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Changes in the Surface Roughness and Friction Coefficient of Orthodontic Bracket Slots Before and After Treatment

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Summary: In this study, we tested the surface roughness of bracket slots and the friction coefficient between the bracket and the stainless steel archwire before and after orthodontic treatment. There were four experimental groups: groups 1 and 2 were 3M new and retrieved brackets, respectively, and groups 3 and 4 were BioQuick new and retrieved brackets, respectively. All retrieved brackets were taken from patients with the first premolar extraction and using sliding mechanics to close the extraction space. The surface roughness of specimens was evaluated using an optical interferometry profilometer, which is faster and nondestructive compared with a stylus profilometer, and provided a larger field, needing no sample preparation, compared with atomic force microscopy. Orthodontic treatment resulted in significant increases in surface roughness and coefficient of friction for both brands of brackets. However, there was no significant difference by brand for new or retrieved brackets. These retrieval analysis results highlight the necessity of reevaluating the properties and clinical behavior of brackets during treatment to make appropriate treatment decisions. SCANNING 35: 265–272, 2013. © 2012 Wiley Periodicals, Inc.

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Introduction

Retrieval analyses of orthodontic materials have recently become of increasing interest (Eliades and Bourauel, 2005) because the morphological, structural, and compositional characteristics and mechanical properties of the materials may be altered after exposure to the oral environment. During orthodontic treatment, the materials might not perform to the manufacturers' specifications with increasing time in the mouth. Adsorption and calcification of biofilm could increase the porosity and roughness of brackets and archwires, and could lead to inaccurate torque expression (Gioka and Eliades, 2004) and variation in friction between the brackets and the archwires (Bourauel *et al.*, '98; Eliades and Bourauel, 2005). It is important for clinicians to understand changes in the materials and evaluate their clinical behavior, and to modify the treatment process accordingly. Among all orthodontic materials, brackets stay in the patient's mouth for the longest time. Their biodegradation and associated complications are often a major concern.

In orthodontic treatment, resistance to sliding (RS) between brackets and archwires greatly influences the force transmitted to the teeth, because sliding mechanics are widely used to close the extraction space, and they may reduce the orthodontic force by 50% (Drescher *et al.*, '89). The coefficient of friction (COF) of the bracket and archwire materials is an important factor in RS (De Franco *et al.*, '95; Choi *et al.*, 2011), which may depend on the roughness, texture, and/or hardness of the contacting material surfaces (Loftus *et al.*, '99). Thus, studies of bracket surface roughness and COF are of great clinical interest with regard to RS.

Previous studies have measured the surface roughness of brackets and archwires using scanning electron microscopy (SEM; Saunders and Kusy, '94; Marques *et al.*, 2010), a contact surface profilometer (Bourauel *et al.*, '98; Zinelis *et al.*, 2005), and atomic force microscopy (AFM; Bourauel *et al.*, '98; Lin *et al.*, 2006; Alcock *et al.*, 2009; Lee *et al.*, 2010; Choi *et al.*, 2011). SEM can visualize only sample surface morphology two dimensionally, and does not provide quantitative information regarding the selected area. A contact profilometer allows visualization and determination of surface roughness parameter values. However, the measured area is in the form of a line, and the sample surface adjacent to the scanning line may be damaged. In contrast, AFM provides many advantages, such as three-dimensional (3D) configuration and quantitative measurements of the selected surface. However, sample preparation is necessary, such as grinding the bracket wings to expose the slot surface. Additionally, the measurement range of AFM is on a micrometer scale, which may not describe macroscopic characteristics well. In contrast, a noncontact surface profilometer is now available, which is based on white-light interferometry methods and can allow 3D imaging and determination of surface-roughness parameter values. The measurement is nondestructive, and needs no sample preparation. The test range can cover ~10 mm. To date, there have been few reports of the effect of clinical treatment on the surface roughness of bracket slots using this type of noncontact surface profilometer.

The aim of this study was to evaluate changes in brackets before and after orthodontic treatment. Specifically, the surface roughness of bracket slots and the COF between the bracket and the stainless steel (SS) archwire were measured before and after exposure to the oral environment. The surface roughness was measured using a noncontact surface profilometer (ADE phase shift MiroXAM-3D).

Materials and Methods

Sample preparation

Two types of commonly used SS canine brackets were selected: 3M Unitek Orthodontic Metal Brackets (3M Unitek, Monrovia, CA, USA) and BioQuick self-ligation brackets (Forestdent, Pforzheim, Germany) with a slot size of 0.022 × 0.028 inch (in). The surface morphology of each specimen was observed by SEM (Quanta 200, FEI, Eindhoven, the Netherlands). The SEM was operated at 15 kV accelerating voltage and low vacuum-chamber pressure. Furthermore, X-ray energy-dispersive spectrometry (EDS) was used for the elemental analysis of the new bracket surface slots.

There were four experimental groups ($n = 10$ each): groups 1 and 2 were 3M new and retrieved brackets, respectively, and groups 3 and 4 were BioQuick new and retrieved brackets, respectively. All retrieved brackets were collected from patients after orthodontic treatment with first premolar extraction and using sliding mechanics to close the extraction space at the Department of Orthodontics, Peking University School and Hospital of Stomatology, China. A detailed description of the retrieved samples is provided in Table I. These brackets were exposed to the oral cavity for 21.5 ± 3.3 months, and therefore experienced the leveling and space closure stages.

TABLE I Descriptions of the retrieved samples used in this study

	Gender	age mean ± SD, years	Intraoral exposure, mean ± SD, months
Group 2 ($n = 10$)	4M and 6F	17.8 ± 5.1	19.8 ± 2.5
Group 4 ($n = 10$)	4M and 6F	18.1 ± 5.7	22.9 ± 3.4

Surface roughness measurements

The surface roughness of specimens was evaluated using an optical interferometry profilometer (ADE phase shift MiroXAM-3D, Tucson, AZ, USA). The machine was placed on a vibration isolation table in a super-silent room. The profilometer scanned all 40 experimental samples with images of approximately 376 × 260 μm^2, and the scanning area was situated at the distal part of the bracket slot surface (Fig. 1). The readings measured by the data acquisition and image processing system were processed with a scanning probe image processor (SPIP, ver. 4.4; Image Metrology, Denmark). Three parameters were selected to evaluate the amplitude properties of the slot surface: Sa, Sq, and Sz (Sa, roughness average; Sq, root mean square; and Sz, ten-point height). The parameters were calculated using SPIP software.

COF measurements

The COFs of the specimens and SS archwires were tested using a Universal Micro-Tribotester (UMT-2, Center for Tribology (CETR), Campbell, CA, USA). Test specimens were attached on the UMT-2 plate using dental resin (Ormco Corporation, Glendora, CA, USA) by one experimenter in a standardized way. This guaranteed that the bracket slots stayed parallel to the archwire during the experiment. SS wire segments (Plasdent Corporation, Pomona, CA, USA) with a cross-section of 0.016 × 0.022 in and a length of 9 cm were used. As the counterpart sample, the surface roughness of the SS wires was also tested (the test condition was the same as that for the bracket

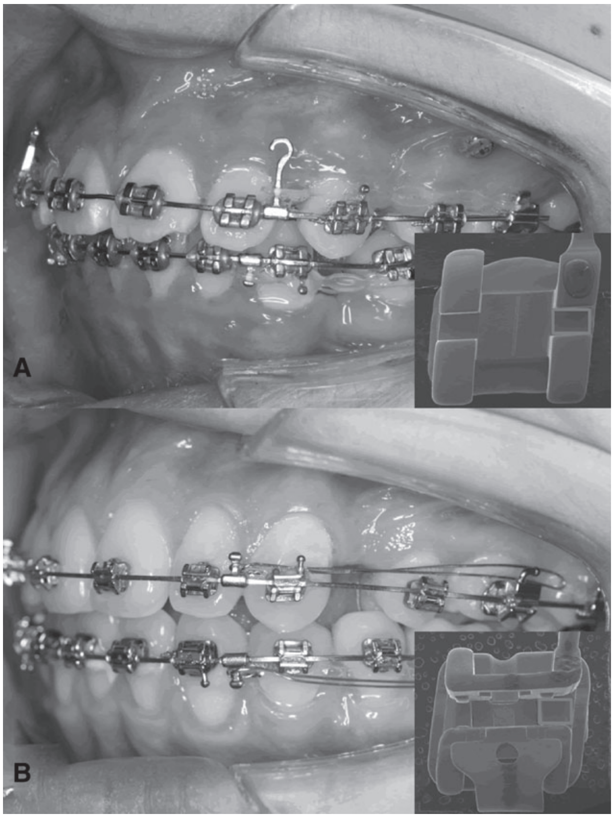

Fig 1. The retrieved brackets were collected from patients after orthodontic treatment with first premolar extraction: (a) 3M bracket, and (b) BioQuick bracket. The area scanned by the profilometer was situated at the distal part of the bracket slot surface (the red area in the image).

specimens). The wires were cleaned with 95% alcohol and each segment was used only once. The electric motor pulled the archwire across the bracket slot at a speed of 6 mm/min for 1 min with 1.47 N vertical force, maintaining 0° torque and 0° tip angle between the archwire and the bracket slot. The experiments were conducted in a dry environment at a temperature of 25°C. The COF was calculated by averaging that registered between the 10th and 60th s, including 10,000 test data points (Fig. 2).

Statistical analyses

Results of the three surface roughness parameters and COF analyses are expressed as means ± standard deviation (SD). The results were analyzed using two-way analysis of variance (ANOVA) with brand and intraoral aging as discriminating variables. The STATA version 11.0 software was used, and p values < 0.05 were considered to indicate statistical significance.

Results

Figure 3 shows SEM images of the two types of SS brackets. The original magnification was 500×. The slot surface of the BioQuick bracket looks more irregular than that of the 3M bracket before

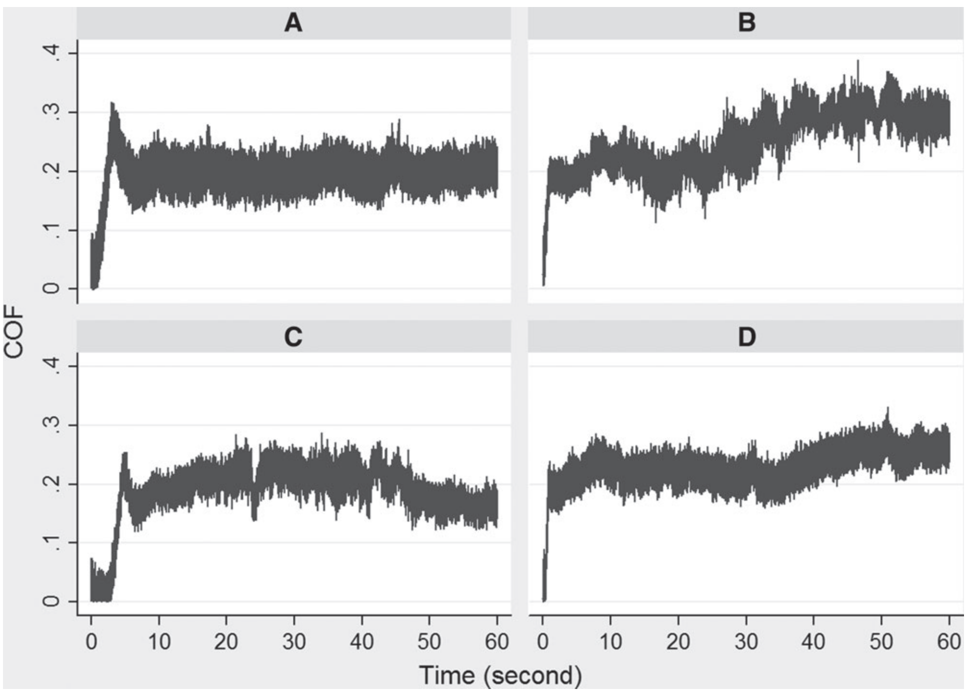

Fig 2. Representative COF findings with respect to the four groups of brackets: (a) 3M new bracket, (b) 3M retrieved bracket, (c) BioQuick new bracket, (d) BioQuick retrieved bracket. The COF was calculated by averaging that registered between the 10th and 60th s.

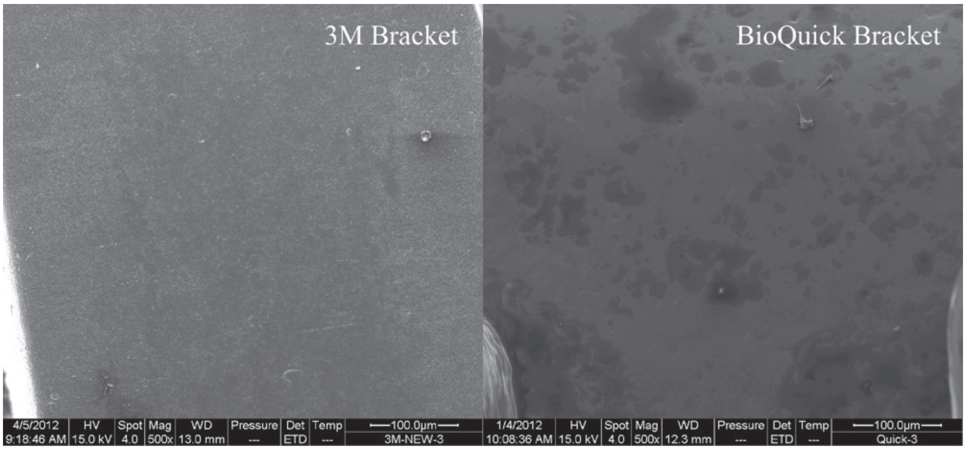

Fig 3. SEM images of the two types of stainless steel brackets. Original magnification, 500×. The slot surface of the BioQuick bracket (right) appears more irregular than that of the 3M bracket (left) before treatment.

TABLE II EDS analysis results showing the percentages by weight (Wt%) of the elements identified in 3M and BioQuick brackets

3M bracket		BioQuick bracket	
Element	Wt%	Element	Wt%
Fe	68.29	Fe	62.91
Cr	15.12	Cr	16.78
C	4.43	Mn	8.96
Ni	3.98	C	4.76
O	3.71	Mo	3.58
Cu	3.40	O	2.19
Si	0.64	Si	0.65
Al	0.43	Al	0.17

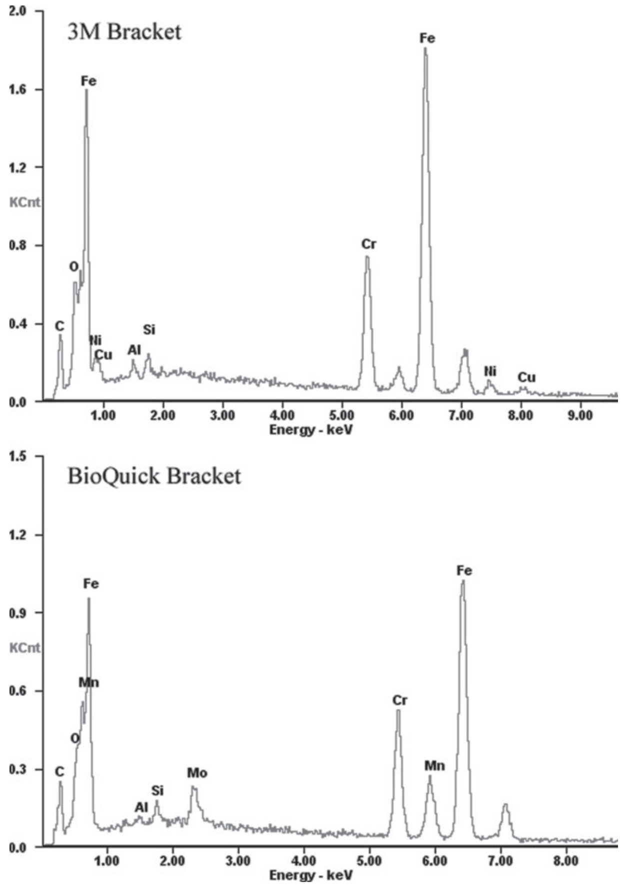

Fig 4. EDS analysis of the elemental composition of the new bracket surface slots. The main components of the two brands of brackets are identical, but the trace components differ somewhat.

treatment. EDS analysis showed that the 3M bracket is composed mainly of iron (Fe) and chromium (Cr), while some carbon (C), nickel (Ni), oxygen (O), copper (Cu), silicon (Si), and aluminum (Al) are also present. Similarly, the main components of the BioQuick bracket are iron (Fe) and chromium (Cr), but there are traces of manganese (Mn), carbon (C), molybdenum (Mo), oxygen (O), silicon (Si), and aluminum (Al). (Table II; Fig. 4).

Figure 5 shows representative white-light interferometry profilometer topographies and 3D images (376×260 μm^2) of the bracket slot surfaces of the four groups. Three roughness parameters (Sa, roughness average; Sq, root mean square; and Sz, ten-point height) were used to evaluate the surface topography, and one parameter (COF) was used to evaluate the mechanical properties quantitatively (Table III). Sa, Sq, and Sz in the four groups showed similar tendencies.

Two-way ANOVA (Table IV) indicated that all parameters were significantly affected by intraoral aging, but there was no significant difference by brand. That is to say, retrieved brackets (Groups 2 and 4) showed significant increases in all surface roughness parameters and COF for both 3M and BioQuick brackets ($p < 0.05$) compared with the new groups (Groups 1 and 3). No parameter showed a significant difference between the two bracket brand groups (Groups 1 and 3; Groups 2 and 4).

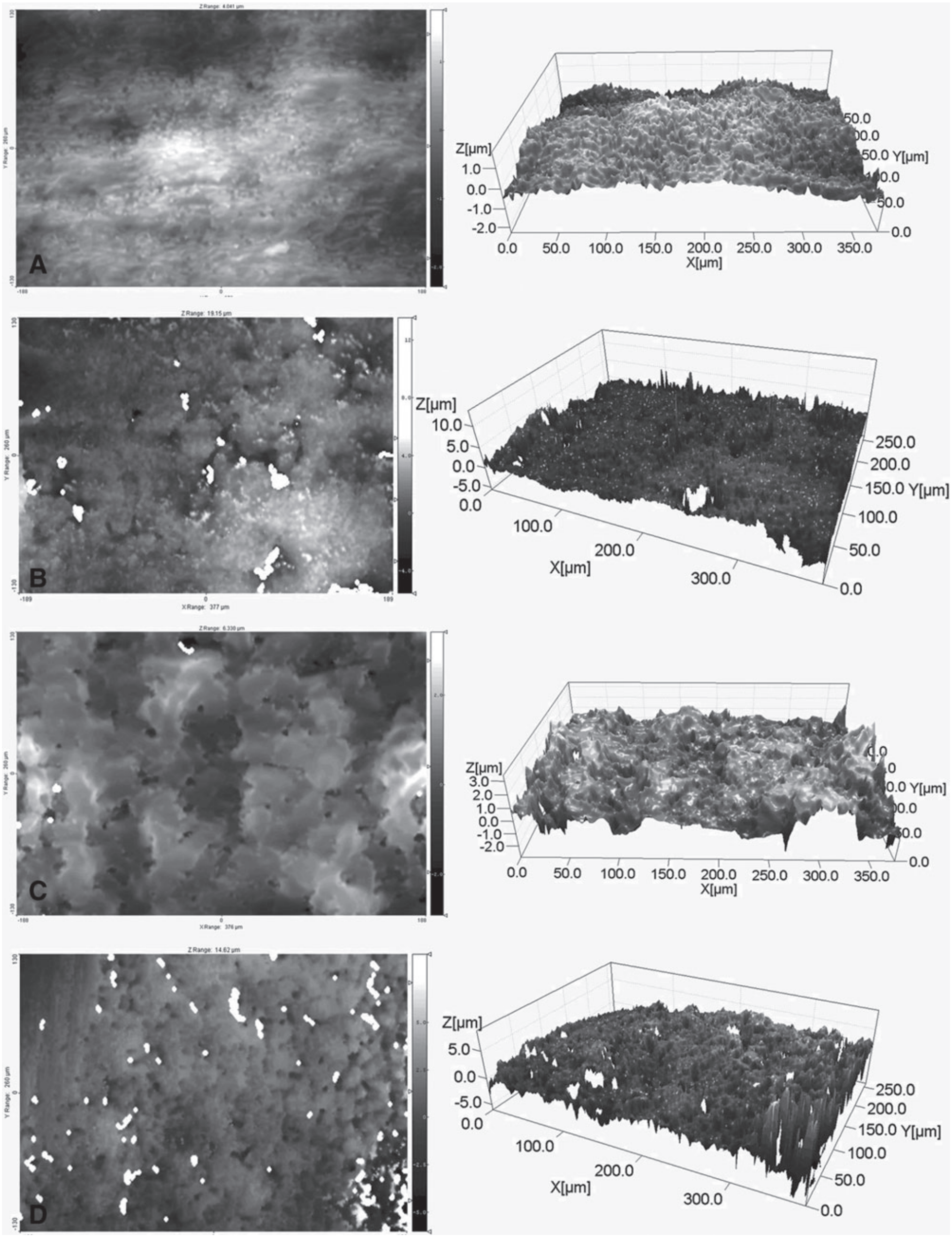

Fig 5. Representative white-light interferometry profilometer topographies and 3D images of the bracket slot surfaces: (a) 3M new bracket, (b) 3M retrieved bracket, (c) BioQuick new bracket, (d) BioQuick retrieved bracket.

TABLE III Descriptive statistics of surface roughness and COF of each group of brackets and archwires

Parameters	Group 1 (95% CI)	Group 2 (95% CI)	Group 3 (95% CI)	Group 4 (95% CI)	Archwire (95% CI)
Sa (nm)	523.0 ± 280.2 (622.5–1,023.5)	1,474.8 ± 665.1 (999.0–1,950.6)	611.4 ± 64.7 (565.1–657.7)	1,224.1 ± 407.8 (932.3–1,515.9)	183.3 ± 25.0 (126.7–239.9)
Sq (nm)	1,000.5 ± 323.7 (769.0–1,232.0)	2,112.6 ± 938.2 (1,441.4–2,783.8)	783.3 ± 89.4 (719.4–847.2)	1,624.2 ± 580.9 (1,208.7–2,039.7)	229.2 ± 30.6 (159.9–298.5)
Sz (nm)	5,684.6 ± 1,326.0 (4,736.0–6,633.2)	21,396.5 ± 13,488.3 (11,747.5–31,045.5)	6,221.2 ± 1,142.1 (5,404.2–7,038.2)	13,912.6 ± 6,536.4 (9,236.8–18,588.4)	831.5 ± 163.3 (462.2–1,200.8)
COF	0.20 ± 0.02 (0.18–0.21)	0.25 ± 0.06 (0.20–0.29)	0.20 ± 0.02 (0.18–0.21)	0.23 ± 0.04 (0.20–0.26)	

Note: Results are expressed as means ± standard deviations.
Group 1: 3M new brackets, group 2: 3M retrieved brackets, group 3: BioQuick new brackets, group 4: BioQuick retrieved brackets.

TABLE IV Two-way ANOVA of Sa, Sq, Sz, and COF

	Sa		Sq		Sz		COF	
	F	Prob > F	F	Prob > F	F	Prob > F	F	Prob > F
Intraoral Aging	23.75	<0.0001	29.02	<0.0001	22.92	<0.0001	10.90	0.0021
Brand	3.17	0.0830	3.79	0.0592	2.02	0.1636	0.79	0.3790

Discussion

SS brackets have long been widely used in everyday orthodontic practice, but changes in their clinical effectiveness due to intraoral exposure have not been investigated. Much research regarding changes in the properties of brackets has been conducted in the laboratory, seeking to simulate intraoral conditions (Zinelis *et al.*, 2005; Faltermeier *et al.*, 2008; Morina *et al.*, 2008; Krauss *et al.*, 2010). However, the clinical situation in the oral cavity is too complex to simulate successfully in *in vitro* (Eliades and Bourauel, 2005). Many factors in the mouth may influence the properties of dental materials, such as the oral flora and its byproducts, salivary components and the saliva flow rate, and the intraoral temperature. These parameters act in combination and result in biodegradation of biomaterials, which is impossible to simulate in the laboratory. Thus, retrieval analysis shows the value of evaluation of the functional and effective alterations of dental materials (Eliades and Bourauel, 2005).

Most specimens in retrieval analyses of orthodontic brackets were mixed, comprising incisor, canine, and premolar devices (Eliades *et al.*, 2002, 2003; Lindel *et al.*, 2011; Regis *et al.*, 2011). Few studies have focused on brackets from only one tooth position, except Pandis *et al.* (2007) and Gkantidis *et al.* (in press), who focused on incisor brackets, and Choi *et al.* (2011), who investigated the second premolar brackets. In the first premolar extraction case, the force transmitted to the incisor brackets is vertical, and the incisors are retracted in the sagittal direction. Usually, the second premolar brackets experience classical sliding with the archwire while closing the space. In this study, only canine brackets were selected because the tooth is in a unique position in the arch (Fig. 1). The canine has the longest root and is located in the corner of the arch. During the space-closure stage, it experiences a “tip-upright-tip-upright” sequence of movements (Drescher *et al.*, ’89). To some extent, the canine brackets experience the most complex interaction with archwires. Groups 2 and 4 specimens were taken from orthodontic patients with the first premolar extraction, so these results may have more clinical significance.

The surface roughness of the bracket slots increased significantly after orthodontic treatment (Table III). The amplitude parameters were selected because the amplitude property is one of the most important surface morphology characteristics. Historically, Sa (Ra in two dimensions) is one of the parameters used most commonly to quantify surface texture; it quantifies the “absolute” magnitude of the surface heights. Once a surface has been processed, Sa may be used to evaluate changing as a monitor. However, Sa is insensitive to the spatial distribution and the “polarity” of the surface texture in a deep valley or a high peak. Therefore, Sq and Sz were also used. Sq is the root-mean-square deviation of the assessed area, which has more statistical significance than Sa. Sz is the ten-point height, which quantifies the “peak-valley” range of the surface, characterizing the extreme features. As the results in Tables III and IV indicate, the three parameters exhibited similar tendencies in all four groups. This indicated that the selected parameters were comprehensive and reasonable, which is consistent with previous reports (Lee *et al.,* 2010; Choi *et al.,* 2011; Regis *et al.,* 2011). Immediately upon being bonded on the patients’ teeth the orthodontic brackets begin to be affected by the oral environment. Many factors may lead to the slots becoming rougher after intraoral exposure. Biological factors include biofilm accumulation, saliva, and carbonic acid drink erosion. Mechanical factors include brushing the teeth, orthodontist activities (removing and engaging the archwire at each monthly visit), and friction between brackets and archwires. The surfaces of the retrieved brackets were more irregular than those of new brackets. Surface alterations may affect the dimensional accuracy of the slot, which may in turn affect the complete engagement of the archwire to the bracket. Bracket performance, such as torque and tip expression, and rotation control, might be decreased as a result.

Additionally, an increased slot surface roughness may be associated with changes in the COF. Our data confirm that the COF values of the retrieved groups increased significantly (Tables III and IV). The results are consistent with the findings of Regis *et al.* (2011) that metallic brackets underwent significant degradation during orthodontic treatment, with increased friction. However, various bracket types were evaluated (premolar, canine, and incisor for both arches) in their study, and it was not possible to compare the sliding resistance. Thus, the percentage differences expressed as sliding resistance alteration ratios between retrieved and as-received brackets were compared.

These retrieval analysis results highlight the necessity of reevaluating the properties and clinical behavior of brackets during treatment to make appropriate treatment decisions.

Many previous studies of friction showed that self-ligating brackets reduced the classic frictional force more than conventional brackets in *in vitro* experiments (Shivapuja and Berger, '94; Kapur *et al.,* '98; Cacciafesta *et al.,* 2003; Hain *et al.,* 2006; Yeh *et al.,* 2007; Franchi *et al.,* 2008). However, some recent studies and reviews have reported that the evidence that self-ligating brackets have advantages in clinical usage is insufficient (Willems *et al.,* 2001; Harradine, 2003; Clocheret *et al.,* 2004; Burrow, 2009; Oz *et al.,* 2012). The results of this study suggest that the COF values of the two brands produced no significant differences in both the new and retrieval groups (Table III), although the composite elements of the two brands differed slightly (Table II). Further studies are needed to explore the clinical significance of the findings.

The test instrument used to measure surface roughness in this study was a noncontact profilometer (ADE Phase Shift MicroXAM). This instrument is faster and nondestructive compared with a stylus profilometer, and provides a larger field, needing no sample preparation, in comparison with AFM. The system has a repeatability (precision mode) of 0.1 nm and a field of view of 8×10 mm (at $0.78\times$) to 0.084×0.063 mm (at $100\times$). There are few reports of use of a white-light interferometry technique to determine the surface roughness of bracket slots. Lee *et al.* (2010) and Choi *et al.* (2011) analyzed the surface roughness of bracket slots by AFM. However, the images scanned were only approximately 30×30 and $32 \times 32\ \mu m^2$ respectively, and before scanning, the bracket wings had to be ground with a high-speed hand drill and a chamfer bur to expose the slot surface. The observed range in this study was $376 \times 260\ \mu m^2$. The size of the scanned area was roughly equal to the distal part of the BioQuick self-ligation bracket (Fig. 1). The middle part of the self-ligation bracket slot is processed hollow. Therefore, the only contact areas between the slot surface and the archwire were the distal and mesial parts. In order to compare the test results, the scanned area of the 3M bracket was also $376 \times 260\ \mu m^2$. The area was larger, and so our data may better reflect the overall characteristics of the bracket slot. The bracket wings needed no grinding, ensuring that the slots would not be damaged.

Conclusions

Two types of commonly used brackets (3M Unitek traditional and BioQuick self-ligation brackets) were investigated in this study. Orthodontic treatment resulted in significant increases in the surface roughness and COF of brackets of both brands. However, there was no significant difference by brand in terms of either new or retrieved brackets.

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