Comparison of the frictional coefficients for selected archwire-bracket slot combinations in the dry and wet states

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Nicolls,[1] Andreasen and Quevedo,[2] Riley et al.,[3] Frank and Nikolai,[4] and Garner et al.[5] have investigated several aspects of the frictional forces that oppose tooth motion during sliding: effects of different archwire-bracket combinations (e.g., material, size, shape, and angulation); influence of ligation (e.g., material and contact force); and interaction of appliances with the surrounding environment (e.g., interbracket distances and oral fluids). Despite the progress that has been made within a wide variety of sliding regimes, many issues still hamper the understanding of sliding mechanics. How sliding of wires within polycrystalline alumina and stainless steel bracket slots compares, how sliding of wires within polycrystalline alumina and single crystal sapphire brackets compares, and whether saliva from different patients influences sliding are just three questions that require further elucidation. In this study we investigated the first question by passing archwires of representative alloys through the two standard bracket slots of representative stainless steel and polycrystalline alumina brackets under dry and wet conditions. Our results show that differences in frictional resistance exist among the various archwires, the two bracket materials, and the dry and wet states.

Materials and methods

Four archwire alloys and two bracket materials were chosen for this study (Table 1). Using a crossed design, a nominal 0.018″ or 0.022″ slot of each bracket was drawn past each archwire, nominally 0.018″ x 0.025″ or 0.021″ x 0.025″ in cross-section. The initial appearance and surface roughness of each respective wire and

Abstract

Coefficients of friction were evaluated in the dry and wet (saliva) states for stainless steel, cobalt-chromium, nickel titanium, and beta-titanium wires against either stainless steel or polycrystalline alumina brackets. For both operators' experiments, an 0.010″ stainless steel ligature wire pressed each archwire into the 0.018″ or 0.022″ bracket slot at 34°C.

In the dry state and regardless of slot size, the mean kinetic coefficients of friction were smallest for the all-stainless steel combinations (0.14) and largest for the beta-titanium wire combinations (0.46). The coefficients of the polycrystalline alumina combinations were generally greater than the corresponding combinations that included stainless steel brackets. In the wet state, the kinetic coefficients of the all-stainless steel combinations increased up to 0.05 over the dry state. In contrast, all beta-titanium wire combinations in the wet state decreased to 50% of the values in the dry state. The mixed reports that saliva may promote adhesive and lubricious behaviors may have some substance.

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Key Words

Alumina • Archwire • Bracket • Friction • Saliva • Stainless steel

Table 1
Archwire and bracket materials

General Class (Nominal wt.%)	Code	Product	Wire Size (inch)	Slot Size (inch)
Archwires:				
Stainless steel (71 Fe, 18 Cr, 8 Ni, <0.2 C)	S.S.	Standard Rectangular™*	0.018 x 0.025 0.021 x 0.025 (straight)	
Cobalt-chromium (40 Co, 20 Cr, 15 Ni, 15 Fe)	Co-Cr	Yellow Elgiloy™**	0.018 x 0.025 0.021 x 0.025 (straight)	
Nickel titanium (52 Ni, 45 Ti, 3 Co)	NiTi	Nitinol SE™*	0.018 x 0.025 0.021 x 0.025 (preformed)	
Beta-titanium (79 Ti, 11 Mo, 6 Zr, 4 Sn)	β-Ti	TMA™***	0.017 x 0.025**** 0.021 x 0.025 (preformed)	
Brackets:				
Stainless steel (71 Fe, 18 Cr, 8 Ni, <0.2 C)	S.S.	Uni-Twin*		0.018***** 0.022*****
Polycrystalline alumina (99.8$^+$ Al_2O_3)	Al_2O_3	Transcend*		0.018***** 0.022*****

*Unitek/3M Corporation, Monrovia, CA.
**Rocky Mountain Orthodontics, Denver, Co.
***Ormco Corporation, Glendora, Ca.
****In the present effort this wire is nominally categorized as an 0.018" x 0.025".
*****Lower second premolars with 0° angulation and -22° torque.

bracket have been evaluated previously by scanning electron microscopy and laser specular reflectance. The latter technique has quantitatively shown that surface roughness decreases in the following order: NiTi (roughest) > β-Ti > Co-Cr > S.S. for the archwires and Al_2O_3 (roughest) > S.S. for the bracket slot surfaces.[6,7]

Frictional forces were measured at a sliding velocity[8] of 1 cm/min and at 10 nominal normal loads from 0.1 to 1.0 kg in 0.1 kg increments. For each slot size, eight archwire-bracket combinations (i.e., "couples") were tested by one of the operators in the dry state in prevailing air at ambient oral temperature (34°C) and in the wet state by two healthy operators using their own saliva at 34°C. Although each evaluation was made only once, 48 couples were prepared (32 by operator 1 and 16 by operator 2) for a total of 480 normal loads each on the stainless steel brackets and the polycrystalline alumina brackets. Prior to each determination, the as-received archwires and brackets were cleansed with 95% ethanol.

The friction apparatus (Figure 1)[9] consisted of a special jig that was mounted to the transverse beam of a tensile testing machine (Instron Model TTCM, Instron Corp., Canton, Mass.). Coaxial springs (not shown) exerted a normal force on a bracket that had been cemented onto an inclined cylinder, for which the angle of inclination negated any effect of pre-torquing of the slot (cf footnote in Table 1). This experimental arrangement was equivalent to the archwire being drawn through a 0° pre-torqued bracket slot as it also contacted two 0.010" S.S. ligature wires (Item PL1010 Ligature Wire, GAC International, Commack, NY). While the assembly of bracket and ligature wires was drawn along the archwire, in the wet cases a peristaltic pump injected fresh saliva onto the wire-bracket-ligature assembly at a flow rate of 3 cc/min (Figure 1). Whether the system was run in the dry or wet state, both the output from the drawing force transducer of the tensile testing machine (T_P) and the normal force transducer (T_N) were recorded as functions of time — and hence, dis-

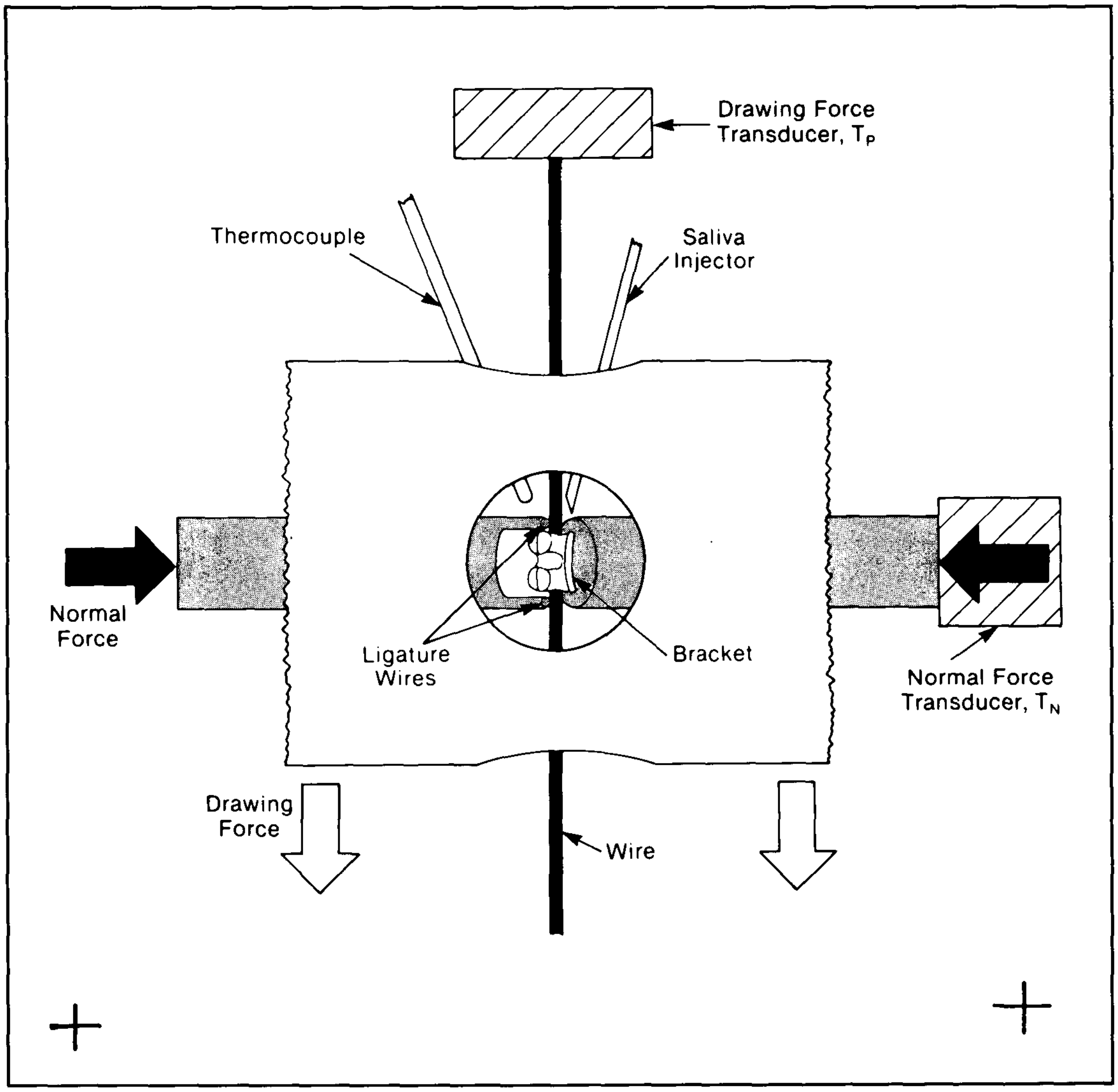

Figure 1
Schematic illustration of friction apparatus with archwire, bracket, and ligature wires appropriately positioned.

tance. By this procedure the drawing force-sliding distance (P-δ) traces were obtained at each of the 10 normal forces (N).

A multi-factor ANOVA of 96 observations (one per cell) was performed. The effects of operator, archwire alloy, bracket material, bracket slot size, and fluid medium on the static and kinetic frictional coefficients were evaluated in terms of main effects, pairwise interactions, and selected three-way interactions. The estimate for random error variance was based on all higher-order interactions. Statistically significant main effects and interactions were further considered by pairwise comparisons of ANOVA model adjusted means.

Results

Examples of the P-δ traces at N=300 g are shown in the wet state for four 0.018″ x 0.025″ archwires that passed through the 0.018″ S.S. bracket slots (Figure 2) and for four 0.021″ x 0.025″ archwires that passed through the 0.022″ Al_2O_3 bracket slots (Figure 3). From one-half of the maximum value at the onset of motion (P_{MAX}) and one-half of the mean value of the computer-acquired data in the plateau region (some 500 values from x=1 to x=n; cf Figure 2, left-hand frame),* the static and kinetic drawing forces (f) versus N were plotted for each archwire-bracket slot couple, respectively. The data reduction of each P-δ plot, such as the eight representative plots shown in Figures 2 and 3, resulted only in one data point for each of the two lines of an f-N plot. Sixteen representative f-N plots by operator 2 are illustrated for the 0.018″ and the 0.022″ slots of the S.S. and Al_2O_3 brackets, respectively (Figures 4-7), where each bracket was tested against each wire in the wet

*The factor of two occurs because the free body diagram of the experimental set-up may be represented by two normal forces and two frictional forces. Since the drawing force transducer of the tensile testing machine (T_P) can only monitor the sum of both frictional forces, the drawing force must be halved. In effect, the mean frictional force is assumed for all computations, regardless of the bearing surfaces that are under consideration.

Figure 2

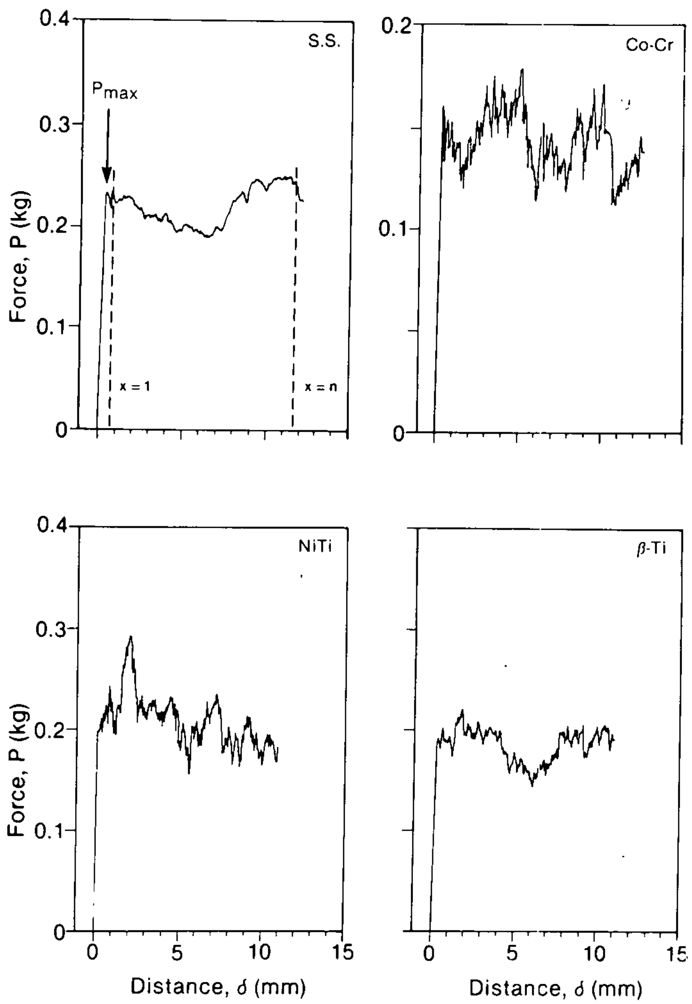

Figure 3

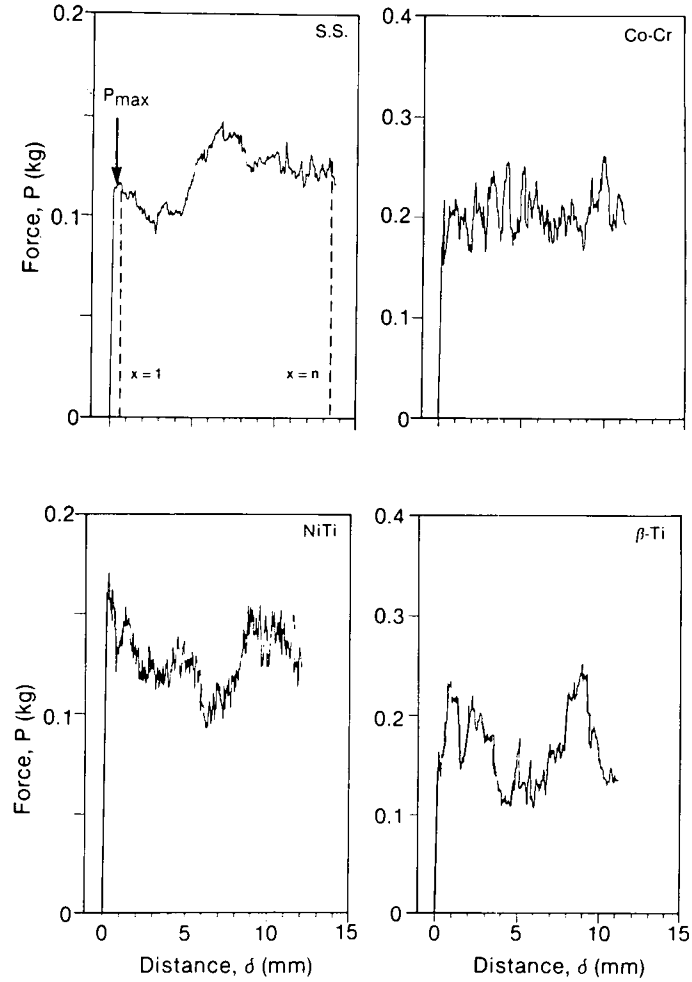

Figure 2
Force-distance (P-δ) traces of 0.018" stainless steel (Uni-Twin™) brackets against four archwires. All combinations were tested in saliva at 34°C under a nominal normal force (N) of 300 g.

Figure 3
Same as Figure 2, except with 0.022" polycrystalline alumina (Transcend™) brackets.

state. Note that many of the regression lines, the slopes of which represent the static and kinetic coefficients of friction, indicate highly significant ($p < 0.001$) linear relationships between frictional and normal forces. Moreover, these relationships are nearly collinear. The range for corresponding correlation coefficients was 0.831 to 0.998 with a median of 0.954, and they pass close to the origin. From among the 96 frictional coefficients of Table 2, the 64 coefficients of operator 1 are presented for the 0.018" x 0.025" wires in 0.018" bracket slots and the 0.021" x 0.025" wires in 0.022" bracket slots (Figures 8 and 9).

Discussion

A multi-factor ANOVA of frictional coefficients (Table 2) showed the measurements were not significantly different for static versus kinetic, operator 1 versus 2, or 0.018" versus 0.022" slot size. Statistically significant differences were observed between dry and wet states, although the overall magnitudes and directional changes depended on the specific bracket-slot and archwire-alloy couples. For the wet state, the measurements of S.S. were lower than the other three archwire alloys, although no significant differences were found among the latter three. In the dry state, significant differences were found among all pairs of archwire alloys ($p < 0.001$) with an increase progressing from S.S. to Co-Cr to NiTi to β-Ti, irrespective of bracket material.

The consolidation of the first operator's results from Table 2 (Figures 8 and 9) provided further insight into the behavior of the dry versus wet state and S.S. versus Al_2O_3 brackets. In general, the dry couple of S.S. archwire and S.S. bracket had the lowest coefficients of friction; however, these values were somewhat greater in the wet state ($p < 0.05$). When Al_2O_3 brackets were substituted for S.S. brackets, the values for the S.S. archwires in the dry state increased. As so often is the case, the Co-Cr wires followed a trend that was similar to that of the S.S. archwires, the major difference being that the

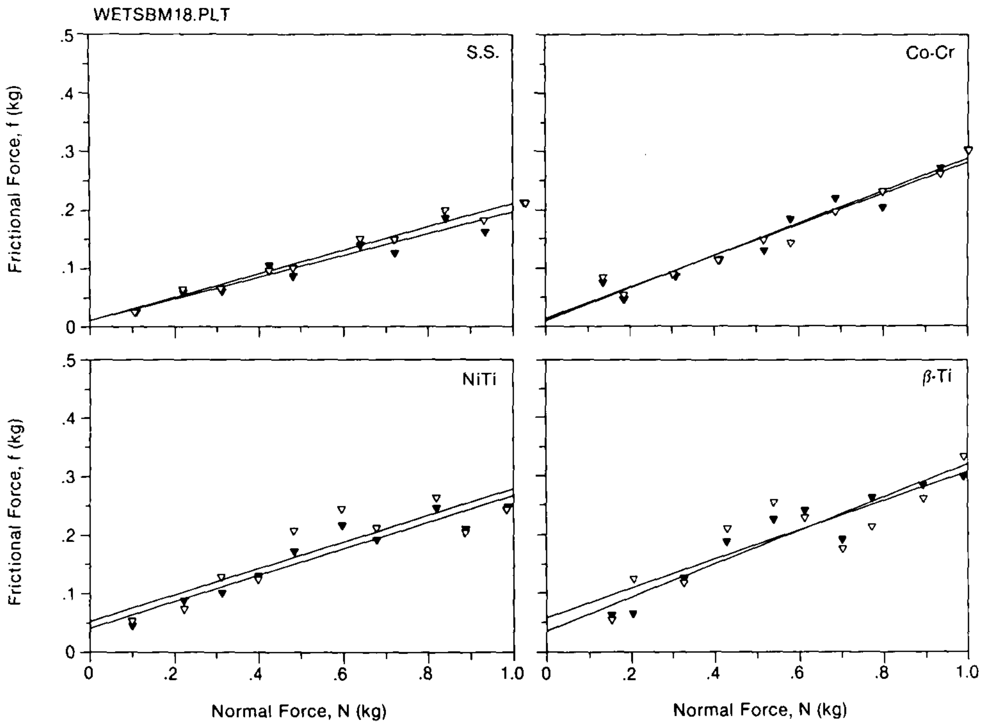

Figure 4
Plots of frictional force (f) versus normal force (N) in the wet state for 0.018″ stainless steel (Uni-Twin™) brackets against four archwires. From the slopes of the regression lines of these static (△) and kinetic (▲) data, the coefficients of friction were determined (cf Table 2, operator 2).

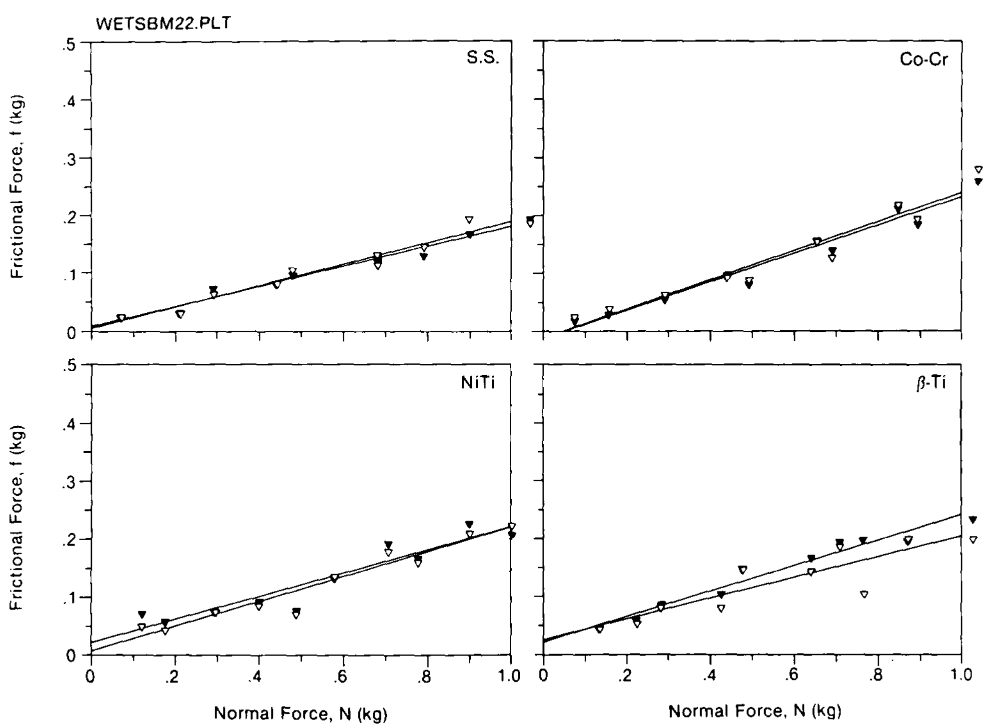

Figure 5
Same as Figure 4 except with 0.022″ stainless steel (Uni-Twin™) brackets.

Figure 6
Same as Figure 4 except with 0.018" polycrystalline alumina (Transcend™) brackets.

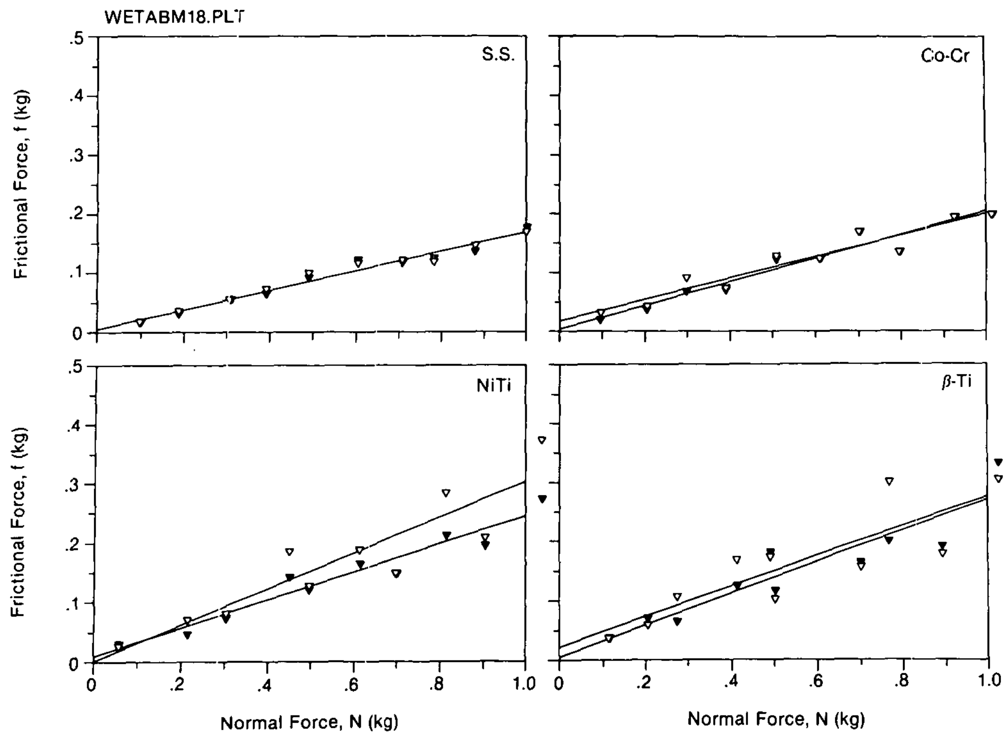

Figure 7
Same as Figure 4 except with 0.022" polycrystalline alumina (Transcend™) brackets.

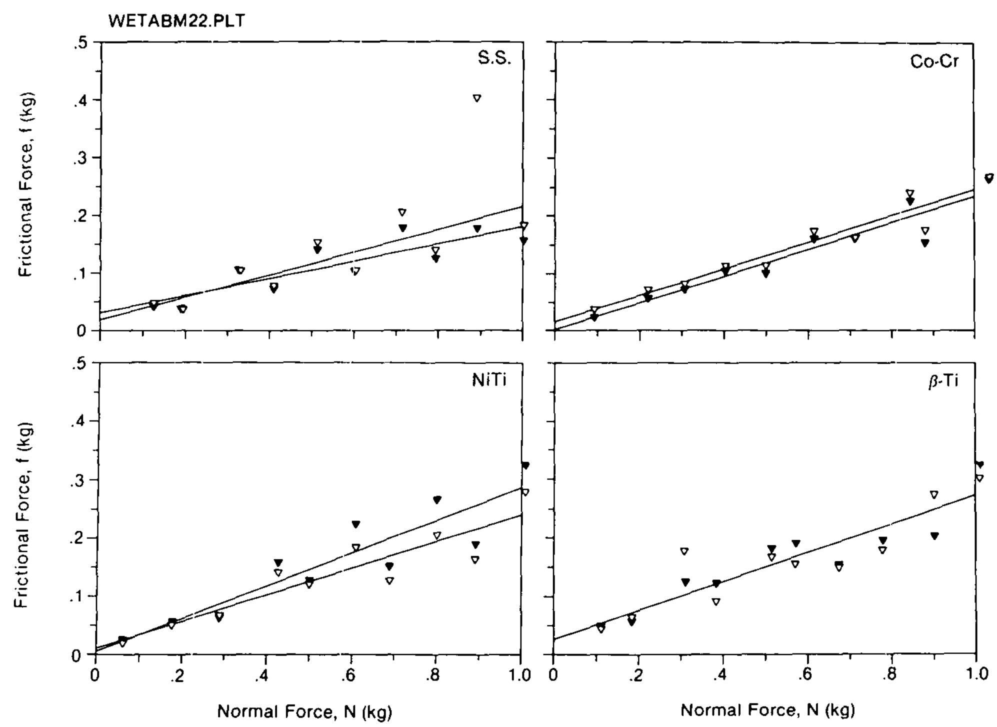

Table 2
Summary of the frictional coefficients
for selected archwire-bracket slot combinations*

Archwire alloy	Stainless steel (Uni-Twin) bracket: Coefficients of static friction, Operator 1 Dry	Operator 1 Wet	Operator 2 Wet	Stainless steel (Uni-Twin) bracket: Coefficients of kinetic friction, Operator 1 Dry	Operator 1 Wet	Operator 2 Wet	Polycrystalline alumina (Transcend) bracket: Coefficients of static friction, Operator 1 Dry	Operator 1 Wet	Operator 2 Wet	Polycrystalline alumina (Transcend) bracket: Coefficients of kinetic friction, Operator 1 Dry	Operator 1 Wet	Operator 2 Wet
0.018 x 0.025 inch archwire — 0.018 inch bracket slot**												
S.S.	0.126 (0.014)	0.141 (0.029)	0.201 (0.012)	0.138 (0.024)	0.160 (0.029)	0.187 (0.016)	0.150 (0.016)	0.199 (0.020)	0.162 (0.009)	0.164 (0.016)	0.178 (0.011)	0.166 (0.010)
Co-Cr	0.202 (0.019)	0.194 (0.017)	0.268 (0.018)	0.199 (0.019)	0.174 (0.016)	0.277 (0.020)	0.232 (0.039)	0.247 (0.025)	0.184 (0.018)	0.250 (0.035)	0.196 (0.010)	0.201 (0.016)
NiTi	0.302 (0.016)	0.232 (0.017)	0.225 (0.038)	0.386 (0.012)	0.222 (0.014)	0.224 (0.024)	0.233 (0.015)	0.298 (0.030)	0.305 (0.046)	0.296 (0.015)	0.253 (0.042)	0.234 (0.020)
β-Ti	0.451 (0.076)	0.199 (0.038)	0.251 (0.043)	0.559 (0.089)	0.224 (0.032)	0.286 (0.029)	0.421 (0.044)	0.182 (0.018)	0.258 (0.050)	0.478 (0.038)	0.199 (0.017)	0.266 (0.034)
0.021 x 0.025 inch archwire — 0.022 inch bracket slot												
S.S.	0.107 (0.015)	0.191 (0.015)	0.183 (0.013)	0.140 (0.014)	0.191 (0.012)	0.173 (0.009)	0.146 (0.021)	0.179 (0.008)	0.199 (0.034)	0.183 (0.026)	0.202 (0.016)	0.153 (0.027)
Co-Cr	0.168 (0.005)	0.227 (0.023)	0.248 (0.022)	0.163 (0.003)	0.199 (0.018)	0.243 (0.017)	0.229 (0.037)	0.258 (0.011)	0.229 (0.022)	0.234 (0.029)	0.226 (0.015)	0.231 (0.024)
NiTi	0.315 (0.028)	0.200 (0.024)	0.212 (0.018)	0.337 (0.038)	0.180 (0.010)	0.198 (0.024)	0.345 (0.034)	0.310 (0.024)	0.282 (0.041)	0.411 (0.054)	0.249 (0.012)	0.230 (0.032)
β-Ti	0.373 (0.033)	0.167 (0.023)	0.178 (0.030)	0.354 (0.027)	0.197 (0.028)	0.220 (0.014)	0.448 (0.057)	0.258 (0.045)	0.246 (0.039)	0.509 (0.045)	0.260 (0.032)	0.246 (0.033)

*Frictional coefficients were measured at a relative velocity of 1 cm/min and at an ambient temperature of 34°C. Each frictional coefficient equaled the slope of a regression plot, such as those shown in Figures 4 and 5. Below each entry and in parentheses are reported the standard errors of the estimate. All correlations of normal forces with frictional forces were significant ($p < 0.01$).
**An 0.017 x 0.025 inch wire was used for the β-Ti alloy.

absolute magnitudes of the Co-Cr coefficients were somewhat greater than those for the S.S. wires. In the dry state, both NiTi and β-Ti archwires exhibited coefficients that were greater than those from either S.S. or Co-Cr archwires. In the wet state, the frictional coefficent from wires of the two titanium alloy archwires decreased below those of the dry state. In the extreme case in which the adhesive or abrasive wear had been documented by scanning electron microscopy in combination with energy dispersive X-ray analysis,[9] the coefficents of friction for the β-Ti archwires decreased by a factor of two in the dry versus the west state, independent of bracket material ($p<0.001$).

Although it would be premature to speculate about the detailed mechanisms that govern each of the friction couples studied here, some discussion regarding the limiting cases of the S.S. and β-Ti couples would be appropriate. In orthodontics, the relatively unusual state of low load and single cycle wear dominates. Consequently, the phenomena of break-in, run-in, and wear-in[10] have little meaning for at least one-half of the couple, since as-received surfaces of the archwires are constantly being encountered throughout the sliding process. Additionally, the friction and wear (i.e., the "tribology") of orthodontic appliances have not been studied in saliva to the same extent that other disciplines have studied the tribological effects of other fluid media (e.g., water, oils, oligomers, acids, or alcohols). The role that saliva plays in sliding mechanics — namely, that of a boundary lubricant, a full-film lubricant, a mixed-film lubricant, or a dry contact[11] — requires in-depth clarification.

Having stated the unique circumstances under which orthodontic appliances function, the couples formed with S.S. and β-Ti archwires suggest that different mechanisms are dominating.

In the all-S.S. couples in the dry state, the overall low magnitudes of the coefficients of friction suggest that the chromium oxide layer, which renders the surface chemically passive,

Figure 8

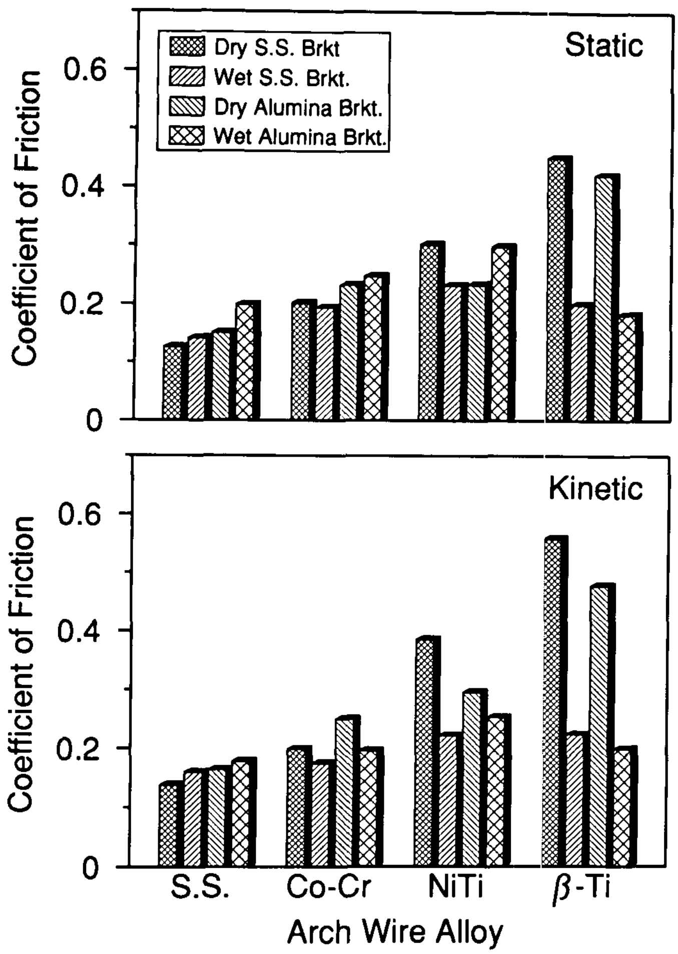

Figure 9

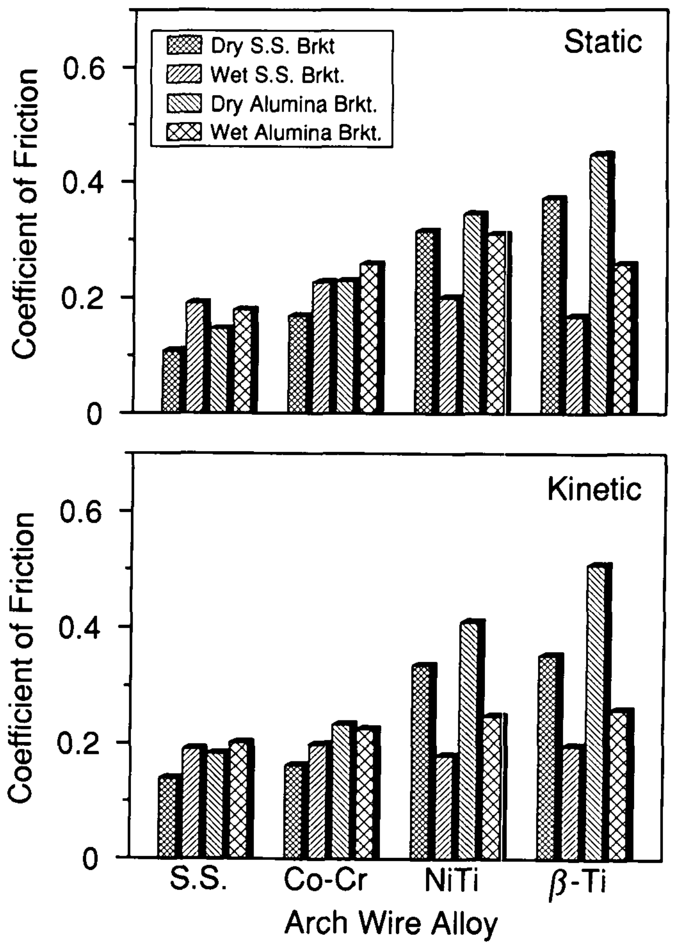

Figure 8
Comparison of the frictional coefficients from selected 0.018" x 0.025" archwire-0.018" bracket slot combinations in the dry and wet states (cf Table 2, operator 1).

Figure 9
Same as Figure 8 except selected 0.021" x 0.025" archwire-0.022" bracket slot combinations are compared.

promotes a lower initial coefficient of friction. When the Al_2O_3 bracket is substituted for the S.S. bracket, the coefficients increase slightly, although the increase is not statistically significant. Nonetheless, the behavior of the Al_2O_3 bracket may be caused by the surface roughness of the slot and/or because the nature of the protective oxide layer is different than that of its counterpart. When saliva is introduced, the values of both couples increase. Conceivably, saliva could be acting to chemically break down the surfaces; alternatively, saliva could be acting as an adhesive because of surface tension effects.

In the β-Ti couples in the dry state, the situation is different. Adhesive and abrasive wear have been documented for β-Ti wires sliding in S.S. and Al_2O_3 bracket slots, respectively.[9] In the former case, the titanium-rich oxide layer breaks down, reacts, adheres, and breaks away, resulting in a "stick-slip" phenomenon.[12] In the latter case, the rough Al_2O_3 surfaces remove layers of the soft wire material much like a hardened steel file removes wood. When saliva is introduced, the frictional coefficients decrease to a level that is more comparable with those of the Co-Cr and S.S. couples. For β-Ti in the wet state, full-film lubrication must be preventing solid-to-solid contact. Although the reduction of the frictional coefficient in the wet state seemingly suggests that β-Ti couples would make effective appliances in the oral cavity, high pressure contacts between archwires and bracket slots forecast that more boundary lubrication would likely occur. As more boundary lubrication occurs, more solid-solid contacts would appear in conjunction with solid-liquid contacts; thereby, more stick-slip phenomenon would occur as sliding would be hampered. Some promise of improving the sliding mechanics of β-Ti wires is documented in surface modification experiments that use ion implantation,[13] but the behavior of saliva as a lubricant and/or an adhesive requires further elaboration within the context of a normal patient population.

Conclusions

1. In the dry state, the all-S.S. archwire-bracket slot couples have the lowest coefficients of friction, and the β-Ti archwire-bracket slot couples have the highest coefficients. These trends were observed regardless of bracket material or slot size.

2. In the dry or wet states, the static and kinetic coefficients of friction were often higher with Al_2O_3 than with S.S. brackets.

3. The greatest differences between dry and wet states occurred with β-Ti archwires, in which the kinetic coefficients of friction in the wet state were reduced to 50% of the values in the dry state.

4. The conflicting reports that saliva promotes lubricious and adhesive behavior may have some substance, depending on which archwire-bracket couple is being evaluated. Specifically, couples comprised of β-Ti wires exhibit lubricious behavior in the wet versus the dry state, while couples comprised of S.S. wires suggest some adhesive behavior in the wet versus the dry state.

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