Frictional Resistances of Metal-lined Ceramic Brackets Versus Conventional Stainless Steel Brackets and Development of 3-D Friction Maps

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Abstract: The frictional resistances of 2 metal-lined ceramic brackets (Luxi[®] and Clarity[®]) were compared with 2 conventional stainless steel brackets (Mini-Taurus® and Mini-Twin®) in vitro. In method 1, we varied the second-order angulation from 0° to 12° while maintaining the normal or ligature force constant at 0.3 kg; in method 2, we varied the ligature force from 0.1 kg to 0.9 kg while maintaining the angulation at $\theta = 0^{\circ}$ or $\theta = 11^{\circ}$. The hardware simulated a 3-bracket system in which the interbracket distances were always 18 mm. All couples were evaluated at 34°C using the same size stainless steel archwire (19 \times 26 mil) and ligature wire (10 mil). In the passive region, the static and kinetic frictional forces and coefficients of friction were key parameters; in the active region, the static and kinetic binding forces and coefficients of binding were critical parameters. From outcomes of methods 1 and 2, the 4 aforementioned parameters, and a knowledge of the critical contact angle for binding, 3-dimensional friction maps were constructed in the dry and wet states from which the frictional resistances could be determined at any ligature force or second-order angulation. Those 3-dimensional maps show that metallined ceramic brackets can function comparably to conventional stainless steel brackets and that 18-kt gold inserts appear superior to stainless steel inserts. As the morphologies of metal inserts are improved, these metal-lined ceramic brackets will provide not only good esthetics among ceramic brackets but also minimal friction among conventionally ligated brackets. (Angle Orthod 2001;71:364–374.)

Key Words: Brackets; Ceramic; Friction; Sliding mechanics; Stainless steel

INTRODUCTION

Angle used a gold prototype of edgewise brackets over 75 years ago.¹ In 1933, Dr Archie Brusse presented a table clinic on the first stainless steel appliance system.² Since that time, stainless steel brackets have displaced gold. Because they were stiffer and stronger,³ stainless steel could be made smaller—in effect, increasing their esthetics via their reduced dimensions. Their frictional characteristics were so satisfactory that they are today's standard of the profession.^{4–6}

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Neither patient nor practitioner was satisfied, however, and both desired to have esthetic appliances. In about 1970, plastic brackets first appeared that were injection molded from an aromatic polymer called polycarbonate. Very soon thereafter, stains and odors were noticed. Moreover, the inherent stiffness and strength were such that these brackets plastically deformed under load and subsequently creped with time.⁷ Alternative esthetic materials have been sought, but even composites made of chopped glass fibers could only modestly enhance stiffness without alleviating the other problems associated with crazing and deformation.

About 10 years passed before ceramics were developed for orthodontic applications. These first brackets were literally sculpted from single-crystal boules of sapphire using diamond tooling.^{8,9} In close succession, sintered polycrystalline sapphire (ie, alumina) brackets were manufactured and sintered using special binders to thermally fuse the particles together.^{10,11} A zirconia material¹² was flirted with too, but only 1 product did not have inherent problems with color, and that one was not a true twin bracket. In torquing tests, ceramics were prone to early fracture.¹³ Regardless of form, the friction was the worst for any combination (ie, couple) of ceramic, whether bearing against stainless steel,

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| Product | Туре | Lot Number | Slot Size | Preangulation | n Pretorque | Wire Dimensions |
|--------------------------|-----------------------------------|------------|-----------|---------------|-------------|-----------------------|
| Brackets | | | | | | |
| Clarity ^a | Stainless steel insert in alumina | None | 0.022" | 0 | -7 | |
| Luxi ^b | 18-kt-gold insert in alumina | 5920 | 0.022" | 0 | 0 | |
| Mini-Taurus ^₅ | Stainless steel | 519612 | 0.022" | 0 | -7 | |
| Mini-Twin ^c | Stainless steel | 9G43G | 0.022" | 0 | -7 | |
| Archwires | | | | | | |
| Tru-Chrome ^₅ | Stainless steel | 822523 | | | | 0.019'' 	imes 0.026'' |
| Ligatures | | | | | | |
| Item 47-010-05d | Stainless steel | G8520 | | | | 0.010″ |

TABLE 1. Materials Evaluated

^a 3M/Unitek, Glendora, Calif.

^b RMO Corporation, Denver, Colo.

° SDS Ormco, Monrovia, Calif.

^d GAC International, Islandia, NY.

cobalt-chromium, nickel-titanium, or beta titanium archwires.^{6,14–16}

Within the last 5 years, 2 manufacturers have recognized that ceramics have desirable esthetics but that other materials have superior frictional characteristics. Consequently, a stainless steel and a gold liner have now been placed in an otherwise polycrystalline alumina bracket. But how do these brackets compare with the stainless steel standard? And how do they compare between themselves? This manuscript measures the frictional characteristics of 2 types of metal-lined brackets and 2 types of stainless steel brackets. What will be shown is that these metal-inserted products capitalize on the best of both worlds, namely, pleasing esthetics and competitive frictional characteristics. These outcomes are true whether saliva is present or whenever it is squeezed out at the archwire-bracket interface.

MATERIALS AND METHODS

Four brackets evaluated

Two types of metal-insert ceramic brackets were evaluated: a stainless steel-lined polycrystalline alumina bracket (Clarity®, 3M/Unitek, Monrovia, Calif) and an 18-kt goldlined polycrystalline alumina bracket (Luxi®, RMO Corp, Denver, Colo). A stainless steel Mini-Taurus[®] (RMO Corp) and an Ormco Mini-Twin bracket (SDS/Ormco, Glendora, Calif) served as controls. All brackets had 22 mil (ie, 0.022") slots. Representative gross morphologies of the 4 bracket products were obtained by first sputter-coating a 150Å layer of gold-palladium and then viewing using a JEOL 6300 Scanning Electron Microscope at an accelerating voltage of 15 kV. Preangulation, pretorque, and lot numbers are also provided in Table 1. Opposing each bracket was a $0.019'' \times 0.026''$ stainless steel archwire (RMO Corp). Dead soft 0.010" stainless steel ligature wires (item 47-010-05, GAC International, Commack, NY) provided the normal forces.

Experimental method 1

Resistances to sliding (*RS*) were determined by 2 experiments. In the first experiment, the wire was drawn relative to the bracket at a fixed normal or ligature force (*N*) of 0.3 kg (300 cN) as the angulation was varied from -12° to $+12^{\circ}$. This is the same apparatus as that reported earlier^{17,18} except that poly(tetrafluoroethylene) bearings are now used instead of steel bearings to simulate the 2 contiguous brackets. These were set to the maximum distance of 18 mm to simulate an extraction site in which the archwire stiffness and resilience have little interaction with the bracket being investigated.

Having obtained the drawing force (P) as a function of the distance traversed (δ) (Figure 1, lower left) for each test angle, each static drawing force was obtained from the initial force maximum at which motion is imminent, and each kinetic drawing force was obtained from the average of the 150 data points during which motion occurred. After dividing this average value of P by 2 to obtain its RS (circled in Figure 1, upper), other kinetic RS data were obtained and plotted against angulation. A second-order polynomial¹⁸ was applied to the collective 32 points (Figure 1, upper) that were based on 32 δ -P plots (Figure 1, lower left). Using numerical analyses, the true position of zero angulation (ie, when $\theta = 0^{\circ}$) was established without expending unnecessary effort to try to initially align the bracket on its mounting post. After adjusting all θ 's according to this true $\theta = 0^{\circ}$, the data for the negative angles were virtually folded at true zero onto the positive angle data (Figure 1, bottom right). By running each bracket through both the positive and negative angles, both sets of diagonals were evaluated, in effect replicating each run without removing the archwire-bracket couple.

Using 2 linear regression analyses, the passive and active regions were defined by *RS* as a function of θ along with the boundary conditions at which elastic binding first occurs, ie, at the so-called critical contact angle (θ_c) (Figure 1, bottom right). For this experiment, 2 operators each test-



FIGURE 1. Data reduction procedures of frictional measurements. For each angulation (θ) at a constant normal force (*N*), a drawing force (*P*) against distance (δ) plot is acquired from which the static and kinetic resistances to sliding (*RS*) data are calculated (*RS* = *P*/2) (lower left). From this kinetic drawing force plot, 1 data point results (circled point, upper). After dozens of determinations are made, the derivative of a second-degree polynomial regression of the kinetic *RS* data plotted against θ determines the true $\theta = 0^{\circ}$ (upper). Having adjusted all test θ 's by any offset of $\theta = 0^{\circ}$, the data at negative θ 's are graphically folded onto the data at the positive θ 's (lower right). Regressions of the data below and above the theoretical θ_c indicate the passive and active regions, respectively.

ed an as-received couple of each archwire-bracket combination. From those combined outcomes, the magnitudes of *RS* could be determined at N = 0.3 kg, from which the coefficients of friction (μ_{FR}) and the coefficients of binding (μ_{BI}) could be calculated from the *RS* against θ plots in the passive and the active regions, respectively, ie, when $\theta \leq \theta_c$ and $\theta \geq \theta_c$.

Experimental method 2

In the second experiment, the wire was drawn relative to the bracket at a fixed $\theta = 0^{\circ}$ or $\theta = 11^{\circ}$ as *N* was varied from 0.1 kg to 0.9 kg in 0.2 kg increments. The first angle represented the passive region ($\theta \le \theta_c$; Figure 1, lower right), where only classical friction (*FR*) occurred, whereas the second angle represented the active region ($\theta \ge \theta_c$; Figure 1, lower right) in which elastic binding (*BI*) dominates. From these plots of *RS* as a function of *N*, μ_{FR} could be calculated from the regression slopes at both $\theta = 0^{\circ}$ and $\theta = 11^{\circ}$ along with *BI* at $\theta = 11^{\circ}$, which for each value of θ is different but invariant with *N*.

Testing of sliding resistance

After all couples were wiped down with 95% ethanol, each frictional test was conducted at 34°C either under prevailing atmospheric humidity or in the wet state using fresh whole human saliva at a flow rate of 3 cm³/min. The details of gathering and evaluating the saliva have been presented previously.^{19,20} In both experiments, static (μ_{FR-S}) and kinetic (μ_{FR-K}) coefficients of friction were calculated from the appropriate drawing force data (Figure 1, lower left).^{6,21} Clearly, the kinetic value should be more reliable in terms of its substantial database.

Data analyses

All aforementioned regression analyses were performed using Excel 97 (Microsoft, Redmond, Wash). From the correlation coefficient and the number of data points, a level of confidence was expressed as a probability, $P < .001.^{22}$ Unless otherwise stated, this *P*-value represents the level of confidence of all plots of *RS* as a function of θ or *N*. An analysis of variance (ANOVA) was performed to determine the significant differences between the brackets and the dry and wet states (SYSTAT Version 5, SYSTAT, Inc, Evanston, IL). The static and kinetic data were combined prior to performing these ANOVA's.

RESULTS

General morphology

Clarity and Luxi brackets illustrate the geometry of an insert slot relative to the monolithic structure of Mini-Taurus and Mini-Twin brackets (Figure 2). In the case of Clarity (upper left), the stainless steel insert neither extends to the top of the tie-wings nor maintains a constant slot width at the upper extent of the insert. This could present problems when torquing teeth. In the case of Luxi (lower left), the 18-kt gold insert is quite thick and substantially extends to the full height of the slot; although at the top of the slot, a gap appears between the alumina material and the insert slot. This could host bacteria. Both Mini-Taurus and Mini-Twin brackets (upper and lower right, respectively) appear to have parallel slot walls with rather square corners at the roots of their slots.

RS against θ experiment

The first experiment illustrates the resistance to sliding (*RS*) as a function of angulation (θ) for Clarity, Luxi, and Mini-Taurus in the dry state (Figure 3) and the wet state (Figure 4) in which static (left-hand columns) and kinetic (right-hand columns) conditions prevail. Since a common bracket slot size, archwire alloy, archwire size, and ligature force (N = 0.3 kg) were utilized, the brackets that had metal inserts could be directly compared with one another and with the frictional standard of the profession—stainless steel on stainless steel. In the dry state (Figure 3), the regression lines of the static and kinetic plots that were associated with each bracket superposed. The same was generally true for the data in the wet state (Figure 4), too,



FIGURE 2. Morphology of the 4 brackets used to measure the frictional characteristics: a stainless steel-lined alumina bracket (Clarity®; 3M/ Unitek), an 18-kt gold-lined alumina bracket (Luxi®; RMO), a stainless steel bracket (Mini-Taurus®; RMO), and a second stainless steel bracket (Mini-Twin®; SDS Ormco).

although the regression lines of the kinetic plots were just slightly lower than those of the static plots, particularly for the Mini-Taurus bracket.

In the passive region ($\theta \leq \theta_c$ and $\mu_{FR} = RS/N$) and in the dry state, the *RS* values for Clarity and Luxi were comparable, averaging about 0.045 kg (Table 2). Given that $\mu_{FR} = RS/N$, where *N* was fixed at 0.3 kg, the mean coefficient of friction averaged about 0.15 (Table 3). This value is comparable with that of the present conventional stainless steel couple and with previous observations reported in the literature.^{6,15,16,21} The experimental values of θ_c range from 2.1 to 2.5° for Clarity, from 2.6 to 2.9° for Luxi, and from 3.0 to 3.2° for Mini-Taurus. Since the wire portion of the couple is invariant, a larger value of θ_c means that the quotient of the bracket's width to its slot (ie, *WIDTH/SLOT*) is greater in magnitude.²³ This could mean that the bracket is wider or that the actual slot dimension is smaller or that both are true.

In the active region ($\theta \ge \theta_c$ and $\mu_{BI} = RS/\theta$), Clarity and Luxi are comparable, the former having a lower coefficient

of binding (μ_{BI}) in the dry state and the latter being some 11% less (and hence better) in the wet state (Table 4). Both metal-insert brackets are comparable to the Mini-Taurus bracket in the wet state, whereas their μ_{BI} values are from 31% to 38% less (better) than the conventional bracket in the dry state. An ANOVA indicated that differences between these 3 brackets were statistically significant (P < .001). Likewise, the interaction between the bracket and the dry and wet states was also significant (P < .001), although the influence of the state alone was not significant.

RS against N experiment

The second experiment shows *RS* as a function of normal or ligature force (*N*) in the dry state (Figure 5) and the wet state (Figure 6) in which the 2 metal-insert brackets (left-hand columns) are compared with 2 stainless steel brackets (right-hand columns). For each product, the linear regression lines of the grouped static and kinetic data show similar slopes in both the passive ($\theta = 0^\circ$) and active ($\theta =$



FIGURE 3. Combined regression lines of the resistance to sliding (*RS*) against second-order angulation (θ) *in the dry state* for a constant normal or ligature force (N = 0.3 kg) and interbracket distance (*IBD* = 18 mm) in which the black triangles represent run 1 and the grey triangles represent run 2 and in which θ_c is the experimentally determined critical contact angle.

11°) regions, separated only by a constant value of *RS* that represents *BI*. The encircled data points, most of which just happen to occur for the Clarity product, were not used in the linear regression lines presented. Tabulation of μ_{FR} and *BI* for the individual runs that were grouped in Figures 5 and 6 are shown in Tables 5 and 6.



FIGURE 4. Combined *RS* against θ *in the wet state* for N = 0.3 kg and *IBD* = 18 mm (see Figure 3 for details).

In the case of μ_{FR} , mean values were lowest in the passive region ($\theta = 0^{\circ}$) for the gold-inserted appliance and equaled 0.13 \pm 0.01 and 0.15 \pm 0.02 in the dry and wet states, respectively (Table 5). Among those regression lines that were statistically significant (see footnotes, Table 5), Luxi and Mini-Twin appeared most consistent, their overall standard deviations equaling 0.02 and 0.01, respectively, vs 0.04 and 0.03 for Clarity and Mini-Taurus, respectively. An ANOVA indicated that the influence of the bracket was

| TABLE 2. Magnitudes of the Resistanc | e to Sliding (<i>RS</i>) in kg ^a as Measured in the Pa | assive Region ($\theta \leq \theta_{c}$) When $N = 0.3$ kg |
|--------------------------------------|---|--|
|--------------------------------------|---|--|

| | | D | ry | | | W | /et | |
|---------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| | Sta | atic | Kin | netic | Sta | atic | Kin | etic |
| Bracket | Run 1 | Run 2 |
| Clarity | 0.048 | 0.054 | 0.043 | 0.051 | 0.062 | 0.067 | 0.062 | 0.066 |
| Luxi Mini-Taurus | 0.043 0.055 | 0.044 0.055 | 0.041 0.054 | 0.042 0.049 | 0.053 0.056 | 0.057 0.062 | 0.046 0.055 | 0.053 0.061 |

^a One kilogram (kg) \approx 1000 centi-Newtons (cN).

TABLE 3. Coefficients of Friction (μ_{FR}) as Derived From $\mu_{FR} = RS/N$ in the Passive Region ($\theta \le \theta_c$) When N = 0.3 kg

| | | Dry | | | | Wet | | | |
|---------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--|
| | Sta | atic | Kin | etic | Sta | atic | Kin | etic | |
| Bracket | Run 1 | Run 2 | |
| Clarity | 0.16 | 0.18 | 0.14 | 0.17 | 0.21 | 0.22 | 0.21 | 0.22 | |
| Luxi Mini-Taurus | 0.14 0.18 | 0.15 0.18 | 0.14 0.18 | 0.14 0.16 | 0.18 0.19 | 0.19 0.21 | 0.15 0.18 | 0.18 0.20 | |

TABLE 4. Coefficients of Binding (μ_{BI}) in kg/° as Determined From the Slopes of the RS against Angulation (θ) in the Active Region ($\theta \ge \theta_{c}$) When $N = 0.3 \text{ kg}^{a}$

| | | D | ry | | | W | /et | |
|-------------|----------------|-------|-------|--------|-------|---------|-------|-------|
| | Static Kinetic | | etic | Static | | Kinetic | | |
| Bracket | Run 1 | Run 2 | Run 1 | Run 2 | Run 1 | Run 2 | Run 1 | Run 2 |
| Clarity | 0.038 | 0.041 | 0.035 | 0.040 | 0.054 | 0.054 | 0.054 | 0.051 |
| Luxi | 0.047 | 0.042 | 0.045 | 0.039 | 0.048 | 0.052 | 0.043 | 0.046 |
| Mini-Taurus | 0.070 | 0.058 | 0.067 | 0.055 | 0.049 | 0.053 | 0.050 | 0.050 |

^a All are statistically significant at P < .001.



Normal Force or Ligation Force, N (kg)

FIGURE 5. Combined regression lines of RS against N in the dry state for 2 constant values of θ (0° and 11°) and an *IBD* = 18 mm, in which ▲ represents the static data and ▼ represents the kinetic data. Although the circled and stenciled-in data points are shown, they were omitted from the regression analyses.



FIGURE 6. Combined regression lines of RS against N in the wet state for $\theta = 0^{\circ}$ or $\theta = 11^{\circ}$ and IBD = 18 mm (see Figure 5 for details). Note that Mini-Taurus had a second outlier at the (N, RS) coordinates of (0.1 kg, 0.83 kg).

TABLE 5. Coefficients of Friction (μ_{FR}) as Determined from the Slopes of the RS against N Plots in the Passive Region ($\theta \leq \theta_c$) When $\theta =$ 0° and in the Active Region ($\theta \ge \theta_{c}$) When $\theta = 11^{\circ a}$

| | | | Dry | | | | Wet | | | | |
|-------------|-----|----------------------|---------|-----------------------|-------------------|--------|---------|-----------------------|-------------------|--|--|
| | | $\theta = 0^{\circ}$ | | $\theta = 11^{\circ}$ | | θ = | = 0° | $\theta = 11^{\circ}$ | | | |
| Bracket | Run | Static | Kinetic | Static | Kinetic | Static | Kinetic | Static | Kinetic | | |
| Clarity | 1 | 0.21 | 0.17 | | | 0.16 | 0.16 | 0.16⁵ | 0.13⁰ | | |
| | 2 | 0.18 | 0.17 | 0.09 ^d | 0.06° | 0.19 | 0.17 | 0.08 ^e | 0.12 ^e | | |
| | 3 | 0.20 ^b | 0.18 | 0.14 ^d | 0.08 ^d | | | | | | |
| | 4 | 0.16 | 0.17 | 0.14 [⊾] | 0.11 | | | | | | |
| Luxi | 1 | 0.13 | 0.12 | | | 0.16 | 0.16 | 0.13° | 0.17 ^ь | | |
| | 2 | 0.14 | 0.13 | 0.12 ^d | 0.13⁵ | 0.13 | 0.13 | 0.11° | 0.11 [⊾] | | |
| | 3 | 0.13 | 0.13 | 0.13 ^e | 0.12 | | | | | | |
| Mini-Taurus | 1 | 0.21 ^b | 0.16 | 0.15 | 0.15 | 0.19 | 0.17 | 0.18 [⊾] | 0.15⁵ | | |
| | 2 | 0.20 ^b | 0.17 | 0.12 ^d | 0.13 ^e | 0.22 | 0.17 | 0.15⁵ | 0.14 | | |
| Mini-Twin | 1 | 0.14 | 0.14 | 0.15 ^d | 0.14⁵ | 0.16 | 0.16 | 0.17⁵ | 0.17 | | |

^a All are statistically significant at P < .001 except for those indicated by the following:

[▶] *P* < .01.

° P < .02.

 $^{d}P > .05$ (not statistically significant).

^e *P* < .05.

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TABLE 6. Magnitudes of Binding (*BI*) in kg as Determined from the Intercepts of the *RS* against *N* Plots in the Active Region ($\theta \ge \theta_c$) When $\theta = 11^\circ$

| | | Dry | | Wet | | |
|-------------|-----|--------|---------|--------|---------|--|
| Bracket | Run | Static | Kinetic | Static | Kinetic | |
| Clarity | 1 | | | 0.45 | 0.46 | |
| | 2 | 0.32 | 0.35 | 0.51 | 0.48 | |
| | 3 | 0.47 | 0.49 | | | |
| | 4 | 0.35 | 0.36 | | | |
| Luxi | 1 | | | 0.36 | 0.31 | |
| | 2 | 0.27 | 0.26 | 0.39 | 0.38 | |
| | 3 | 0.24 | 0.24 | | | |
| Mini-Taurus | 1 | 0.29 | 0.30 | 0.32 | 0.39 | |
| | 2 | 0.35 | 0.35 | 0.36 | 0.34 | |
| Mini-Twin | 1 | 0.36 | 0.35 | 0.36 | 0.37 | |

significant (P < .001) for the 0° data but not for the 11° data. For both of these sets of data, the differences between the dry and wet states were not significant.

In the case of *BI* (Table 6), values ranged widely from 0.24 kg to 0.51 kg and had a mean value of 0.36 kg. Although the variance was great, the mean value fell within the general envelope observed for the 4 bracket materials—that of 0.34–0.37 kg. Only Clarity in the wet state and Luxi in the dry state were above and below this benchmark, respectively. ANOVA showed that the results were highly influenced by both the bracket (P < .001) and the dry and wet states (P < .002).

DISCUSSION

Overview of classical friction and binding

In principle, binding (BI) and classical friction (FR) can occur at any time during treatment. Although the practi-

tioner may be confronted with *FR* and *BI* in the occlusalgingival, mesial-distal, or labial-lingual directions, the present work considers only second-order angulation and the presence of adjacent teeth. Future work will need to consider other directions and utilize the superposition principle to determine the total contributions to *FR* and *BI*. And although *in vitro* tests can be a valid indication of *in vivo* performance,²⁴ the complexity that is associated with the coordinated movement of potentially 2 arches poses substantive challenges. Nonetheless, a 3-dimensional (3-D) mapping can now be proposed to facilitate the understanding of, at least, second-order angulation.

General elements of 3-D friction maps

As the normal or ligature force (*N*) and/or the angulation (θ) are varied, the resistance to sliding (*RS*) changes (Figure 7). When all *N*- θ combinations are considered, 2 surfaces are generated: 1 for classical friction (*FR*) and 1 for elastic binding (*BI*) (see Figure 7a). The *FR* surface appears as a 3-D wedge upon which the *BI* contribution rests (*RS* = *FR* + *BI*).^{6,25–27} And once *BI* occurs, that magnitude is constant for a given value of θ , equaling zero for $\theta \leq \theta_c$ and equaling a unique nonzero value for each successive angle of $\theta > \theta_c$.

More specifically, if the *RS* values of the right-hand side of a 3-D map are considered (see Figure 7b), *RS* remains constant (see portion labeled 1) until the demarcation line labeled 2 is reached. Here the vertical dashed line corresponds to the critical contact angle (θ_c), below which only classical friction exists and above which binding additionally occurs.^{26–28} Thereafter, *BI* increases linearly (see portion labeled 3) to some point, which is yet to be identified, that



FIGURE 7. Schematic layout of 3-D maps showing how *N* and θ influence *RS*. In (a), 2 surfaces are defined: the classical friction region (*FR*) and the elastic binding region (*BI*). The *FR* region underlies all combinations of *N* and θ . Once $\theta > \theta_{e}$, however, the *BI* region must be added to the ubiquitous (albeit lower magnitude) *FR* region. In (b), 5 types of lines are defined: *FR*, θ_{e} , μ_{BI} , μ_{FR} , and the zero-friction region, which are 1, 2, 3, 4, and 5, respectively.

Resistance to Sliding, RS (kg)

1.0

0.8

0.6

0.4

0.2

0

0

Dry

0.2 0.4 0.6 0.8 1.0⁰

(a)



Normal or Ligation Force, N (kg)

Clarity

Wet

0.2 0.4 0.6 0.8 1.0⁰

(b)

1.0

0.8

0.6

0.4

0.2

0

0

FIGURE 8. The 3-D maps of pooled static and kinetic data for the 22 mil Clarity bracket against a 19×26 mil stainless steel archwire in the (a) dry and (b) wet states. (See text for details.)



Luxi



FIGURE 9. The 3-D maps for the 22 mil Luxi bracket under the same restrictions and conditions as in Figure 8.

is dependent on material (eg, metal, ceramic, or composite), mechanical (eg, yield strength, hardness, or modulus), dimensional (eg, archwire, bracket, or ligature), and anatomical (eg, interbracket distance, degree of aligning and leveling, or arch curvature) parameters. The slope of the portion labeled 3 is independent of normal or ligature force.²⁹ Consequently, binding occurs to the same extent even when no ligature force is present if $\theta > \theta_c$ (see portion labeled 3 on left-hand side of 3-D map of Figure 7b). Such general behavior coincides with method 1, of which Figures 3 and 4 are representative.

The lines that are marked with a 4 are derived from method 2, such as those depicted in Figures 5 and 6. As Figure 5 has shown, the passive region starts at the origin

Mini-Taurus



FIGURE 10. The 3-D maps for the 22 mil Mini-Taurus bracket under the same restrictions and conditions as in Figure 8.



FIGURE 11. The 3-D maps for the 22 mil Mini-Twin bracket under the same restrictions and conditions as in Figure 8.

and increases linearly in accordance with its value of μ_{FR} . Like the μ_{BI} discussed as the slope of the line labeled 3 in the preceding paragraph, μ_{FR} is the slope of the line labeled 4 whether it be in the passive region at $\theta = 0^{\circ}$ (Figure 7b, foreground line labeled 4), the boundary between the passive and active regions at $\theta = \theta_{c}$ (Figure 7b, intermediate line labeled 4 at the demarcation line labeled 2), or the terminus of elastic binding— θ_z in reference 26 (Figure 7b, background line labeled 4). Thus, although the classical friction that is associated with *RS* systematically increases with increasing *N*, its contribution to *RS* is independent and constant for all θ 's at a given *N*. For example, with no normal or ligature force (N = 0) at $\theta \le \theta_c$, RS = 0 (see Figure 7b, the line labeled 5), wherein the magnitude there-

after equals only BI as defined by the slope of the line labeled 3 (see Figure 7b, left-hand line labeled 3). As you move from left to right across the diagram, these same magnitudes exist except that the constant magnitude of FR must be superposed, which is dependent only on N. At the far right-hand terminus, this magnitude of FR corresponds to the hatched area below the line labeled 1.

As a consequence of these superposition capabilities and the common slopes of the lines labeled 3 and also the lines labeled 4, a 3-D map can be generated for a given archwirebracket-ligature wire system at a specified set of material, mechanical, dimensional, and anatomical parameters-if 3 parameters can be determined: θ_c , μ_{FR} , and μ_{BI} . After analyzing a vertical section of the 3-D map (foreground-tobackground) at a constant value of N (method 1), Figures 3 and 4 along with their accompanying analyses of Tables 2–4 provide all 3 parameters. At $\theta \leq \theta_c$, $RS = FR = \mu_{FR}N$, whereas at $\theta \ge \theta_c$, $RS = FR + BI = \mu_{FR}N + \mu_{BI}\theta$. The intersection of these 2 regression lines yields the experimental value of θ_c . In contrast, Figures 5 and 6 along with their accompanying analyses in Tables 5 and 6 provide 2 of the required parameters after analyzing vertical sections of the 3-D maps (left-to-right) at, at least, 2 constant θ 's (method 2): one at $\theta \ll \theta_c$ and one at $\theta \gg \theta_c$. The first θ establishes the value of μ_{FR} (Table 5), which is shown in the foreground of Figure 7 as the line labeled 4. The second θ establishes the value of BI from the intercepts of its RS versus N plot, which corresponds to a point on the lefthand line labeled 3. For that line, RS = FR + BI = BI = $\mu_{BI}\theta$. To use Figures 5 and 6, θ_c must be determined by measuring 3 geometric dimensions: the size of the archwire (SIZE), the width of the bracket (WIDTH), and the slot of the bracket (*SLOT*). From the approximation, $\theta_c = 57.32[1]$ - (SIZE/SLOT)]/(WIDTH/SLOT).^{23,26}

Application of 3-D friction maps to present work

Using both methods for Clarity, Luxi, and Mini-Taurus brackets and method 2 along with its calculation of θ_c = 57.32[1 - (SIZE/SLOT)]/(WIDTH/SLOT) for the Mini-Twin brackets, 3-D maps were determined for a wide range of N and θ (where N = 0 - 1.0 kg and $\theta = 0 - 15^{\circ}$ in Figures 8 through 11, respectively). In the first 3 of these figures (Figures 8 through 10), redundancy was intrinsic to both μ_{FR} and μ_{BI} . Here θ_c was determined experimentally from the RS against θ plot when N = 0.3 kg via method 1. In the fourth of these figures (Figure 11), θ_c was calculated to be 2.4°, having measured the SIZE, SLOT, and WIDTH to be 0.01875", 0.0241", and 0.1264" (see Materials and Methods section and Table 1 for some nominal dimensions). Having observed no significant difference between static and kinetic values of RS, the regression lines $(- \bullet \bullet)$ were pooled for the dry and the wet states. To summarize then, Figures 8 through 11 illustrate the overall influence of normal or ligature force (N) and second-order angulation (θ)

on the resistance to sliding (*RS*) when (1) no first- or thirdorder effects are present, (2) contiguous brackets are identically represented by low friction contacts at an interbracket distance (*IBD* = 18 mm) far from the subject tooth, (3) static and kinetic data are pooled, (4) a common nominal slot size is used (22 mil), (5) the same archwire (19×26 mil stainless steel) and ligature wire (10 mil stainless steel) are used, and (6) 1 operator is used. Indeed, the redundant analyses afforded by methods 1 and 2 (see Figures 8 through 10) corroborate that the intraoperator variations are inconsequential.

From such 3-D maps, an amplification of the trends occurs in very few tests that could only be otherwise achieved by exhaustive measurements and analyses. Although the Clarity bracket (Figure 8) has a similar μ_{FR} in both the dry and wet states, its μ_{BI} is more severe in the presence than in the absence of saliva. Qualitatively, these same effects are seen for the Luxi bracket; however, the magnitudes of both μ_{FR} and μ_{BI} are lower for Luxi than for Clarity. In the dry state, the Mini-Taurus bracket appears identical to the Clarity bracket. Little difference exists between the Mini-Taurus bracket in either its dry or wet states. In the dry state, the magnitudes of FR for the Mini-Twin bracket appear comparable with the Luxi bracket. And although the FR of the Mini-Twin bracket in the wet state increases over its values in the dry state, the overall RS at high values of θ remains fairly comparable with the Luxi bracket in the wet state. Therefore, Clarity and Luxi appear comparable with the 2 conventional stainless steel brackets in the dry and wet states, respectively. In the dry state, moreover, Luxi is superior among the 4 brackets evaluated.

CONCLUSIONS

Under strictly regimented conditions, metal-lined ceramic brackets are not only esthetic but also possess competitive frictional characteristics in the dry or wet states.

In the dry state, Luxi has the lowest resistance to sliding, regardless of the magnitudes of the ligature forces or the second-order angulations, when compared with the other metal-insert ceramic bracket and the 2 stainless steel brackets. We attribute this characteristic to the presence of a non-oxidizing surface of 18-kt gold. In the wet state, Luxi performs similarly to the stainless steel brackets.

In the dry state, Clarity is similar to the conventional stainless steel brackets. In the wet state, its *RS* increases beyond those same brackets as $\theta \ll \theta_c$. Consequently, in the wet state, the difference between Luxi and Clarity is greatest among all brackets tested.

Given that the same nominal archwire-size and bracketslot dimensions are used, the values of θ_c for the 4 products are $\pm 0.5^\circ$. Hence, the demarcation point between relatively low classical friction and relatively high binding is not a factor in these analyses.

The 3-D friction maps of the resistance to sliding can be

helpful indicators of archwire-bracket-ligature system performance.

The morphology of metal inserts could be improved to reduce potential torquing and hygienic problems.

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