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ORIGINAL ARTICLE

Study of force loss due to friction comparing two ceramic brackets during sliding tooth movement

Vergleichende Studie zum reibungsbedingten Kraftverlust während der bogengeführten Zahnbewegung durch zwei Keramikbrackets

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Abstract
Objective To compare the percentage of force loss generated during canine sliding movements in newly introduced ceramic brackets with metal brackets.
Materials and methods Two types of ceramic brackets, namely polycrystalline alumina (PCA) ceramic brackets (Clarity Advanced) and monocrystalline alumina (MCA) ceramic brackets (Inspire Ice) were compared with stainless steel (SS) brackets (Victory Series). All bracket groups (n = 5 each) were for the maxillary canines and had a 0.018-inch slot size. The brackets were mounted on an Orthodontic Measurement and Simulation System (OMSS) to simulate the canine retraction movement into the first premolar extraction space. Using elastic ligatures, $0.016 \times 0.022''$ (0.40×0.56 mm) stainless steel archwires were ligated onto the brackets. Retraction force was applied via a nickel–titanium coil spring with a nearly constant force of approximately 1 N. The OMSS measured the percentage of force loss over the retraction path by referring to the difference between the applied retraction force and actual force acting on each bracket. Between group comparisons were done with one-way analysis of variance.
Results The metal brackets revealed the lowest percentage of force loss due to friction, followed by the PCA and MCA ceramic bracket groups (67 ± 4, 68 ± 7, and 76 ± 3 %, respectively). There was no significant difference between SS and PCA brackets ($p = 0.97$), but we did observe significant differences between metal and MCA brackets ($p = 0.03$) and between PCA and MCA ceramic brackets ($p = 0.04$).
Conclusion PCA ceramic brackets, whose slot surface is covered with an yttria-stabilized zirconia-based coating exhibited frictional properties similar to those of metal brackets. Frictional resistance resulted in an over 60 % loss of the applied force due to the use of elastic ligatures.

Keywords Ceramic brackets · Arch-guided tooth movement · Friction · Force loss

Zusammenfassung
Ziele Vergleich des Kraftverlusts durch Reibung bei der bogengeführten Zahnbewegung unter Einsatz zweier neuentwickelter Keramikbrackets mit einem Metallbracket.
Material und Methoden Zwei Arten von Keramikbrackets, ein polykristallines Aluminiumoxid- (PCA, Clarity Advanced) und ein monokristallines Aluminiumoxid-Keramikbracket (MCA, Inspire Ice), wurden untersucht und mit einem Stahlbracket (Victory Series) verglichen. Alle getesteten Brackets (je $n = 5$) waren Oberkiefereckzahnbrackets mit einer Slotweite von 0,46 mm ($0.018''$). Die Brackets wurden im orthodontischen Mess- und Simulations-System (OMSS) montiert, um eine Eckzahnretraktion in die Extraktionslücke des ersten Prämolaren zu simulieren. Die Führung erfolgte an einem Stahlbogen der Dimension 0.40×0.56 mm ($0.016'' \times 0.022''$), der mittels Elastics in den Brackets ligiert wurde. Die Retraktionskraft wurde über

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eine Nickel-Titan-Zugfeder auf den Zahn aufgebracht, die eine nahezu konstante Kraft von 1 N erzeugte. Mit dem OMSS wurde der prozentuale Kraftverlust über die Retraktionsstrecke aus der Differenz von eingesetzter Retraktionskraft und am Bracket aktiver Kraft ermittelt. Der Gruppenvergleich erfolgte über eine einfaktorielle Varianzanalyse (ANOVA).

Ergebnisse Der prozentuale Kraftverlust durch Friktion war bei den Metallbrackets am geringsten, gefolgt von den PCA- und den MCA-Keramikbrackets (67 ± 4, 68 ± 7 und 76 ± 3 %). Zwischen Stahl- und PCA-Brackets bestand kein signifikanter Unterschied ($p = 0.97$). Die Unterschiede zwischen Stahl- und MCA-Brackets ($p = 0.03$) dagegen sowie zwischen PCA- und MCA-Keramikbrackets ($p = 0.04$) erwiesen sich als signifikant.

Schlussfolgerungen PCA-Keramikbrackets mit einer Slotbeschichtung aus Yttriumoxid-stabilisierter Zirkondioxidkeramik zeigten vergleichbare Reibungsverluste wie Stahlbrackets. Insgesamt betrug der Reibungsverlust mehr als 60 % der eingesetzten Kraft, was aus dem Einsatz elastischer Ligaturen resultierte.

Schlüsselwörter Keramikbrackets · bogengeführte Zahnbewegung · Reibung · Kraftverlust

Introduction

Orthodontic tooth movement occurs when the level of applied force suffices to stimulate cellular activity in the periodontium [18]. If the applied force is adequate, it should overcome the frictional force generated between the bracket and wire interface to initiate tooth movement. Friction is known to be the force that retards the movement of two objects sliding against each other in a direction opposite to the movement force and proportional to the normal force transmitted across the plane of contact [8].

The frictional force between bracket and archwire is omnipresent and can resist any force the orthodontist applies to move the teeth [13]. However, its impact is significant during the space closure stage, during which the sliding mechanics should be optimized to slide the teeth effectively into the extraction spaces. The amount of the applied force loss due to frictional resistance has been estimated in several studies and found to range between 12 % and more than 70 % of the force originally applied [13, 14]. High frictional forces can inhibit or even impede efficient tooth movement, thus, negatively affecting treatment time or outcome [8].

The resistance to sliding (RS) is characterized by three phenomena. Static and sliding friction occur between the brackets and archwire when their surfaces come into contact and a force acts between them, while binding occurs when the force increases and the wire starts to bind via static friction against the bracket corners. Notching, on the other hand, happens when the sliding movement ceases due to permanent wire deformation at the bracket–wire interface [13]. Tooth movement can be viewed as successive cycles of crown tipping and root uprighting in the direction of the applied force. Teeth can therefore be exposed to different combinations of resistance to sliding at any time [3]. The resistance to sliding is by nature multifactorial. These factors are physical, relating to the brackets, characteristics having to do with the archwire material, and geometry. The resistance can also be associated with the type of ligation. Biological factors, on the other hand, include the oral environment such as salivary conditions and acquired pellicles [19].

Ceramic brackets are considered one of the least conspicuous appliances that satisfy most adults' aesthetic needs. Their advantages include excellent biocompatibility, color stability, and resistance to wear in the oral environment. However, their high friction coefficient is a major drawback, as it increases the resistance to sliding [20]. Many investigations comparing the resistance to sliding of ceramic brackets with stainless steel brackets (SS) have proven that they are associated with greater resistance to sliding [11, 13].

The three main types of ceramic brackets are monocrystalline alumina (MCA), polycrystalline alumina (PCA), and (less frequently) zirconia brackets. Both the PCA and MCA have high-purity aluminum oxide (Al_2O_3) as their main chemical component; however, different fabrication methods means their physical properties can differ [20]. The undesirable frictional characteristics of ceramic brackets compelled the manufacturers to modify the slot surface in different ways. One was to fabricate the metal slots made of stainless steel or gold so that the favorable frictional characteristics of metals are combined with the aesthetic appearance of ceramic. Although some might find these products to be superior to the conventional ceramic brackets, they did not necessarily mimic the stainless steel brackets in all tested conditions [7, 15, 24].

As the manufacturers continue to improve the frictional characteristics of ceramic brackets, their claims of efficacy need to be verified. The purpose of the present study was to test force loss due to frictional resistance during sliding tooth movement in a novel PCA ceramic bracket and to compare that with MCA ceramic and SS brackets using a biomechanical test set-up.

Materials and methods

Sample description

Two types of orthodontic ceramic brackets were included in the test groups: Clarity Advanced (3M Unitek,

Monrovia, CA, USA) and Inspire Ice (Ormco, Glendora, CA, USA). They were compared with Victory Series conventional SS brackets (3M Unitek), which served as our control group (Fig. 1). All brackets had a 0.018-inch (0.46 mm) slot size and a Roth prescription. The brackets were ligated to a $0.016 \times 0.022''$ (0.40×0.56 mm) SS archwire using elastic ligatures (Table 1).

Experimental set-up

The brackets were bonded using a cyanoacrylate adhesive to resin model replicas (Palavit G 4004; Heraeus Kulzer, Hanau, Germany) constructed from a Frasaco model (Franz Sachs, Tettnang, Germany) of a normally aligned upper arch. For standardization purposes, one investigator handled all the bonding procedures from the second premolar on one side to the corresponding tooth on the opposite side. Following removal of the canine and first premolar on the left side, the models were mounted in the Orthodontic Measurement and Simulation System (OMSS, Fig. 2) [2, 13]. This system consists of two motor-driven measurement tables, each containing force/moment sensors capable of registering the forces and moments acting on a tooth in all three spatial planes. All the system's mechanical components are in a temperature-controlled chamber and connected to a personal computer from which the commands for simulating orthodontic tooth movement are made.

The left canine bracket was bonded to a bracket holder fixed to the left sensor of the OMSS (Fig. 2). A closed Sentalloy nickel–titanium coil spring (GAC, Central Islip, NY, USA) was attached to the second sensor and hooked over the left canine bracket to apply about 1 N of retraction force (101 g, Fig. 2). The center of resistance of the retracted canine was set by the system software at 8.5 mm apical to the bracket and 4.5 mm lingual. The OMSS simulated the canine sliding movement by dividing it into a maximum of 200 incremental steps along the retraction path. Each increment consisted of a cycle initiated by a simultaneous measurement of the forces and moments delivered by the nickel–titanium coil spring and those acting on the canine bracket. The resultant tooth movement triggered by these forces was then calculated by the software and generated by the system, and the canine bracket was retracted along the extraction space [2, 13, 22].

The amount of force loss during each increment of movement was calculated as the difference between the forces applied by the coil spring and the actual force reaching the canine bracket. Each bracket type was tested five times in the same manner. The sample size was chosen based on a previous study [22]. In each observation, the mean of the percentage of force loss of all executed movement increments was calculated and the weighted means were then obtained for each bracket type.

Statistical analysis

Statistical data analysis was performed using the Statistical Package for Social Sciences, version 21 (SPSS Inc., Chicago, IL, USA). Normal distribution of the data was tested using the Kolmogorov–Smirnov test, and the homogeneity of variance was tested with Levene's test. The differences between the weighted means of the percentage of force loss were analyzed with one-way analysis of variance (ANOVA). Group differences were further analyzed with

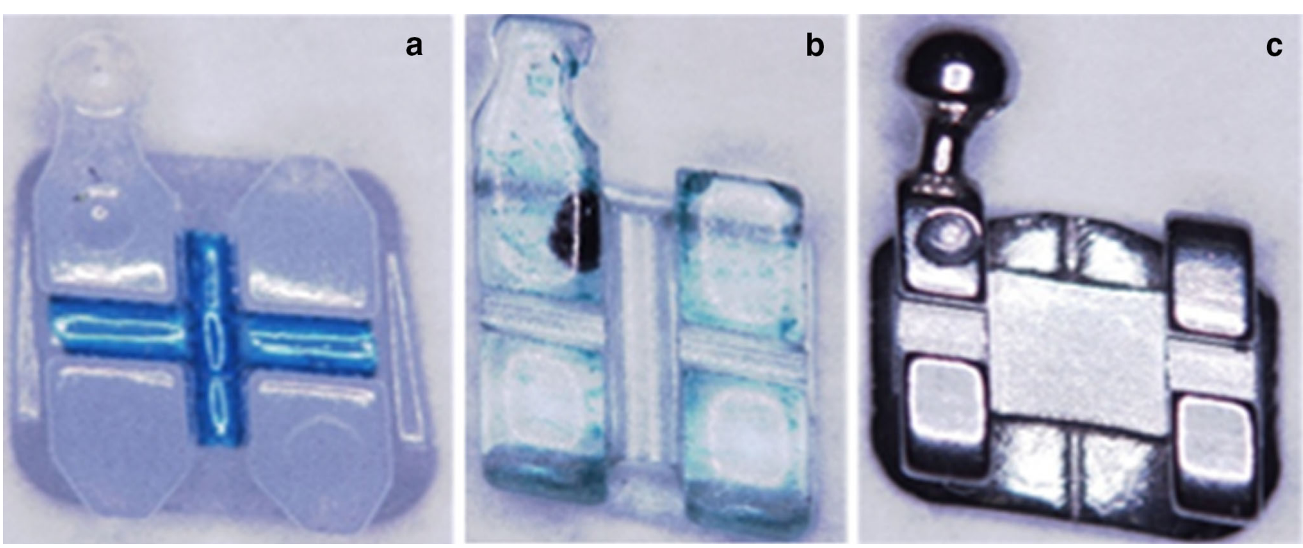


Fig. 1 The tested bracket groups: **a** polycrystalline alumina ceramic brackets, **b** monocrystalline alumina ceramic brackets, and **c** stainless steel brackets

Abb. 1 Untersuchte Bracketgruppen: **a** polykristalline Aluminiumoxid-Keramikbrackets, **b** monokristalline Aluminiumoxid-Keramikbrackets, **c** Stahlbrackets

Tab. 1 Study sample
Tab. 1 In der Studie untersuchte Brackets

Material	Product	Dimensions
Brackets		
Polycrystalline alumina	Clarity advanced[a]	0.018″ × 0.025″
Monocrystalline alumina	Inspire ice[b]	0.018″ × 0.025″
Stainless steel	Victory series[c]	0.018″ × 0.025″
Archwires		
Stainless steel	Rectangular archwire[b]	0.016″ × 0.022″
Ligatures		
Elastic	Elastic easy to tie[a]	0.002″

[a,c] 3 M Unitek, Monrovia, California

[b] Ormco, Glendora, California

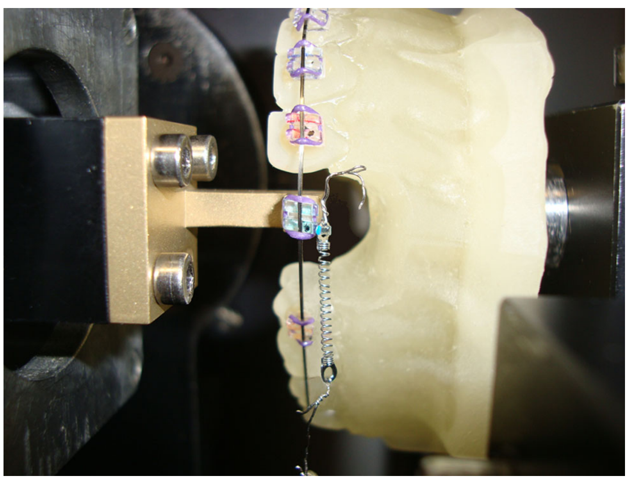


Fig. 2 The model was mounted in the OMSS and the canine bracket to be retracted was attached to the left OMSS sensor. The retraction force of 1 N is applied via a nickel–titanium coil spring, attached to the right sensor
Abb. 2 Das Modell wurde im OMSS montiert und das zu retrahierende Eckzahnbracket wurde auf den linken OMSS-Sensor aufgebracht. Die Retraktionskraft von 1 N wird über eine am rechten Sensor befestigte Nickel-Titan-Zugfeder aufgebracht

Tukey's post hoc comparison test. The level of significance was set at 0.05.

Results

Descriptive statistics of the percentage of force loss during canine sliding movement are presented in Table 2 and Fig. 3. The normality test confirmed that our data was normally distributed and homogeneous ($p = 0.2$), indicating the sample size was representative for each bracket type.

The SS brackets revealed the lowest percentage of force loss: 67 ± 4 % frictional reduction in orthodontic force

Tab. 2 Descriptive statistics of the percentage of force loss during maxillary canine sliding movement among bracket groups
Tab. 2 Deskriptive Statistik des prozentualen Kraftverlusts während der bogengeführten Oberkiefereckzahnbewegung in den unterschiedlichen Bracketgruppen

Bracket groups	Weighted mean	SD	Minimum	Maximum
PCA	68	7	63	79
MCA	76	3	73	79
SS	67	4	61	71

PCA polycrystalline ceramic brackets, *MCA* monocrystalline ceramic brackets, *SS* stainless steel metal brackets, *SD* standard deviation

(Fig. 3), followed by the PCA (68 ± 7 %) and the MCA ceramic bracket groups (76 ± 3 %). The ANOVA test revealed significant differences in the percentage of force loss during canine retraction between the three types of brackets ($p \leq 0.001$).

However, the post hoc test indicated no significant difference in the weighted mean values of force loss between the PCA and SS brackets. However, the mean value of force loss in the MCA ceramic brackets was significantly higher than in the PCA and SS brackets (Fig. 3; Table 3).

Discussion

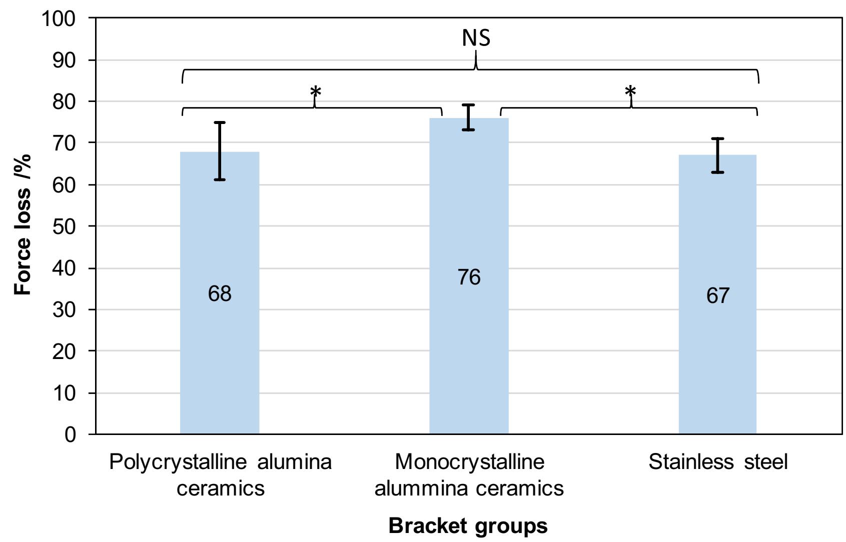
This study was conducted to investigate the percentage of force loss due to friction during canine sliding movement between two types of ceramic brackets. High resistance to friction in fixed orthodontic appliances would result in most of the applied force for tooth movement being dissipated. The control of friction resistance generated between the bracket and archwire is crucial to the efficacy of the sliding movement during space closure.

Although the factors influencing frictional resistance are well defined in the literature, friction is a complex phenomenon not easily simulated in in-vitro studies. Most previous studies tested the frictional resistance in fixed orthodontic appliances by sliding straight wire segments through single or multiple brackets. Although this method is often used, it does not enable biomechanical analysis of all the applied forces. Frictional resistance in this study was tested using a specialized biomechanical set-up, the OMSS, a unique experimental apparatus designed to analyze the static and dynamic behavior of several orthodontic appliances. It measures all the forces and moments resulting from force application away from the center of resistance in all three spatial planes. Moreover, factors such as controlled temperature, interbracket distance, and arch convexity are all taken into consideration [2, 9].

Our comparison was limited to a monocrystalline ceramic bracket and a novel polycrystalline ceramic bracket

Fig. 3 Percentage of force loss during maxillary canine sliding movement among bracket groups. *$P < 0.05$, *NS* not significant

Abb. 3 Prozentualer Kraftverlust während der Oberkiefereckzahnbewegung in den unterschiedlichen Bracketgruppen. *$P < 0.05$, *NS* nicht signifikant



Tab. 3 Multiple comparisons of the mean differences in force loss during canine retraction

Tab. 3 Multiple Vergleiche der mittleren Unterschiede beim Kraftverlust während der Eckzahzahnretraktion

Bracket groups		Mean difference	SE	*P* value
PCA	MCA	–8.14	3.03	0.04
	SS	0.72	3.03	0.97
MCA	PCA	8.11	3.03	0.04
	SS	8.85	3.03	0.03

PCA polycrystalline ceramic brackets, *MCA* monocrystalline ceramic brackets, *SS* stainless steel metal brackets, *SE* standard error

that recently came on the market. We used elastomeric ligatures for ligation for two reasons: first, to circumvent the variability of force levels associated with SS ligature that is known to exceed 50 % among trained clinicians and with the same clinician at different times [10]. The second reason was to simulate daily clinical practice during the space closure stage when elastic ligatures are sufficient to hold the archwire in place, especially when all the teeth are aligned and there is no rotation. The guiding archwire used for sliding was 0.016 × 0.022″ SS since it is the standard wire for sliding teeth in 0.018-inch bracket slots [18].

Our results show that the percentage of force loss during simulated canine retraction was significantly higher in the MCA ceramic brackets than in the PCA and SS brackets, findings that concur with several studies reporting higher frictional forces in MCA ceramic brackets versus PCA ceramic or SS brackets [4, 16, 17]. Nevertheless, those studies were inconsistent when comparing the two types of ceramic brackets. Some investigators stated that MCA brackets generate lower frictional resistance than PCA brackets [1], while others reported no differences between the two types [21].

Many investigators have attributed high friction in ceramic brackets to their rough surface [7, 11, 15, 26]. Contrary to what one might expect, higher frictional resistance does not correlate with a rougher slot surface. In fact, the relationship between the bracket's surface roughness and frictional characteristics has not been equivocally defined. Cha et al. [4] evaluated the surface roughness of brackets using a scanning electron microscope and found that the same type of MCA ceramic bracket used in this study had the smoothest slot surface although it revealed the highest friction forces in all bracket–wire angulations included in their experiment. Choi et al. [6] quantitatively measured the slot surface roughness of their brackets and found that the same type of MCA bracket used in our study had the smoothest slot surface but also the highest friction values. Similarly, the surface roughness of the bracket slots was measured via laser specular reflectance. MCA ceramic brackets were significantly smoother than PCA ceramic brackets, but there were no differences in their frictional characteristics [21], an observation attributed to the fact that MCA ceramic brackets have sharp, hard corners formed by the intersection of the slot and side walls of the bracket, compromising the binding between the archwire and the bracket corners, which may negate any advantage associated with their smoother surfaces. We concur with this explanation.

There is evidence that the design of the bracket corner or the "bevel" affects its frictional characteristics. As the bracket bevel occupies less space and its corners become sharper, friction resistance increases due to the reduction in the critical contact angle at the bracket–wire interface [5] which means more frequent binding [24]. Binding is considered the major determinant of resistance to sliding

during tooth movement. In the OMSS, the canine experiences the binding effect as part of a dynamic reaction to the retracting force, similar to what happens in the genuine clinical situation. The crown tips first as it responds to the moment associated with the retraction force. As the retraction force continues, crown tipping increases until the guiding archwire deforms elastically and binding occurs at the bracket–wire interface. When the stress on the guiding archwire is released, root uprighting simultaneously occurs. Thus, sliding movements occur as the retracted tooth experiences successive cycles of crown tipping and root uprighting [3, 8].

The present study revealed no difference in the percentage of force loss due to friction resistance between the PCA and SS brackets we tested. To the best of our knowledge, this type of PCA bracket is new on the market and no previous studies have examined its frictional characteristics. However, the product development team reported that it is the first of its kind to have a low-friction coating based on yttria-stabilized zirconia (YSZ) on the slot surface area deposited via radiofrequency magnetron sputtering. The frictional forces of YSZ-coated ceramic were compared with SS and with uncoated ceramic. YSZ-coated ceramic disks revealed a lower coefficient of friction (COF) during the sliding test against SS compared to the uncoated ceramic disks, while their COF was similar to that of SS. In addition to having a low COF, the YSZ coating is also abrasion-resistant, smooth, and translucent [23].

Previous studies of different types of PCA ceramic brackets have attributed their higher frictional forces compared to SS brackets to their rougher surfaces [4, 7, 15]. Regardless of the contribution of the surface roughness to friction, other physical properties of the raw materials used to manufacture brackets are considered to contribute to friction, e.g., hardness, stiffness, and compressive yield strength [27], implying that the differences in the slot–surface roughness of the brackets may not play an important role in frictional characteristics of the brackets.

Surface treatment of ceramic bracket slots with biocompatible coatings can be considered an effective approach to reduce frictional forces in ceramic brackets without jeopardizing aesthetics. A significant reduction in friction was reported in PCA specimens that had undergone diamond-like carbon coating or parylene coating via plasma deposition [12]. There are also reports that silica-coated PCA ceramic brackets produce frictional forces similar to SS brackets [4]. Application of a YSZ-based coating in ceramic brackets has not been previously studied. However, the tribological behavior of these materials has been acknowledged in the field of surface coating technology [25].

Our study results seem to imply a promising future for the use of surface coating technology to improve the frictional characteristics of ceramic brackets.

Conclusion

There was no significant difference in the amounts of force loss during the sliding movement between PCA ceramic brackets with a YSZ coating on the surface of the slots and SS metal brackets, indicating that the two types have similar frictional properties. MCA ceramic brackets, on the other hand, revealed significantly higher amounts of force loss than both PCA and SS brackets. Frictional resistance caused more than 60 % of the applied force to be lost.

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Compliance with ethical guidelines The accompanying manuscript does not include studies on humans or animals.

Conflict of interest M. AlSubaie, N. Talic, S. Khawatmi, A. Alobeid, C. Bourauel, and T. El-Bialy state that there are no conflicts of interest.

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