Original Article

Frictional Forces Between Lingual Brackets and Archwires Measured by a Friction Tester

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Abstract: Frictional resistance tends to rapidly increase as the angle between a bracket and an archwire increases beyond a critical angle. The purpose of this study was to determine a new measuring method with a pin on disk friction tester for the measurement of the frictional force between lingual brackets and archwires. A lingual bracket is different from a labial bracket in dimensions and in some clinical aspects. The influence of artificial saliva was also surveyed. Two brands of lingual brackets and one brand of labial standard bracket with an 0.018-inch slot size were used. Archwires of three alloys (stainless steel [SS], Ormco; β-Titanium [TM], Ormco; cobalt-chrome, [EL], RMO) with 0.016 × 0.022- and 0.017 × 0.025-inch dimensions were used. Measurements were conducted with an angular velocity of 0.6°/s for 90 seconds and a normal force of 100 *g* at 25°C in a dry and 34°C in an artificial saliva environment. For SS and EL archwires, the frictional force with the FJT bracket was greater than that with ORM bracket ($P < .01$). Compared with SS and TM archwires, 0.016 × 0.022-inch EL archwire showed a higher frictional force with two lingual brackets ($P < .01$). Significant differences in frictional force existed between dry and artificial saliva environments ($P < .05$), and the effects varied by the bracket-archwire couples. The estimated critical contact angles were greater than the theoretical values. This new method can be a useful protocol for measurement of frictional force because it can measure the frictional force under the conditions of continuous angular change between bracket and archwire. (*Angle Orthod* 2004;74:816–824.)

Key Words: Friction, Pin on disk type friction tester, Lingual bracket, Critical contact angle

INTRODUCTION

Frictional resistance is one of the critical factors that determine the efficiency of orthodontic tooth movement, especially when sliding mechanics are adopted. In sliding mechanics, an archwire that is slightly smaller than the slot width is inserted into the bracket slot. All the applied retraction force will contribute to the tooth movement if no friction exists.[1] However, this situation does not occur in clinical applications because some force by the ligation will hinder the movement of the archwire. As the angle between the bracket and archwire (second order angulation) increases, frictional forces (more specifically, binding) tend to increase rapidly, and more rapidly beyond a certain angle (ie, the critical contact angle).[1]

Ideally, tipping will only occur until contact is established between the diagonal corners of the bracket slot and the archwire. The amount of tipping and rotation depend on the difference between the sizes of the archwire and slot and will occur immediately after force application. If the archwire does not bend (elastically deform), the angulation cannot increase beyond the critical contact angle (established angulation). Anytime a resistance to sliding occurs, some portion of the retraction force is lost.

A tooth under retraction force can easily rotate rather than move bodily because of the moment developed by the differences in the point of force application and the center of resistance. The rotation (tipping) of the tooth appears as the angle between the bracket and archwire increases. The critical contact angle (θ_c) is the angle between the archwire and bracket slot when they contact each other for the first time. Kusy and Whitley[2] measured the critical contact angles from the set of data at certain fixed angulations and calculated them theoretically by the following formula.

$$\theta_c = 57.32\ [1 - (W/S)]/\ (B/S)$$

where W is the archwire dimension that contacts the floor

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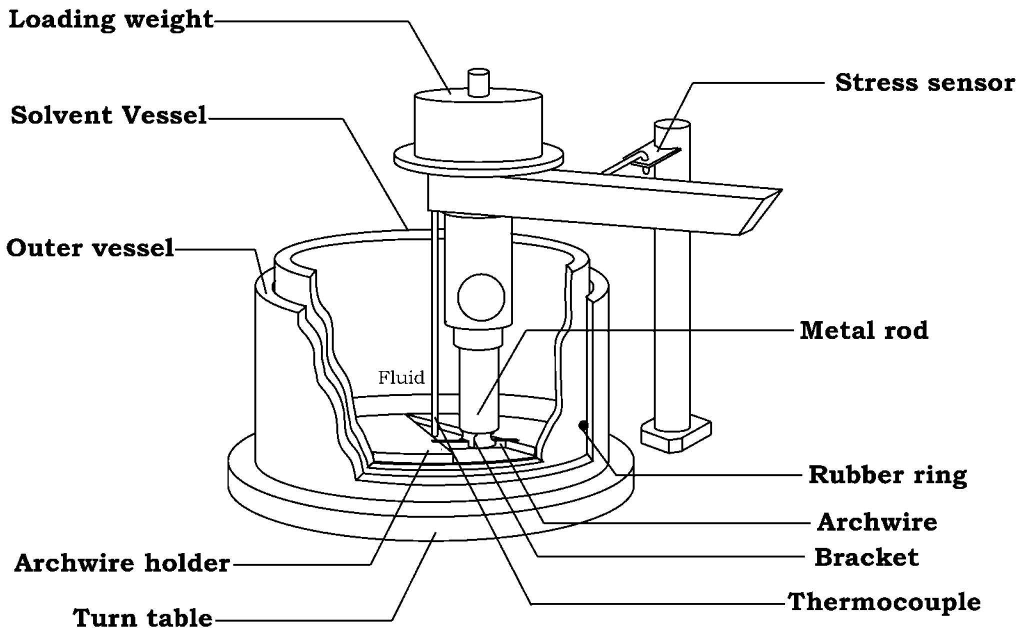

FIGURE 1. The pin on disk type friction tester used in this study.

of the slot; S, width of bracket slot; and B, mesiodistal dimension of the bracket.

Orthodontic tooth movement is not continuous and linear but discontinuous and dynamic.[3] Several factors affecting the frictional resistance in orthodontic treatment should be considered. Kusy[4] suggested that factors affecting the frictional forces between bracket and archwire were material, surface roughness, hardness, wire stiffness, geometry, fluid media, and surface chemistry. Similarly, Vaughan et al[5] listed several variables (archwire, ligation of archwire to bracket, bracket, orthodontic appliance, and intraoral variables) that can contribute to the frictional force level.

Various reports have described methods that measure the frictional forces between the archwire and bracket and archwires and classified them into three large groups that will be discussed later. The three established methods can hardly measure the gradual changes of the frictional force levels in clinically relevant angulation-changing condition.

The pin on disk type friction tester (Figure 1) is a device that has been used to measure the frictional force and the degree of wear between two materials.[6,7] This device can measure movements such as a circular or reciprocal at any given angle with various angular speeds. The motion pattern of the friction tester is suitable for simulating orthodontic tooth movement of gradual angular changes (Figure 2).

So far, few attempts have been made to study the frictional resistance of lingual bracket. Lingual brackets are similar to labial brackets but have some differences in dimensions and clinical aspects. Almost all lingual brackets are single brackets and have narrower M-D width than labial brackets because of the anatomical limitation and intention to obtain adequate interbracket distance. Therefore, they are susceptible to tipping under traction force.

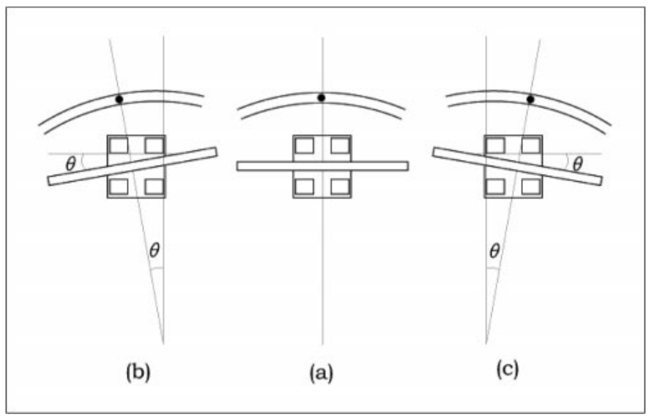

FIGURE 2. The motion of gradual change of angle between a bracket and an archwire by the pin on type friction tester.

The purposes of this study were to determine the possibility of a new measuring method with a pin on disk type friction tester for the measurement of the frictional forces between lingual brackets and archwires under varied conditions, and to measure the difference in frictional force depending on the type of brackets and material and size of archwires under the conditions where the angulation between the bracket and archwire changed continuously.

MATERIALS AND METHODS

Two lingual brackets (FJT: Fujita Corp., Tokyo, Japan; ORM: Ormco Corp., Orange, Calif, USA) with a 0.018-inch slot size were used. One labial standard bracket (CTL:

TABLE 1. Orthodontic Archwires Used in This Study

Code	Alloy	Size (inch)	Batch Number	Manufacturer
SS1	Stainless steel	0.016 × 0.022	254-1622	Ormco, Orange, Calif, USA
SS2		0.017 × 0.025	254-1755	Ormco, Orange, Calif, USA
TM1	β-Titanium	0.016 × 0.022	266-0010	Ormco, Orange, Calif, USA
TM2		0.017 × 0.025	266-0011	Ormco, Orange, Calif, USA
EL1	Cobalt-chromium	0.016 × 0.022	E00302	RMO, Denver, Colo, USA
EL2		0.017 × 0.025	E00308	RMO, Denver, Colo, USA

TABLE 2. Brackets Used in This Study

Code	Slot Width (inch)	Bracket Width (inch (mm))	Batch Number	Manufacturer
FJT	0.018	0.075 (1.9)	F19-18LB0	Fujita, Tokyo, Japan
ORM	0.018	0.106 (2.7)	367-5044	Ormco, Orange, Calif, USA
CTL	0.018	0.126 (3.2)	140-43	Tomy, Tokyo, Japan

TABLE 3. Artificial Saliva Used in This Study

Composition	Concentration
KCl	0.4 g/L
NaCl	0.4 g/L
NaH_2PO_4	0.6 g/L
Na_2S	0.0016 g/L
Urea	1.0 g/L
Mucin	3900 mg/L

Tomy Corp., Tokyo, Japan) with the same slot size was used as a control. The mesiodistal widths of the FJT and ORM brackets were 1.9 and 2.7 mm, respectively. The CTL bracket had a 3.2-mm mesiodistal width. Archwires of three different alloys with 0.016- × 0.022-inch and 0.017- × 0.025-inch dimensions were used (Tables 1 and 2).

Bracket and archwire setup

The brackets were bonded to a metal rod nine mm in diameter and 25 mm in length with a light-curing resin (Transbond XT, 3M Espe, St. Paul, Minn, USA), using a light-curing unit (Ortholux XT, 3M) by irradiation for 40 seconds. Before bonding, the surface of the rod was sandblasted with 90-μm alumina particles. To bond the brackets in the same position on the rods, a custom-made template was used. This template consisted of a resin base, which held the metal rod in the same dimension, and an 0.018- × 0.025-inch wire segment (full size for 0.018-inch slot) to set the zero-torque slot in the same position to the metal rod for all the brackets.

Each archwire was cut into 35-mm lengths. A wire holder was fabricated with an acrylic resin plate, matching the shape of the specimen container of the friction tester. A groove for the archwire was made in the wire holder, and the line for the alignment of archwire was marked. After fixing the wire holder in the specimen container with screws, the wire specimen was inserted in the groove of the wire holder. After rotating, the axis of the specimen container was adjusted to a suitable position for measurement. The bracket-bonded metal rod was inserted and fixed in the pin holder of the friction tester and aligned into a passive relationship with the archwire specimen.

Measurement of frictional force

A pin on disk type friction tester (FPR 2000, Rhesca, Tokyo, Japan) was used to measure the frictional force (Figure 1). Each bracket-archwire couple was tested in the dry and artificial saliva environments. Each measurement was conducted with an angular velocity of 0.6°/s (0.1 rpm) for 90 seconds under a normal force of 100 *g* at 25°C for the dry and 34°C for the artificial saliva environment. In the artificial saliva environment, the specimen container was filled with the modified Fusayama artificial saliva (Table 3) mixed with mucin (3900 mg/L). The motion between the bracket slot and the archwire was a reciprocal action with continuous changes in the second order angulations (from 0° to 5°), which was similar to that of an archwire in sliding mechanics. Three sets of bracket-archwire combinations for each case were measured, and the measurements were repeated five times for each bracket-archwire couple.

Changes of the frictional force level over the angular changes during 90 seconds were plotted. The time variable was converted to an angle. Student's *t*-test ($P = .05$) was used to determine the difference in dry and wet conditions. Scheffe's multiple range test ($P = .01$) was used to compare the friction forces by the archwire-bracket combinations at the angle of 4°. Three-way analysis of variance (ANOVA) by the factors of archwire, bracket, and dry or wet condition on the frictional forces was performed ($P = .01$).

RESULTS

Changes of the frictional force level depending on time (which can be converted to angulation between bracket slot and archwire) are plotted in Figure 3. During a reciprocal movement of 5°, the frictional force between bracket and archwire increased gradually and reached a maximum value

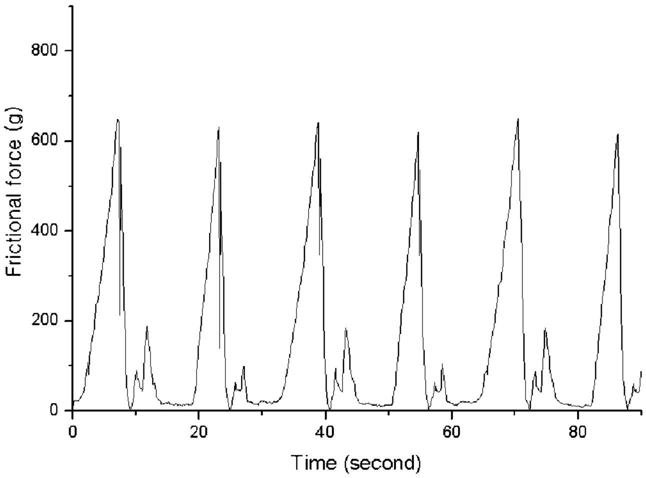

FIGURE 3. Time-frictional force curve for ORM-SS2 couple (ORM indicates Ormco; SS2, stainless steel 2).

at the end of the reciprocal movement. All the bracket-archwire couples showed similar patterns.

The average values and standard deviations from the starting point to the maximum frictional force for each test are plotted in Figures 4 and 5. Time was converted to angulation in these graphs.

Examples of frictional force levels at the angle of 4° for each bracket-archwire couple are shown in Table 4. The frictional force was significantly higher in the FJT bracket than in the ORM bracket ($P < .01$), except for the β-titanium (TM) archwire in a dry environment and an (cobalt-chrome) EL1 archwire in an artificial saliva environment.

Three-way ANOVA by the factors of archwire, bracket, and dry or wet condition on the frictional force at the angle of 4° was performed. As a result, three variables were shown to influence the frictional force significantly ($P < .05$).

The types of archwire significantly influenced the frictional force ($P < .01$). EL archwires showed the highest values except for the ORM bracket–TM2 archwire couple and the CTL bracket–SS2 archwire couple in a dry environment and the FJT bracket–TM2 archwire couple and ORM bracket–SS2 archwire couple in an artificial saliva environment.

In a dry environment, the frictional force levels were significantly different from those in artificial saliva ($P < .05$) except for the CTL bracket–TM1 archwire couple and the ORM bracket–EL2 archwire couple.

The frictional forces for 0.017- × 0.025-inch archwires were significantly higher than those for 0.016- × 0.022-inch archwires in a dry environment ($P < .05$). Similar results were obtained in artificial saliva except for the ORM bracket–EL archwire and the CTL bracket–EL archwire couples.

All measured values for the critical contact angle of each bracket-archwire couple were higher than the theoretical ones (Table 5). The theoretical value of the critical contact angle with a 0.016- × 0.022-inch archwire was 1.5° for FJT bracket, 1.1° for ORM bracket, and 0.9° for CTL bracket. With a 0.017- × 0.025-inch archwire, the value was 0.8° for FJT bracket, 0.6° for ORM bracket, and 0.5° for CTL bracket.

DISCUSSION

There have been many reports on the frictional force between brackets and archwires using various methods. The frictional force levels showed a wide range of distribution from about 0 to 1000 *g* depending on the measuring methods.[8–13]

Methods that measure the frictional forces between archwire and bracket can be classified into three large groups. The first method uses a universal testing machine.[2,4,8,10,14,15] The apparatus on which brackets were bonded was designed to fix the contact angle between archwire and bracket.[4,10,16] The critical contact angle (θ_c) is the angle between the archwire and bracket slot when they first contact each other. The frictional force between the archwire and bracket tends to increase rapidly above this angle.[1] With this method, the angulation between the bracket and archwire can be adjusted. But a single angulation is allowed for each test, and therefore, the gradual change of angulation during tooth movement cannot be simulated in the previous methods. However, the pin on disk type friction tester used in the present study can make a motion with a gradual angular change in one sequence of tests.

In the second method, Willems et al[3] introduced a method to measure the frictional forces using a fretting machine with a relatively rapid oscillating motion (1 Hz) compared with a universal testing machine. This machine consists of a high precision x-y-z positioning system device and a control unit. A short length oscillating action was applied between the archwire and bracket instead of a continuous drawing action. They stated that an oscillating, sliding setup was used instead of a linear, unidirectional one because tooth movement is not a linear and continuous motion but a discontinuous and dynamic one. The range of the frictional forces was 0 to 150 *g* in their study. However, Braun et al[16] reported that the velocity of orthodontic tooth movement is as slow as 0.23×10^{-4} mm/min, and therefore, it is reasonable to measure the frictional forces at near static condition rather than in a dynamic condition. However, in a laboratory test, it is hard to obtain this slow speed. Various velocity setups were applied in previous laboratory studies eg, 0.5 mm/min,[8,17] 0.625 mm/min,[18] 2 mm/min,[19,20] 5 mm/min,[21] 5.1 mm/min,[5] 10 mm/min,[2,10,11,13] and 12.7 mm/min.[22] In the present study, the linear velocity calculated from the angular velocity was 18.8 mm/min, and this velocity was somewhat higher than in the other studies although this was the slowest value with the device used.

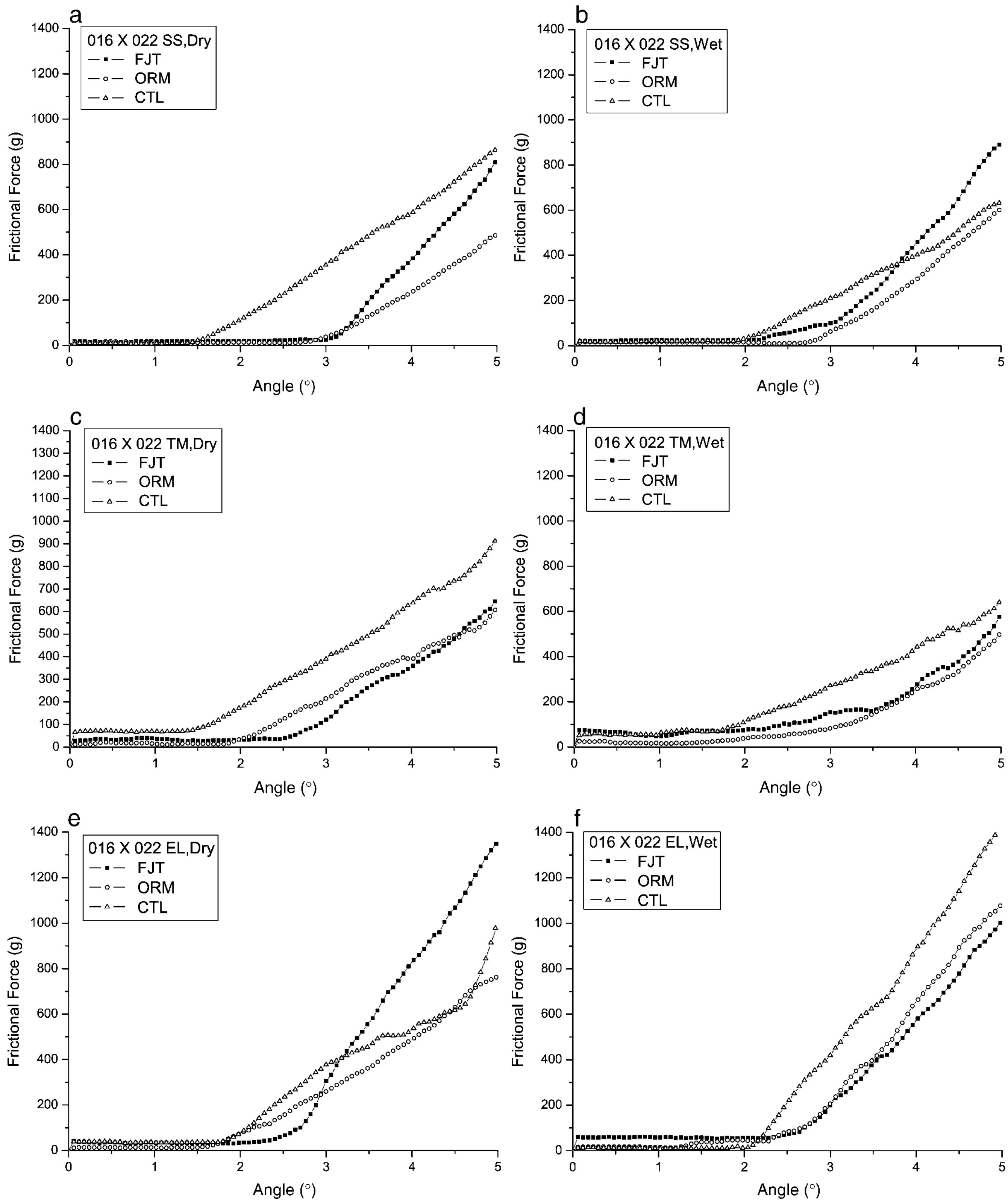

FIGURE 4. (a) Angulation-frictional force curve for SS1 archwire in dry state. (b) Angulation-frictional force curve for SS1 archwire in wet state. (c) Angulation-frictional force curve for TM1 archwire in dry state. (d) Angulation-frictional force curve for TM1 archwire in wet state. (e) Angulation-frictional force curve for EL1 archwire in dry state. (f) Angulation-frictional force curve for EL1 archwire in wet state. SS indicates stainless steel; TM, β titanium; and EL, cobalt-chrome.

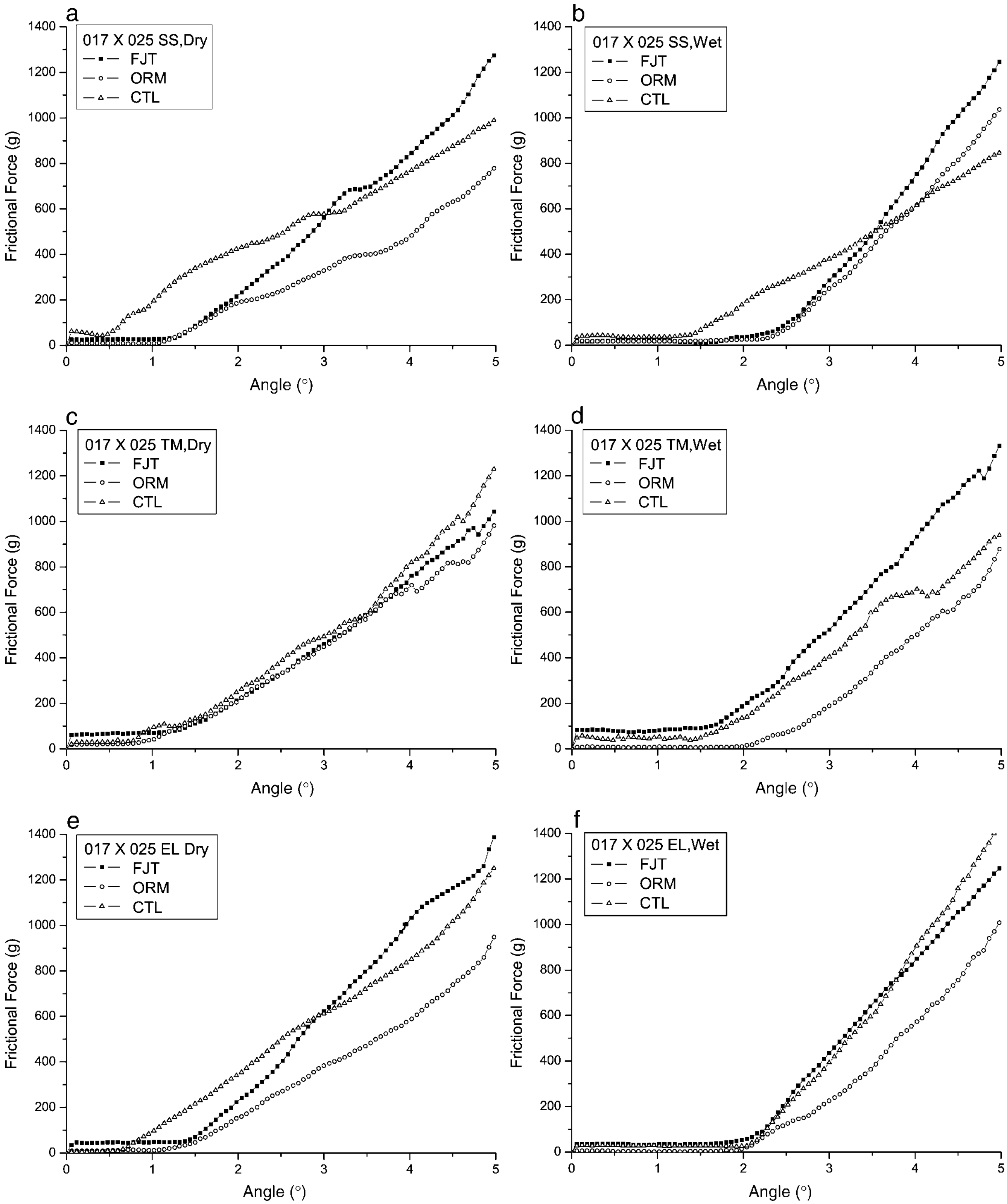

FIGURE 5. (a) Angulation-frictional force curve for SS2 archwire in dry state. (a) Angulation-frictional force curve for SS2 archwire in wet state. (c) Angulation-frictional force curve for TM2 archwire in dry state. (d) Angulation-frictional force curve for TM2 archwire in wet state. (e) Angulation-frictional force curve for EL2 archwire in dry state. (f) Angulation-frictional force curve for EL2 archwire in wet state. SS indicates stainless steel; TM, β titanium; and EL, cobalt-chrome.

TABLE 4. Frictional Forces at the Angle of 4° (gram-force)[a]

Condition	Wire	Size (inch)	FJT	ORM	CTL
Dry (25°C)	SS1	0.016 × 0.022	374.2 (27.6)	233.2 (23.3)	582.5 (28.7)
	SS2	0.017 × 0.025	831.5 (80.1)	474.7 (35.3)	763.3 (18.8)
	TM1	0.016 × 0.022	353.3 (18.4)	392.8 (38.6)	478.1 (39.0)
	TM2	0.017 × 0.025	732.1 (59.7)	708.6 (82.5)	809.0 (60.8)
	EL1	0.016 × 0.022	823.4 (40.8)	487.1 (25.5)	528.4 (66.7)
	EL2	0.017 × 0.025	1019.7 (36.6)	582.2 (24.5)	843.9 (38.3)
Artificial saliva (34°C)	SS1	0.016 × 0.022	446.3 (43.8)	289.8 (29.1)	397.6 (34.0)
	SS2	0.017 × 0.025	736.6 (34.4)	605.4 (37.5)	607.5 (48.8)
	TM1	0.016 × 0.022	266.9 (41.5)	249.0 (43.1)	433.8 (40.2)
	TM2	0.017 × 0.025	918.0 (39.0)	496.2 (29.3)	693.5 (39.6)
	EL1	0.016 × 0.022	566.8 (67.3)	649.6 (41.6)	877.9 (32.9)
	EL2	0.017 × 0.025	836.4 (83.0)	562.7 (36.7)	888.8 (57.3)

[a] Results are given as mean with standard deviations in parentheses. FJT indicates Fujita; ORM, Ormco; CTL, Tomy; SS, stainless steel; TM, β titanium; and EL, Elgiloy.

TABLE 5. Estimated Value and Theoretical Value of Critical Contact Angle (°)[a]

Bracket-wire Couple	0.016 × 0.022 inch Dry	Wet	Theoretical Value	0.017 × 0.025 inch Dry	Wet	Theoretical Value
FJT-SS	3.0	2.3	1.5	1.4	2.0	0.8
FJT-TM	2.5	2.4	1.5	1.4	1.7	0.8
FJT-EL	2.2	2.5	1.5	1.5	2.0	0.8
ORM-SS	3.0	2.8	1.1	2.2	2.3	0.6
ORM-TM	2.0	2.2	1.1	1.0	2.1	0.6
ORM-EL	1.7	1.4	1.1	1.2	2.0	0.6
CTL-SS	1.6	2.0	0.9	0.6	1.5	0.5
CTL-TM	1.1	1.9	0.9	0.8	1.6	0.5
CTL-EL	1.9	2.1	0.9	0.7	2.1	0.5

[a] FJT indicates Fujita; ORM, Ormco; CTL, Tomy; SS, stainless steel; TM, β titanium; and EL, Elgiloy.

Correlations between the drawing velocity and the frictional force should be further investigated.

The third method used a dentoalveolar model. Drescher et al[19] and Loftus et al[17] presented another measuring method for the frictional force, where the measuring technique was similar to that with a universal testing machine. However, they used a flexible dentoalveolar model to simulate the physiological response of the periodontal ligament to an external force. Because the frictional force might be measured at near the critical contact angle in this method, it seems impossible to measure the frictional forces at any intentional angle. The method for measuring the frictional force was similar to that of the first method.

A tooth under a retraction or protraction force, rather than moving bodily, can easily rotate (tip) because of the moment developed by the distance in the point of force application from the center of resistance. This phenomenon changes the bracket-archwire angulations continuously and makes elastic or permanent deformation of the archwire. Therefore, the above-mentioned three methods cannot measure changes in the frictional force levels under clinically relevant angulation-changing conditions.

A new method is necessary to measure orthodontic frictional forces in the simulated clinical conditions of gradual changes in angulation between archwire and bracket and interbracket distance. The pin on disk type friction tester (Figure 1), which is used mainly to measure the frictional force between two materials, may be used to measure the frictional force under angulation-changing condition. This machine has been used to measure the friction or abrasion between two solid materials.[6] Because its pattern of motion is a reciprocal rotation at any given angle, it can create a motion within a certain angular range (Figure 2). Therefore, changes in frictional force under gradual angular change can be measured sequentially. In the previously mentioned methods, only one angulation was possible for each measurement. In addition, a lubricating solution vessel can be easily installed and removed. On the basis of the results of the present study, this device could be used successfully for the measurement of frictional forces.

It is important to note the relationship between the archwire length used in the present study and the clinical condition. Because of the characteristics of the motion of the friction tester (reciprocal action), compared with clinical situation a longer archwire was needed in this study. We used archwires of 35 mm in length. However, in clinical situations, the interbracket span or extraction space to be closed is much less than 35 mm. Because the frictional force can be affected by the stiffness of archwire and the stiffness can be affected by interbracket span, the frictional force measured in the present study might be different from that of the clinical situation. Because the interbracket length was longer than the clinical situation, the measured frictional force was relatively smaller than that of the clinical situation. These facts should be considered when interpreting the results of the present study.

In a clinical situation, the archwire in the bracket slot almost always contacts the edge of the slot and is subjected to bending forces with binding to some extent, especially when sliding mechanics are applied. Therefore, a slightly higher value than the exact critical contact angle would be useful to determine the fictional forces in the clinical applications. Consequently, the frictional force at an angle of 4° was analyzed in the present study.

The frictional force levels of β-titanium and nickel-titanium archwires were greater than those of stainless steel and cobalt-chrome archwires from the measurement of fixed angulation and fixed interbracket distance.[2,5,17,23] But if the angulation and interbracket distance changed gradually, the cobalt-chrome archwire can show a higher frictional force because of higher stiffness.[2,11] Kusy and Whitley[4] suggested that stainless steel archwire showed the lowest frictional forces and β-titanium archwire showed the highest values in dry conditions. It was also reported that, in artificial saliva condition, the frictional force of stainless steel archwire increased significantly and that of β-titanium archwire decreased. In the present study, a significant difference was observed between the dry and the artificial saliva conditions ($P < .05$). TM archwire showed higher frictional force in the dry condition than in the artificial saliva condition as Kusy stated. The frictional forces were proportional to the size of archwires similar to the results from the previous studies.[24]

Because the frictional forces tend to increase rapidly above the critical contact angle and can easily be affected by the size and materials of archwire and bracket and test environment, the critical contact angle is important in orthodontic treatment, especially when the sliding mechanics are applied because the binding between the brackets and archwire increases rapidly. Kusy and Whitley,[2] Rucker and Kusy,[25] and Thorstensen and Kusy[24] stated that the measured values of the critical contact angle were always greater than the theoretical values, and the difference between two values was from 0.1° to 2.3°, depending on the width of the slot and the size and material of the archwire. In the present study, the range of difference was 0.1° to 1.9°.

A couple of differences exist between lingual and labial orthodontic treatments. In lingual orthodontic treatment, the M-D bracket width is relatively smaller. This allows the teeth to rotate or tip more easily than in labial orthodontic treatment because of the anatomical limitation that reduces the interbracket span. Therefore, the interbracket span in lingual orthodontic treatment is shorter than with labial brackets, which makes the same archwire stiffer. Consequently, the tooth control is difficult in lingual orthodontic treatment, especially when sliding mechanics are applied. Thus the frictional forces of lingual brackets were measured in the present study.

CONCLUSIONS

The friction tester was useful to simulate the bracket-archwire relationship and measure the frictional force between the brackets and archwires. The motion pattern of the friction tester is similar to that of the teeth when tipping occurs. It is possible to obtain more reliable and precise data after refinement of the operating method of this machine such as an adjustment of the bracket and archwire and selection of the velocity.

For SS and EL archwires, the frictional force was higher with the FJT bracket than with the ORM bracket ($P < .01$), but general trends could not be drawn for the TM archwire. Compared with the SS and TM archwires, 0.016- × 0.022-inch EL archwire showed the greatest frictional force with two lingual brackets, and 0.017- × 0.025-inch EL archwire showed similar trends ($P < .01$). There were significant differences in frictional force between the dry and artificial saliva environment ($P < .05$), but the effects of artificial saliva were different depending on the bracket-archwire couples. Frictional force with a 0.017- × 0.025-inch archwires was higher than that with 0.016- × 0.022-inch archwires. Experimental critical contact angles were greater than theoretical values.

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