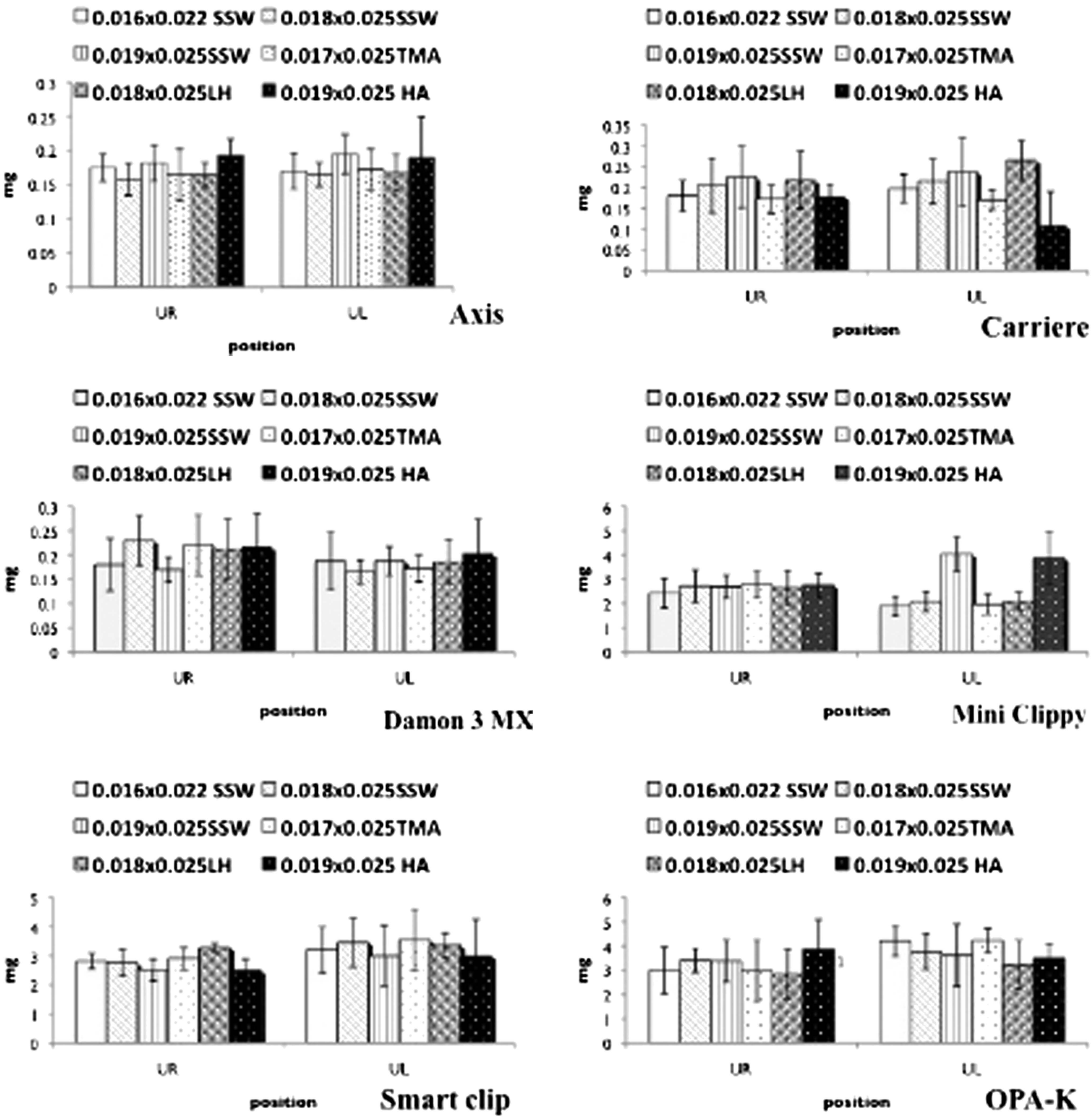

Figure 3 The kinetic friction force of various self-ligating metal brackets with various archwires. UR: upper right side first bicuspid self ligation bracket, UL: upper left side first bicuspid self ligation bracket . The data are mean ± standard deviation.

SLB ($P < 0.05$). A similar kinetic friction force was seen in the same SLB bracket combined with SS, TMA, LH, and HA archwires ($P > 0.05$).

SEM morphology observation

A post-frictional test of bracket morphologies is displayed in Figure 4. The Axis SLB surface showed an intact structure under low magnification (×120; Figure 4A and 4B) but displayed increased roughness under ×500 magnification (Figure 4C). A similar result was seen with Carriere (Figure 4A and 4B), Damon III MX (Figure 4A and 4B), mini-Clippy (Figure 4A and 4B), Smart Clip (Figure 4A and 4B), and OPA-K (Figure 4A and 4B). Figure 4D shows the morphology of metal crystal under ×2000 magnification.

EDS analysis

EDS analysis showed that the main components of Axis, Damon III MX, Carriere, and Smart Clip SLB were

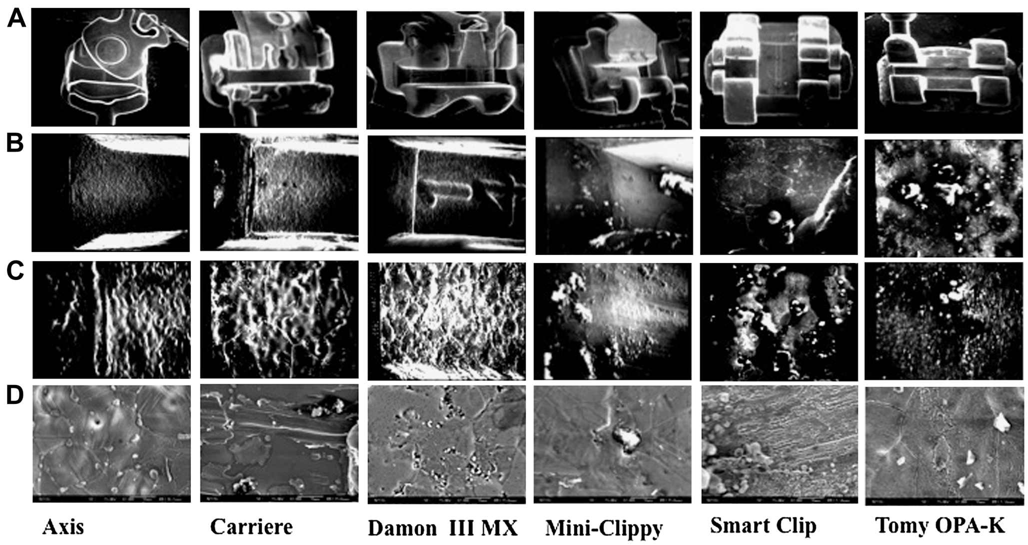

Figure 4 The bracket surface under scanning electron microscopy observations. (A) ×10 magnification of bracket. (B) ×120 magnification of bracket slot surface. (C) ×500 magnification of bracket slot surface. (D) ×2000 magnification.

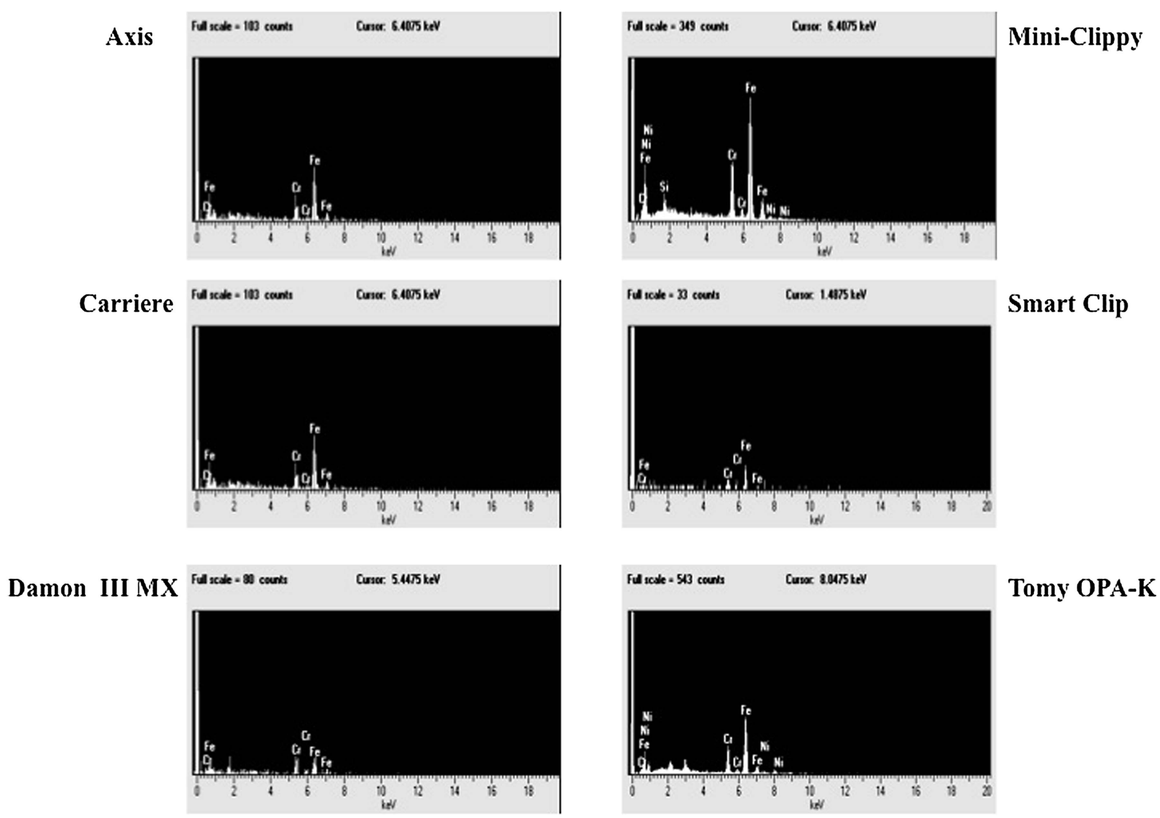

Figure 5 The main components of the bracket were shown on energy-dispersive spectroscopy analysis.

ferric and chromium ions in Figure 5. The EDS analysis of mini-Clippy and OPA-K SLB showed nickel ions (Figure 5).

Discussion

This study shows that passive SLB exhibits low static and kinetic friction forces. It is suggested that binding effect of active SLB might be higher than that of passive SLB. In Frank and Nikolai (1980) and Tidy (1989), studies showed friction or binding may appear in orthodontics when maligned bracket are engaged onto an archwire, during bodily tooth movement along archwire or when active torque is applied (Frank and Nikolai, 1980; Tidy, 1989). Cash described that binding may occur at point contacts are formed between bracket, archwires, and/or ligatues producing a froce couple that resists sliding. This binding force may block tooth movement and may result in damage to the surface of the orthodontic appliance resulting notching (Cash *et al.*, 2004). In Fidalgo *et al.* study, the orthodntic brackets and wire submitted to mechanical traction tests were evaluated by using a profilometer to check the changes on the surface. The results of their study showed a decreased in the roughness of wire and brackets tested (Fidlgo *et al.*, 2010). To clinician, the binding effect of SLB is lower and reducing quickly may provide better orthodontic effects.

The Smart Clip SLB, although classified as a passive type SLB, showed high levels of friction. The reason may be its structure because Smart Clip designs are different than other passive SLB designs. The Smart Clip SLB structure design consists of two clips at mesial and distal wings to hode the archwire. When the wire was in the SLB slot, the wire–bracket contact interface located at the bracket wings was increased. As the sliding occurred, the wire was seen to bind to the bracket at the wings. This increases the friction associated with the Smart Clip brackets. When binding occurred between the wire and the bracket, a wearing effect was seen on the surface. In this study, the surface of the bracket did not show any wear under SEM observation. But some bracket slots showed irregular levels of roughness.

Higher frictional forces for active and passive SLBs with NiTi wire were observed in comparison to SS (Thomas *et al.*, 1998). Damon SL II and Smart Clip (passive SLB) and In-ovation and Time (active SLB) displayed distinct differences in frictional parameters in comparison to NiTi (Krishnan *et al.*, 2009). This agreed with our present findings. A study that evaluated Damon SL II and Smart Clip with NiTi archwires in various cross sections, with first-order rotation, second-order intrusion, and third-order labial crown inclinations, showed that there were no significant bracket differences in terms of friction once binding occurred in the second-order distances (Yeh *et al.*, 2007).

In orthodontic tooth movement, sliding along an archwire is not continuous but occurs as a series of intermittent movements. Thus, the bracket–archwire relationship is needed to overcome the static friction and binding, enabling sliding movements. At present, inevitable wear occurs on brackets or archwires, which increases friction and binding in subsequent movements. In our study, the observed bracket–wire systems after EZ testing were associated with fewer wearing effects on bracket or wire surfaces under microscopic examination. This may be due to the wire sizes being smaller than bracket slot sizes or due to the test system consisting of only one bracket and one straight wire. Such parameters are different than an oral environment *in vivo*, which consists of many brackets with a curved archwire.

The friction between the bracket and the archwire can result in loss of force of up to a 50 per cent (Keith *et al.*, 1993). Although the normal periodontal blood pressure is 25 g, in an optimal bracket–wire combination system, approximately 40 g of frictional force must be applied to the tooth to initiate movement (Taylor and Ison, 1995; Wadhwa *et al.*, 2004). It is understood that close to 15 g of force is needed to overcome the frictional resistance or binding forces. In the present study design consisting of a single bracket–wire test, the frictional resistance may have been lower. It is different than a multiple bracket–wire system. After overcoming the frictional resistance and binding forces, a multiple bracket–wire system's residual force is also difficult to accurately calculate. As a result, optimal levels of force for tooth movement are difficult to achieve in clinical settings.

The OPA-K bracket was the conventional control bracket used in this study. The static or kinetic friction forces associated with OPK were higher than for other SLB, except for the Smart Clip bracket and Clippy bracket. An elastomeric modular ligation was used to tie the OPK bracket to the wire. The elastomeric modules lose approximately 50 per cent of their initial force within 24 hours of load application, with the force decreasing from 30 to 40 per cent after 4 weeks (De Genova *et al.*, 1985). Because the frictional force observed in conventional brackets is directly related to the force of the elastomeric modules, there can be a concomitant reduction in friction after 4 weeks of intraoral use clinically (Krishnan *et al.*, 2009).

Because there are many factors which affect the friction force. One of them is the different material surface characteristic. In present study, the SEM applications were to shown and understanding the surface topography of SLB. To discover if there were any connections within surface topography and friction force. EDS technique is used to identify the elemental composition of a sample or small area of interest on the sample. The EDS analysis was to demonstrate the composition of SLB. It is to know if different metal compositions may affect the friction or not in present study.

Nickel ions may be released from the metal brackets (Huang *et al.*, 2001), which can cause an allergic reaction, cell toxicity, or mutagenicity (Bumgardner and Lucas, 1995). Approximately 10 per cent of the general population exhibits a hypersensitive reaction to nickel. To prevent such adverse reactions, the nickel ions were gradually added onto the metal bracket materials. The present EDS test showed that Clippy SLB and OPA-K conventional brackets were associated with nickel ions. The rest of the SLB did not display nickel ions. It is recommended that nickel-hypersensitive patients not be exposed to brackets that may increase the risk of reactions.To reduce the corrosion and to increase the hardness of metal bracket surfaces, a diamond-like coating (DLC) was studied on the bracket surfaces (Huang and Kao, 2010). A wearing effect on the bracket surfaces was noticed. Future studies may consider applying DLC on bracket slots in order to observe their physical characteristics.

The present study does not replicate the clinical orthodontic situation. The limitations of present study include a frictional testing system that did not include wet condition and the fact that the testing archwire was a straight not a curved wire. The clinical application of this *in vitro* study is that if the sliding technique is applied on orthodontic tooth movement, the orthodontist may consider the passive type of SLB.

Conclusions

This study showed that passive SLBs are associated with a lower static or kinetic friction force than active SLBs or conventional brackets. Wear on the bracket slots was not observed.

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References

Bhushan B 1999 Principles and applications of tribologyJohn Wiley and Sons Inc., New york, pp. 1

Bumgardner J D, Lucas L C 1995 Cellular response to metallic ions released from nickel-chromium dental alloy. Journal of Dental Research 74: 1521–1527

Cash A, Curtis R, Garrigia-Majo D, McDonald F 2004 A comparative study of the static and kinetic frictional resistance of titanium molybdenum alloy archwires in stainless steel brackets. European Journal of Orthodontics 26: 105–111

Cengiz A, Ucar M 2006 Determination of the effect of temperature and relative humidity on the friction of V-belt mechanism. Journal of Engineering and Materials Science 13: 405–410

Chen S S, Greenlee G M, Kim J E, Smith C L, Huang G J 2010 Systematic review on self-ligating brackets. American Journal of Orthodontics and Dentofacial Orthopedics 137: 726.e1–726.e8

De Genova D C, McInnes-Ledoux P, Weinberg R, Shaye R 1985 Force degradations of orthodontic elastomeric chains—a product comparison study. American Journal of Orthodontics 87: 377–384

Dowlig P A, Jones W B, Lagerstrom L, Sandham J A 1998 Investigation into the behavioral characteristics of orthodontic elastomeric modules. British Journal of Orthodontics 25: 197–202

Fidlgo T K, Pithon M M, Maciel J V B, Bolognese A M 2010 Friction between different wire bracket combinations in artifical saliva an in vitro evaluaiton. Journal of Applied Oral Science 19: 57–62

Fleming P S, Johal A 2010 Self-ligating brackets in orthodontics. A systematic review. Angle Orthodontists 80: 575–584

Frank C S, Nikolai R J 1980 A comparative study of frictional redsistance between orthodtic bracket and arch wire. American Journal of Orthodontics and Dentofacial Orthopedics 78: 593–609

Harradine N W 2001 Self-ligating brackets and treatment efficiency. Clinical Orthodontics Research 4: 220–227

Henao S P, Kusy R P 2004 Evaluation of the frictional resistance of conventional and self-ligating bracket designs using standardized archwires and dental typodonts. Angle Orthodontists 74: 202–211

Huang T H, Kao C T 2010 A comparison of the friction associated with diamond-like carbon (DLC) or titanium nitride (TiN) plating orthodontic metal brackets. Surface and Coatings Technology 205: 1917–1921

Huang T H, Yen C C, Kao C T 2001 Comparison of ions released between new and recycled brackets. American Journal of Orthodontics and Dentofacial Orthopedics 120: 68–75

Kao C T, Ding S J, Wang C K, He H, Chou M Y, Huang T H 2006 Comparison of frictional resistance after immersion of metal brackets and orthodontic wires in a fluoride-containing prophylactic agent. American Journal of Orthodontics and Dentofacial Orthopedics 130: 568.e1–568.e9

Keith O, Jones S P, Davies E H 1993 The influence of the bracket material, ligation forces and wear on frictional resistance of orthodontic brackets. British Journal of Orthodontics 20: 109–115

Khambay B, Millett D, McHugh S 2004 Evaluation of methods of archwire ligation on frictional resistance. European Journal of Orthodontics 26: 327–332

Krishnan M, Kalathil S, Abraham K M 2009 Comparative evaluation of frictional forces in active and passive self-ligating brackets with various archwire alloys. American Journal of Orthodontics and Dentofacial Orthopedics 136: 675–682

Kusy R P, Whitley J Q 1999 Influence of archwire and bracket dimensions on sliding mechanics: derivations and determinations of the critical contact angles for binding. European Journal of Orthodontics 21: 199–208

Michelberger D J, Eadie R L, Faulkner M G, Glover K E, Prasad N G, Major P W 2000 The friction and wear patterns of orthodontic brackets and archwires in the dry state. American Journal of Orthodontics and Dentofacial Orthopedics 118: 662–674

Pandis N, Polychronopoulou A, Eliades T 2007 Self-ligating vs conventional brackets in the treatment of mandibular crowding: a prospective clinical trial of teatment duration and dental effects. American Journal of Orthodontics and Dentofacial Orthopedics 132: 208–215

Pizzoni L, Ravnholt G, Melsen B 1998 Frictional forces related to self-ligating brackets. European Journal of Orthodontics 20: 283–291

Read-Ward G E, Jones S P, Davies E H 1997 A comparison of self-ligating and conventional orthodontic bracket systems. British Journal of Orthodontics 24: 309–317

Redlich M, Mayer Y, Harari D, Lewinstein L 2003 In vitro study of frictional forces during sliding mechanics of "reduced-friction" brackets. American Journal of Orthodontics and Dentofacial Orthopedics 124: 69–73

Schumacher H A, Bourauel C, Drescher D 1999 The influence of bracket design on frictional losses in the bracket/arch wire system. Journal of Orofacial Orthopedics 60: 335–347

Taylor N G, Ison K 1995 Frictional resistance between orthodontic brackets and archwires in the buccal segments. Angle Orthodontists 66: 215–222

Thomas S, Sherriff M, Birnie D 1998 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. European Journal of Orthodontics 20: 589–596

Thorstenson G A, Kusy R P 2001 Resistance to sliding of self-ligating brackets versus conventional stainless steel twin brackets with second-order angulation in the dry and wet (saliva) states. American Journal of Orthodontics and Dentofacial Orthopedics 120: 361–370

Tidy D C 1989 Frictional forces in fixed appliance. American Journal of Orthodontics and Dentofacial Orthopedics 96: 249–254

Turnbull N R, Birnie D J 2007 Treatment efficiency of conventional vs. self-ligating brackets: effects of archwire size and material. American Journal of Orthodontics and Dentofacial Orthopedics 131: 395–399

Wadhwa P K, Kwon H K, Sciote J J 2004 Friction resistance in ceramic and metal brackets. Journal of Clinical Orthodontics 38: 35–38

Yeh C L, Kusnoto B, Viana G, Evans C A, Drummond J L 2007 In-vitro evaluation of frictional resistance between brackets with passive ligation designs. American Journal of Orthodontics and Dentofacial Orthopedics 131: 704.e11–704.e22