Effect of salivary viscosity on frictional coefficients of orthodontic archwire/bracket couples

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Stimulated whole saliva samples were collected from 30 healthy individuals and analysed with a cone and plate viscometer. On the basis of these dynamic viscosity measurements saliva from patients, who represented the mean value and two standard deviations above and below the mean value, were selected for frictional force testing. Four archwire/bracket couples (SS/SS, SS/PCA, β-Ti/SS, and β-Ti/PCA) were each tested in these three salivas as well as in the dry state a total of five times, each at five different normal loads. With two exceptions no significant differences were found between any of the three wet states for any couple studied. When the dry state was compared to any of the wet states, the SS archwire couples showed a singificant increase in frictional forces, while the β-Ti archwire couples showed a slight decrease in frictional forces, which was not statistically significant.

1. Introduction

In contemporary orthodontics, many practitioners utilize sliding mechanics for both closing extraction spaces and aligning irregular teeth. As this procedure requires the tooth to be displaced relative to the archwire, a portion of any force that is applied to move the tooth must be consumed by overcoming the inherent friction of the system. Numerous investigators [1–19] have focused on elucidating the frictional forces of various archwire/bracket combinations under a multitude of conditions, particularly archwire/bracket materials and appliance geometry. Some researchers, who have performed frictional studies under dry experimental conditions, have projected that friction will be reduced in the oral cavity due to the lubricating effect of saliva [1,4]. Recently, one team has shown that saliva may exhibit both lubricious and adhesive properties depending on the archwire/bracket couple [16], while other investigators have utilized artificial salivas to simulate the wet condition [5–7,10]. These studies have resulted in widely conflicting claims of both increased and decreased frictional values for certain archwire/bracket couples. Unfortunately, the use of artificial saliva to simulate oral conditions in these studies disregards the inherent rheological differences between human saliva and saliva substitutes [17,20].

An understanding of the friction produced during sliding mechanics is critical for the clinician. Merely increasing the force in an orthodontic appliance will not remedy a high friction archwire/bracket couple; that is, doubling the drawing force will merely double the frictional force. Additionally, excessive amounts of archwire/bracket friction may ultimately result in a loss of anchorage or in binding accompanied by little or no tooth movement.

Because orthodontic tooth movement is best accomplished by light physiologic forces of long and constant duration [21], the preferred material for moving a tooth relative to the archwire should be one that produces the least amount of friction at the archwire/bracket interface and has minimal fluctuations in the amount of frictional forces present in the tooth moving system.

Not all fluids are "lubricants" that reduce the friction between contacting materials [2,3,5–7,10,16,17]. The specific composition and behaviour of a fluid in service determines its ability to act as a lubricant. By assuming that a saliva of high viscosity contains larger and/or more protein molecules than one of low viscosity, we postulate that salivary viscosity affects the frictional coefficients of specific archwire/bracket couples. This hypothesis is tested using three representative salivas and four different archwire/bracket couples.

2. Materials and methods

2.1. Saliva sample procurement

The dynamic viscosities of a typical orthodontic patient population were determined from an evaluation of 30 stimulated whole saliva samples, which were collected under well-delineated conditions from healthy patients [20]. The mean salivary viscosities and standard deviations (s.d.) at 34 °C were determined from information generated by a Brookfield Digital Cone and Plate Viscometer Model LVTDV-II CP (Brookfield Engineering Laboratories, Inc., Stoughton, MA). From this data, individual saliva samples were chosen to represent the wet states (Fig. 1): "L" for low viscosity (i.e. the mean viscosity minus two s.d.), "M" for medium viscosity (i.e. the

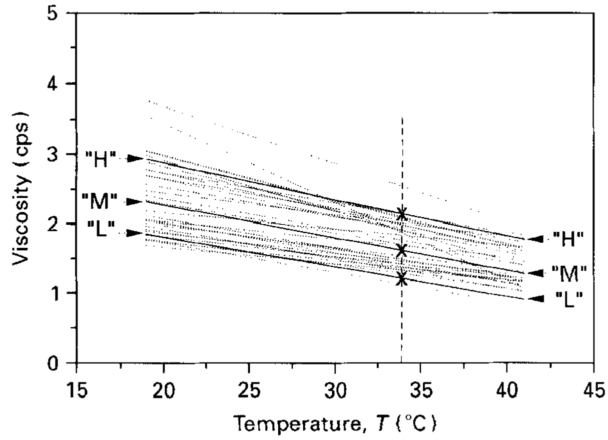

Figure 1 Viscosity–temperature (T) plots of 30 saliva samples. The representative samples ("L", "M", and "H") that were chosen for frictional testing are highlighted along with their viscosities at 34 °C (cps = centipoise = mPa.s).

TABLE I Materials evaluated

General class	Product	Code	Supplier and address
Archwires			
Stainless steel	Standard Rectangular[a]	SS	Unitek/3M Corporation Monrovia, CA
Beta-titanium	TMA[b]	β-Ti	Ormco Corporation Glendora, CA
Brackets			
Stainless steel	Uni-Twin[c]	SS	Unitek/3M Corporation Monrovia, CA
Polycrystal-laine alumina	Allure III[c]	PCA	GAC International Central Islip, NY

[a] 0.018″ × 0.025″
[b] 0.017″ × 0.025″
[c] 0.018″ slot, 0° angulation, −7° torque

mean viscosity), and "H" for high viscosity (i.e. the mean viscosity plus two s.d.). These extremes represent the viscosity regime within which 95% of the typical orthodontic patient population should fall.

2.2. Materials

Previous studies have suggested that frictional coefficients are generally lowest for archwire/bracket couples composed of all stainless steel (SS) [1–18]. In contrast, couples that are comprised of beta-titanium (β-Ti) archwires and alumina brackets are typically associated with the highest recorded frictional coefficients [10, 11, 15–17, 19]. By choosing these two extremes of archwire/bracket couples, any impact of salivary viscosity on sliding arch mechanics in orthodontic treatment should be noted. All SS or polycrystalline alumina (PCA) brackets were designed for use on maxillary bicuspid teeth and had an 0.018″ (0.46 mm) slot, 0° angulation, and −7° torque. The straight archwire segments nominally measured 0.017″ × 0.025″ (0.43 × 0.64 mm) for the β-Ti samples and 0.018″ × 0.025″ (0.46 × 0.64 mm) for the SS samples (Table I).

2.3. Friction testing

The frictional apparatus consisted of a special jig that was mounted to the transverse beam of an Instron Universal Testing Machine (Instron Model TTCM, Instron Corp., Canton, MA) [13–17, 19]. Coaxial springs exerted a normal force (N) on the bracket being tested, which was arranged within the apparatus so that no torque was expressed by the bracket slot. Two 0.010″ (0.25 mm) stainless steel ligatures pressed each archwire into its bracket slot (Fig. 2). The temperature (T) in the test chamber was monitored with a thermocouple probe and maintained at 34 °C. The wet state was created by bathing the system with saliva of predetermined viscosity via a peristaltic pump at a rate of 3 ml/min. The viscosity of the saliva was verified at the start of drawing force (P) measurements to ensure that an appropriate sample had been obtained for each archwire/bracket couple being tested (Fig. 3). Earlier work had shown that no significant change in salivary viscosity occurred as a result of the testing circumstances [19]. The values of P were measured at a sliding velocity of 1 cm/min for five values of N, which ranged from 0.2 to 1.0 kgf (1.0 kgf = 9.8 N) in 0.2 kgf increments. As the apparatus was traversed along the wire, the output from the drawing force and normal force transducers (cf. Fig. 2, T_P and T_N, respectively) were recorded graphically on the Instron and digitally on an IBM XT computer. This procedure resulted in P versus sliding displacement (δ) traces for each value of N. From the digitally stored traces, the static and kinetic frictional forces(f) were determined for each N value by halving each maximum initial drawing force (P_{max}) and the P values between the boundaries of each subsequent force plateau (the dashed lines), respectively. From the plots of f versus N, the slopes of the straight lines were proportional to the static (μ_s) and kinetic (μ_k) coefficients of friction [13–17, 19] (Fig. 2). The compilation of four experimental conditions (the dry state and three wet states), four archwire/bracket couples (SS archwire/SS bracket; SS archwire/PCA bracket; β-Ti archwire/SS bracket; and β-Ti archwire/PCA bracket), five normal loads (0.2, 0.4, 0.6, 0.8, and 1.0 kgf), and five replications resulted in four hundred permutations from which a like number of independent f–N traces were obtained, each resulting in a μ_s and μ_k value.

2.4. Data analysis

By accumulating the static and kinetic force data for each N, the μ values were determined from their linear regression equations. The correlation coefficients were verified, when a statistically significant probability of $p < 0.05$ was obtained.

A multi-factorial ANOVA model was used to evaluate the relationship between the μ values for archwire/bracket couples, frictional coefficients (static or kinetic), fluid states (dry, wet "L", wet "M", or wet "H"), repetitions of a fluid state (one to five), and pairwise interactions. Because the ANOVA test assumes that all variances are equal, when in fact the μ values recorded for β-Ti archwire couples resulted in larger

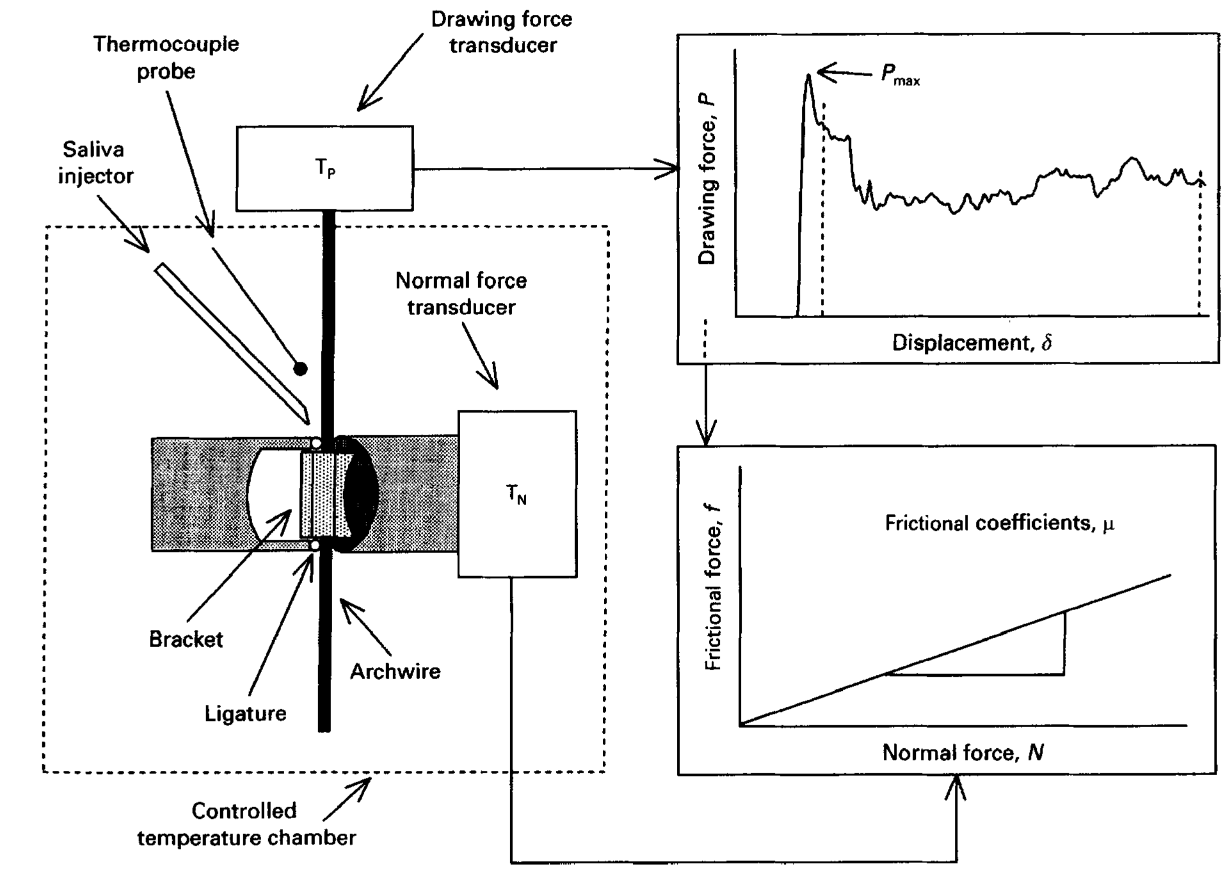

Figure 2 Schematic illustration of frictional apparatus with archwire, bracket and ligatures appropriately positioned, along with representative outputs from the drawing force transducer and the normal force transducer.

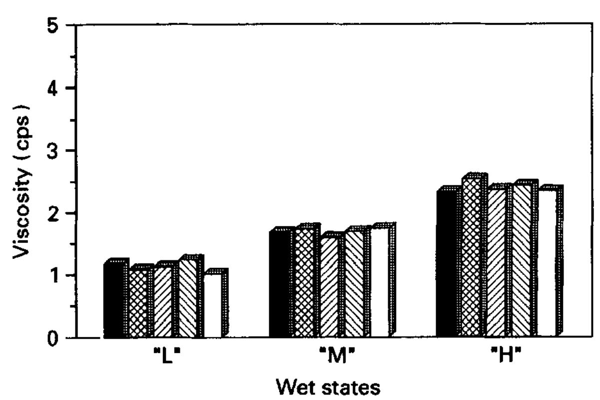

Figure 3 Graph illustrating the range of salivary viscosity used on five different days for the repetitions of frictional tests (■ 1; ▩ 2; ▨ 3; ▧ 4; □ 5).

variances, a logarithmic transformation of the data was necessary. Although previous work had found no significant differences between the static and kinetic coefficients [16], our analysis initially modelled the two coefficients separately, since recent data had indicated that different relationships governed each one [19]. However, static and kinetic coefficients once again appeared to be similar, resulted in similar ANOVA models, and consequently were combined. Nonetheless, because a significant interaction existed between different fluid states for some couples, a separate ANOVA model was required for each couple.

Comparisons between the dry and wet states "L", "M", and "H" for each couple were made using contrasts of ANOVA-adjusted means relative to a standard error that accounted for replicate variability. Due to the statistical circumstances of these comparisons, the Bonferroni correction factor indicated that a p value of about 0.02 versus 0.05 was required for statistical significance.

Differences between archwire/bracket couples were not tested, since these differences had already been well documented elsewhere [13–17, 19].

3. Results

Saliva samples, which were obtained from specific individuals to represent particular wet states, varied somewhat for each frictional-test repetition (Fig. 3). The mean salivary viscosities of the five samples utilized from each patient (1.12, 1.67, and 2.39 cps) closely represented the wet states of "L", "M", and "H", respectively (1.03, 1.69, and 2.35 cps).

Representative P–δ traces of the four archwire/bracket couples at a nominal $N = 0.8$ kgf in the wet state "H" (Fig. 4) underscored the fact that SS couples had the lowest P values. In contrast, the β-Ti couples typically exhibited higher P values with much greater fluctuation— presumably due to a stick/slip phenomena [22]. The corresponding f–N plots for the archwire/bracket couples tested in wet state "H" during repetition number 2 (Fig. 5) demonstrated the overall similarities of the μ_s and μ_k values for SS archwire couples (5a, 5b) as well as the mild differences for β-Ti couples (5c, 5d).

The μ_s and μ_k values that were obtained for all archwire/bracket couples and states (Table II) indicate the

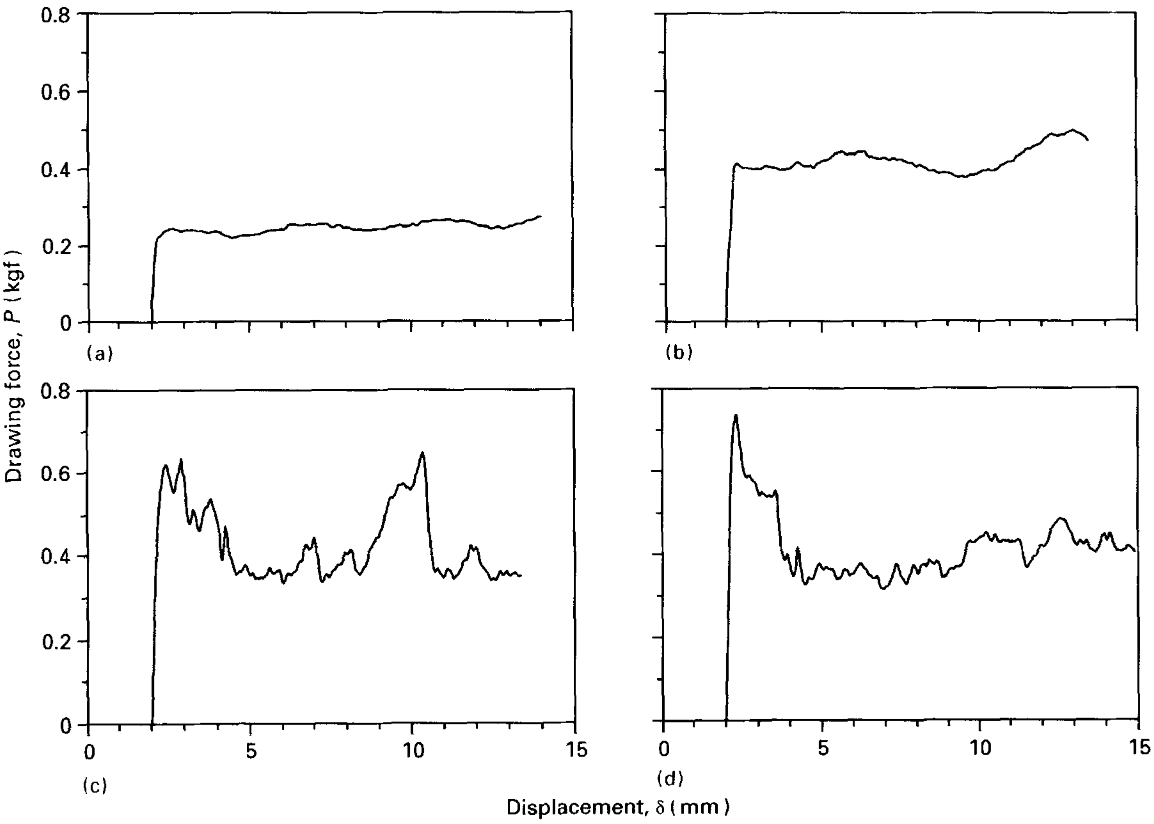

Figure 4 Drawing force–displacement (P–δ) traces of the four archwire/bracket couples tested under a nominal normal force (N) of 0.8 kgf against saliva that represented wet state "H" (mean viscosity plus 2 standard deviations) 1.0 kgf = 9.8 N. (a) SS/SS, (b) SS/PCA; (c) β-Ti/SS, (d) β-Ti/PCA.

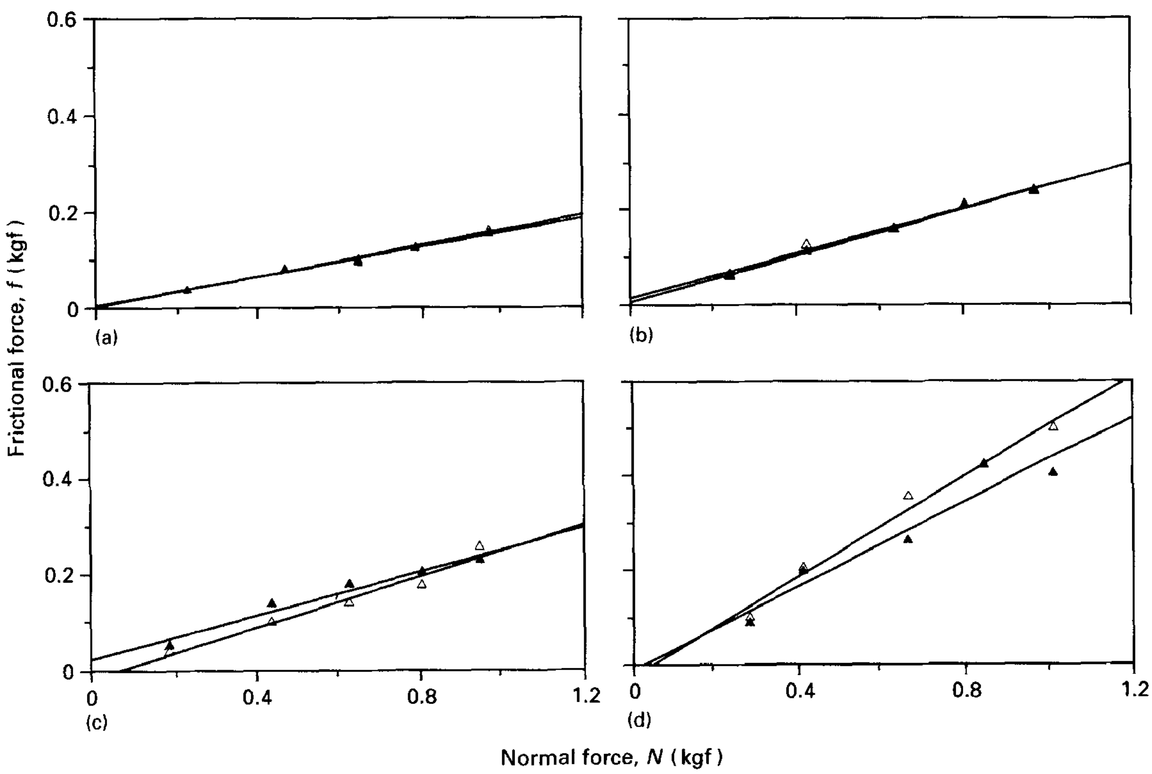

Figure 5 Frictional force–normal force (f–N) plots for the four archwire/bracket couples tested in wet state "H" (mean viscosity plus 2 standard deviations) during repetition number 2. (a) SS/SS; (b) SS/PCA; (c) β-Ti/SS; (d) β-Ti/PCA (△ static; ▲ kinetic).

degree of variability, which is seen for frictional coefficients within a cell. The mean coefficients of friction ($\bar{\mu}$) and their s.d. for each cell (Table III) varied from a high value of 0.439 ± 0.133 for the β-Ti/PCA couple in the wet state "M" to a low value of 0.128 ± 0.043 for the SS/SS couple in the dry state. Despite all the variability noted in Table II, these means agreed with earlier work [15–17, 19]. When saliva was introduced

TABLE II Static and kinetic coefficients of friction, μ

State	Archwire/bracket couple							
	SS/SS		SS/PCA		β-TI/SS		β-Ti/PCA	
	Static	Kinetic	Static	Kinetic	Static	Kinetic	Static	Kinetic
Dry								
1	0.154	0.140	0.209	0.227	0.411	0.500	0.395	0.379
2	0.081	0.086	0.103	0.107	0.356	0.412	0.286	0.377
3	0.097	0.079	0.106	0.117	0.272	0.247	0.470	0.529
4	0.163	0.169	0.267	0.247	0.441	0.439	0.352	0.266
5	0.166	0.165	0.182	0.169	0.481	0.552	0.621	0.560
Wet "L"								
1	0.209	0.199	0.294	0.319	0.244	0.332	0.348	0.422
2	0.190	0.210	0.303	0.299	0.322	0.350	0.255	0.282
3	0.185	0.148	0.430	0.424	0.410	0.394	0.429	0.248
4	0.139	0.172	0.294	0.252	0.370	0.484	0.494	0.465
5	0.252	0.245	0.211	0.267	0.443	0.515	0.489	0.396
Wet "M"								
1	0.184	0.214	0.340	0.285	0.261	0.231	0.432	0.474
2	0.154	0.143	0.225	0.246	0.326	0.409	0.544	0.510
3	0.281	0.238	0.287	0.233	0.287	0.233	0.265	0.262
4	0.189	0.219	0.288	0.267	0.336	0.315	0.362	0.313
5	0.253	0.239	0.320	0.278	0.278	0.319	0.592	0.539
Wet "H"								
1	0.218	0.242	0.303	0.299	0.427	0.393	0.371	0.597
2	0.160	0.151	0.236	0.244	0.269	0.230	0.533	0.447
3	0.157	0.176	0.280	0.274	0.416	0.524	0.464	0.293
4	0.240	0.246	0.258	0.222	0.454	0.414	0.315	0.288
5	0.323	0.323	0.274	0.218	0.418	0.417	0.279	0.253

into the system, the μ values increased for all SS/SS and SS/PCA couples but decreased for most β-Ti/SS and β-Ti/PCA couples.

4. Discussion

4.1. Statistical analyses

The multi-factorial ANOVA of μ values indicated that no significant differences existed between any of the wet states with two exceptions: a borderline association for the β-Ti/SS couples between the wet states "L" and "M" ($p = 0.1$) and between the wet states "M" and "H" ($p = 0.08$). A comparison of the dry state and all wet states (i.e. "L", "M", and "H") for each of the archwire/bracket couples showed that only those couples with a stainless steel archwire showed a significant difference ($p < 0.005$).

The present results differ slightly from earlier work that used the same experimental apparatus and similar archwire/bracket couples. Previously, a statistically significant reduction in μ was observed for the β-Ti/PCA couples in the wet state [16, 19]. Presently, an overall reduction in μ was observed for β-Ti couples in the wet state, but it was not statistically significant. This outcome was attributed to the large variability that is characteristic of the β-Ti archwire couples (Table II) [15–17, 19]. By increasing the number of replications for each state, the possibility of measuring larger differences within each cell was also increased–just by chance. Additionally, the comparison of the dry state to the global wet state pits 5 values against 15. Consequently, if one very low value is observed in the dry state cell, the outcome could conceivably reduce any statistical difference that might exist between the dry and wet states.

4.2. Perceived role of viscosity

Analysis of the viscosity data indicated that the three distinct viscosities persisted for the salivas used in our friction testing. Although some mild variations about the central tendency were observed, each patient's saliva maintained its ranking within the distribution of saliva samples tested (Fig. 3). Viscosity was chosen to discriminate salivas because of prior clinical experience; the obvious differences in the liquid/solid ratios of a patient's saliva seemed a logical starting point for investigation. Intuitively we rationalized that a thick ropey saliva should influence frictional forces more than a thin watery saliva. These apparent viscometric differences are known to have an effect on other forms of oral lubrication [23].

4.3. Actual role of viscosity

These results show that viscosity cannot discriminate the gross differences in the frictional forces, which are reported in the orthodontic literature. Although the presence or absence of saliva does affect the frictional forces and sliding mechanics, viscosity differences do not discriminate between the lubricating or adhesive qualities of saliva. In other disciplines of dentistry, researchers have shown that the glyco-proteins of saliva are essential for adequate and effective oral lubrication [24, 25]. No one knows, however, whether these molecules interact with orthodontic appliances

TABLE III Mean static and kinetic coefficients of friction, $\bar{\mu}$

State	Archwire/bracket couple			
	SS/SS	SS/PCA	β-Ti/SS	β-Ti/PCA
Dry				
Static	0.132 ± 0.040	0.173 ± 0.070	0.392 ± 0.081	0.425 ± 0.128
Kinetic	0.128 ± 0.043	0.173 ± 0.063	0.430 ± 0.116	0.422 ± 0.121
Wet "L"				
Static	0.195 ± 0.041	0.306 ± 0.079	0.358 ± 0.078	0.403 ± 0.102
Kinetic	0.195 ± 0.037	0.312 ± 0.068	0.415 ± 0.081	0.363 ± 0.093
Wet "M"				
Static	0.212 ± 0.053	0.292 ± 0.044	0.298 ± 0.032	0.439 ± 0.133
Kinetic	0.211 ± 0.039	0.262 ± 0.022	0.301 ± 0.074	0.420 ± 0.124
Wet "H"				
Static	0.220 ± 0.068	0.270 ± 0.025	0.397 ± 0.073	0.392 ± 0.105
Kinetic	0.228 ± 0.067	0.251 ± 0.035	0.396 ± 0.106	0.376 ± 0.145

in the same manner or by the same mechanisms that are endemic with its functions of moistening the mucosa, aiding digestion, providing ions for remineralization, chemically buffering the oral cavity, and lubricating the oral tissues. What we do know now is that a saliva of high viscosity, which presumably contains larger and/or more protein molecules, does not outperform a saliva of low viscosity. Given that sliding mechanics can be a three-body phenomenon (i.e. the archwire, bracket, and saliva), the role that the biological material plays is of critical importance to the overall performance of the synthetic materials.

5. Conclusions

A practitioner cannot presume anything about the lubricating quality of a saliva from its dynamic viscosity. In the present effort, the frictional coefficients showed no significant change for any archwire/bracket couple, when comparisons were made between salivas of different viscosities.

Being wet with saliva does not necessarily reduce friction in archwire/bracket couples. For example, frictional coefficients were increased for all couples that contained a stainless steel archwire, when saliva of any viscosity was introduced into the system.

The archwire/bracket couples that most need friction reduction are the ones least likely to receive it from being wet with saliva. Specifically, when saliva of any viscosity was introduced into the system, frictional coefficients showed no statistically significant change for any couple that contained a β-Ti archwire. Nonetheless, most of the couples showed a slight decrease in frictional coefficients in the wet state.

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