Original Article

Effects of sliding velocity on friction
An in vitro study at extremely low sliding velocity approximating orthodontic tooth movement

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ABSTRACT
Objective: To evaluate the effects of sliding velocity on friction, particularly at extremely low sliding velocity approximating orthodontic tooth movement.
Materials and Methods: Stainless-steel (SS) 0.022-inch preadjusted brackets and 0.016- and 0.016 × 0.022-inch SS wires and superelastic nickel-titanium 0.016 × 0.022-inch wires were used for this test. The wire was secured in a SS preadjusted bracket with an elastomeric module. One end of the wire was pulled upward 1.5 mm at a speed of 5.0×10^{-7}, 1.0×10^{-5}, 1.0×10^{-4}, 1.0×10^{-3}, 1.0×10^{-2}, and 1.0×10^{-1} mm/s by the micrometer. The measurements were conducted 10 times and averaged. Tukey-Kramer tests were used to compare the mean differences of each testing measurement among the different sliding velocities.
Results: The frictional forces tended to increase as the sliding velocity decreased. The mean frictional force for 5.0×10^{-7} mm/s sliding velocity (approximating orthodontic tooth movement) was 106.8 cN in 0.016 × 0.022-inch SS wires, almost double the 1.0×10^{-1} mm/s sliding velocity.
Conclusion: The effects of sliding velocity cannot be ignored when we estimate frictional forces in clinical orthodontics. (*Angle Orthod.* 2014;84:451–458.)

KEY WORDS: Friction; Sliding velocity; Orthodontic tooth movement

INTRODUCTION

It is important for orthodontists to know the exact frictional forces encountered at the bracket-wire interface because we have to apply optimal forces in order to elicit the proper biologic response for efficient tooth movement. Tooth movement typically occurs at a rate of 1 mm/mo, that is, an approximate average speed of 2.3×10^{-5} mm/min, namely 3.9×10^{-7} mm/s.[1] Moreover, the velocity for reciprocal closure of a diastema between the two central incisors was nearly 2.4×10^{-4} mm/min[2]; however, most sliding velocities in laboratory tests have been examined at markedly faster velocities, from 2 to 15 mm/min.[3–12] Since relatively high sliding velocities were utilized in these studies, they reported static or kinetic frictional resistance as distinctly separate phases; however, in orthodontic tooth movement, the resolution of static and kinetic frictional resistance is difficult and potentially misleading because static and kinetic frictional resistance are dynamically related, particularly at extremely low sliding velocity in orthodontic tooth movement.[13] These nearly 4- or 5-order differences in sliding velocities between previous in vitro studies and the in vivo state should not be ignored if we are to obtain meaningful values for clinical applications. Although the third law of friction states that friction is independent of sliding velocity,[14] it is generally acknowledged that Coulomb's friction law is not usually followed.[15] It was previously reported that stainless-steel (SS) and nickel-titanium (Ni-Ti) wires were largely unaffected by changes in sliding velocity[1]; however, their study was conducted by measuring frictional forces not against SS brackets with a ligature but against SS contact flats. Thus, this is the first article to evaluate the effects of low sliding velocity approximating in vivo tooth movement on

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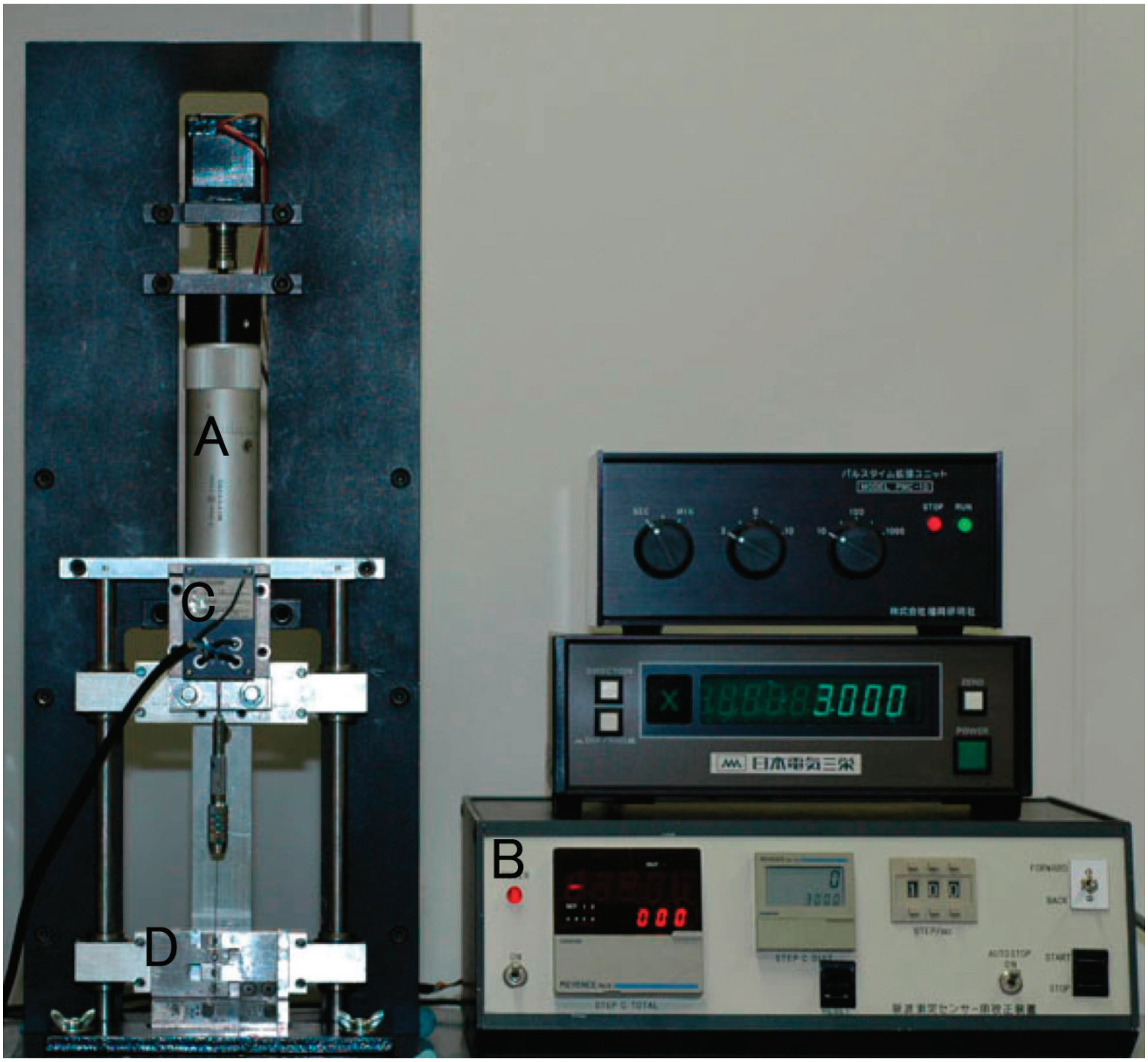

Figure 1. The instruments used for measuring the frictional forces: (A) micrometer, (B) pulse-controller, (C) strain gauge, and (D) stand with bracket fixation table.

frictional forces between wires and brackets tied with elastomeric modules.

The aim of this study was to evaluate the effects of sliding velocity on friction with different wire shapes and materials. In particular, we focused on extremely low sliding velocity approximating the velocity of orthodontic tooth movement.

MATERIALS AND METHODS

The instrument used for this test consisted of a micrometer (164-118, Mitutoyo, Kanagawa, Japan), a pulse-controller (RC-2, Keyence, Osaka, Japan), a strain gauge (UK-1K, Minebea, Tokyo, Japan), and a stand with a bracket fixation table (Figure 1). The measuring range and sensitivity of the micrometer are 0–50 mm and 0.01 mm, respectively. The load cell capacity and sensitivity of the strain gauge are 0–1000 g and 0.1 g, respectively. In addition, 0.022 × 0.028-inch slot size SS preadjusted brackets (Metal-bracket; Dentsply-Sankin, Tokyo, Japan) for the lateral incisor were bonded to the table of the stand, and 0.016- and 0.016 × 0.022-inch SS wires (SUS-wire; Dentsply-Sankin) and 0.016 × 0.022-inch superelastic Ni-Ti wires (Tynilloy wire; Dentsply-Sankin) were used for this test. The brackets were arranged passive to the wires so that their slots were aligned for the SS 0.022 × 0.028-inch wire. The wire was secured in the SS preadjusted bracket with an elastomeric module (Plastic ligatures; American Orthodontics, Sheboygan, Wis). Elastomeric

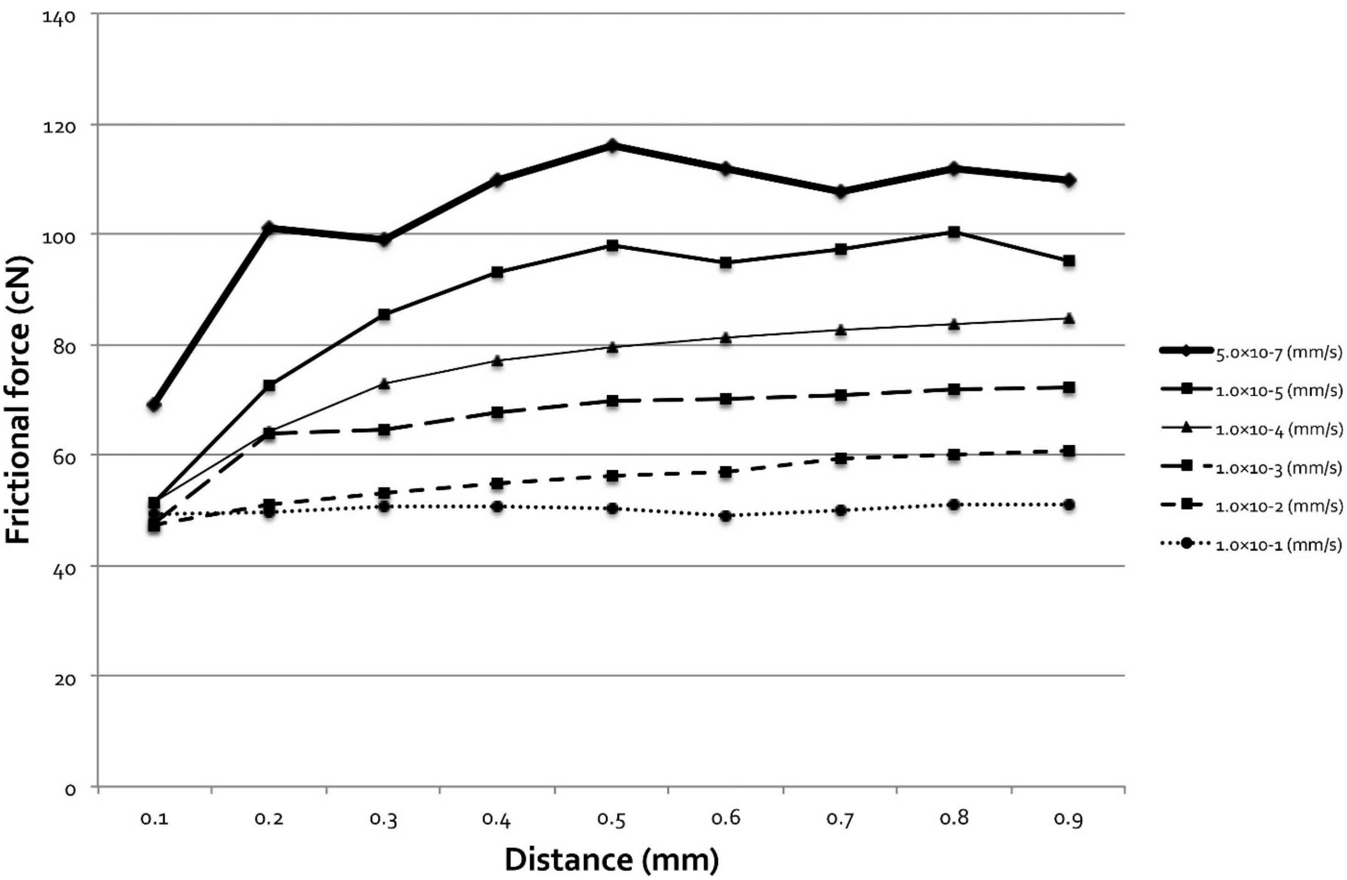

Figure 2. The trend of frictional forces of 0.016 × 0.022-inch stainless-steel wires for different sliding velocities.

modules were tied with a ligature gun (Straight-Shooter; T-P Orthodontics, La Porte, Ind). This method can limit possible stretching differences between elastomeric modules.[16] The upper end of the 15-cm wire was pulled upward 1.5 mm at a speed of 1.0×10^{-5}, 1.0×10^{-4}, 1.0×10^{-3}, 1.0×10^{-2}, and 1.0×10^{-1} mm/s in a stepwise fashion using the micrometer controlled by the pulse-controller for frictional force measurements. The lower end of the wire was free. The bracket was ligated at approximately one-third of the wire length from the lower end of the wire.

The force generated by the testing unit, consisting of a wire, bracket, and elastic module, was measured with the strain gauge and recorded graphically on a X-Y recorder (NEC San-ei, Tokyo, Japan). The strain gauge load cell was calibrated using 100- and 500-g weights. We used these calibrations as the formula to calculate the frictional forces. The frictional forces were measured at 0.3, 0.6, 0.9, 1.2, and 1.5 mm of wire displacement during experiments and were then averaged. For the 0.016 × 0.022-inch SS wire at a speed of 5.0×10^{-7} mm/s, the wire was pulled upward 0.9 mm because of the extremely long measurement duration of the run. For the measurements of 0.016 × 0.022-inch SS wires, the frictional forces were measured at 0.1-mm intervals from 0.1 to 0.9 mm of wire displacement during experiments and were then averaged. The measurements were conducted 10 times with new wires and modules using the same bracket on each wire type. The different bracket was used for each wire type to prevent distortion and wear of the wire.[17] The mean values and standard deviations (SDs) were calculated using these 10 frictional force measurements.

Statistical Analysis

The Kolmogorov-Smirnov test showed normality of distribution for the measurements used in the study. Parametric statistics (analysis of variance with Tukey-Kramer post hoc tests) was used to compare the mean differences of each testing measurement among different sliding velocities with the same materials or among different wire shapes or materials with the same sliding velocities. The minimum level of statistical significance was set at $P < .05$.

RESULTS

The trends of mean frictional forces corresponding to each pulling distance are also shown in Figure 2. The frictional forces tended to increase from 0 to

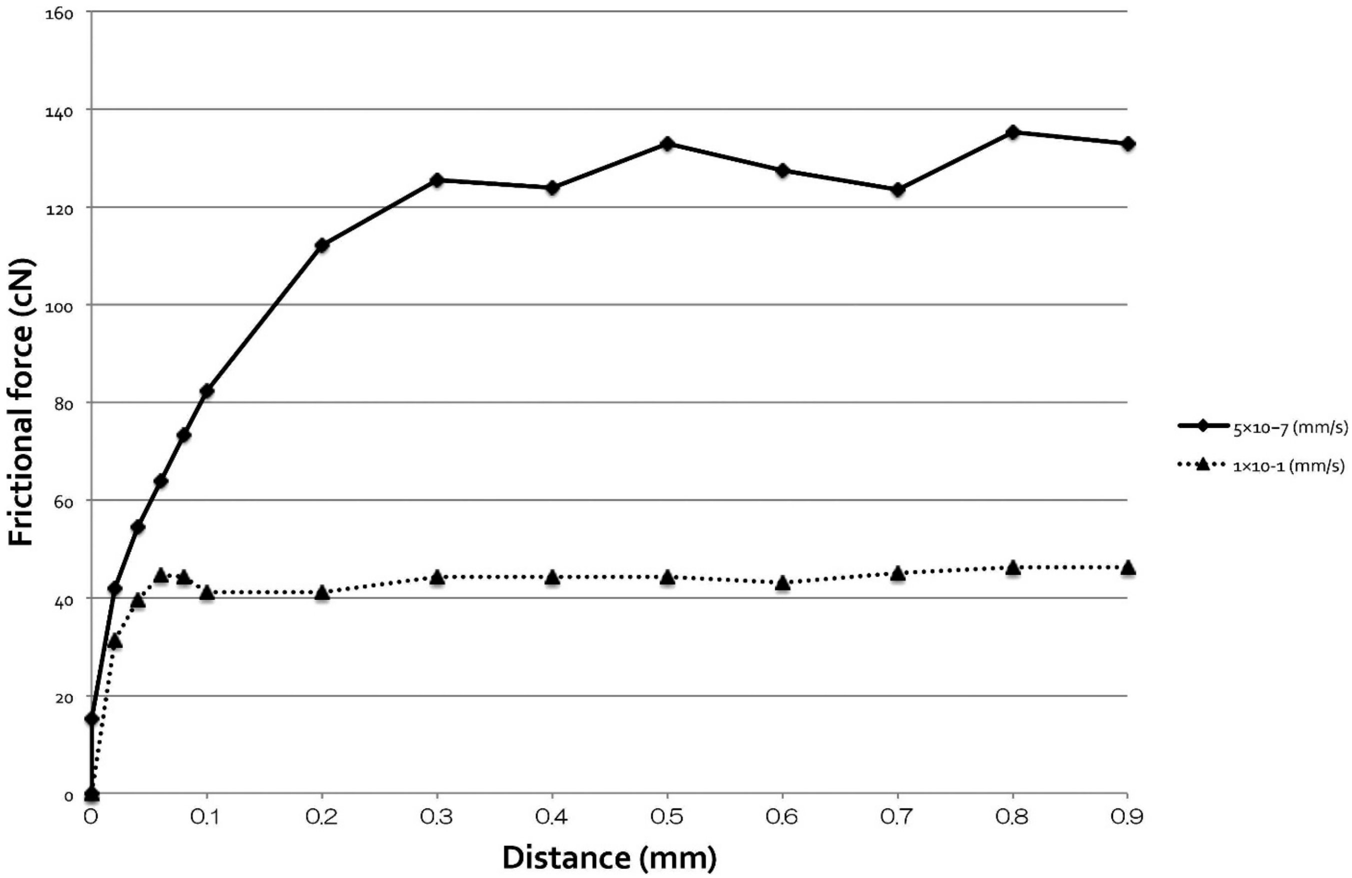

Figure 3. The typical changes of frictional forces of 0.016 × 0.022-inch stainless-steel wires at 1.0×10^{-1} and 5.0×10^{-7} mm/s velocities.

0.5 mm of pulling distance and thereafter remained the same for each of the sliding velocities.

The typical changes of frictional forces of 0.016 × 0.022-inch SS wires at 1.0×10^{-1} and 5.0×10^{-7} mm/s velocity are shown in Figure 3, in which the detailed changes of the frictional forces were demonstrated by means of dividing 0.1-mm wire displacement from 0 to 0.1 mm into six intervals. Although a definite transition from static frictional resistance to kinetic frictional resistance was indicated at measurements of 1.0×10^{-1} mm/s velocity, we did not distinguish the characteristic transition of those phases at measurements of 5.0×10^{-7} mm/s velocity. The mean values and SDs of the frictional forces produced by different sliding velocities in 0.016 × 0.022-inch SS wires are shown in Figure 4. The frictional forces tended to increase as the sliding velocity decreased. Although no significant difference was shown in frictional forces between 5.0×10^{-7} and 1.0×10^{-5} mm/s sliding velocities, the mean frictional force with 5.0×10^{-7} mm/s sliding velocity was significantly larger than at 1.0×10^{-4} mm/s and other, faster velocities. The mean frictional force for 5.0×10^{-7} mm/s sliding velocity was 106.8 cN, almost double that at 1.0×10^{-1} mm/s sliding velocity.

The mean values and SDs of the frictional forces produced by different sliding velocities with 0.016-inch SS wires are shown in Figure 5. The frictional forces tended to increase as the sliding velocity decreased. Although no significant difference was shown in frictional forces between 1.0×10^{-5} and 1.0×10^{-4} mm/s sliding velocities, the mean frictional force of 1.0×10^{-5} mm/s sliding velocity was significantly larger than at 1.0×10^{-3} mm/s and other, faster velocities. The mean frictional force for 1.0×10^{-5} mm/s sliding velocity was 88.0 cN, almost double that at 1.0×10^{-1} mm/s sliding velocity.

The mean values and SDs of the frictional forces produced by different sliding velocities with superelastic 0.016 × 0.022-inch Ni-Ti wires are shown in Figure 6. The mean frictional force of 1.0×10^{-5} mm/s sliding velocity was significantly larger than that at 1.0×10^{-4} mm/s and other, faster velocities. The mean frictional force at 1.0×10^{-5} mm/s sliding velocity was 88.4 cN, almost double that at 1.0×10^{-1} mm/s sliding velocity.

The comparisons of the mean differences of frictional forces among different wire shapes or materials at the same sliding velocities are shown in Table 1. No significant difference was shown at 1.0×10^{-5} mm/s sliding velocity; however, at higher sliding velocities of

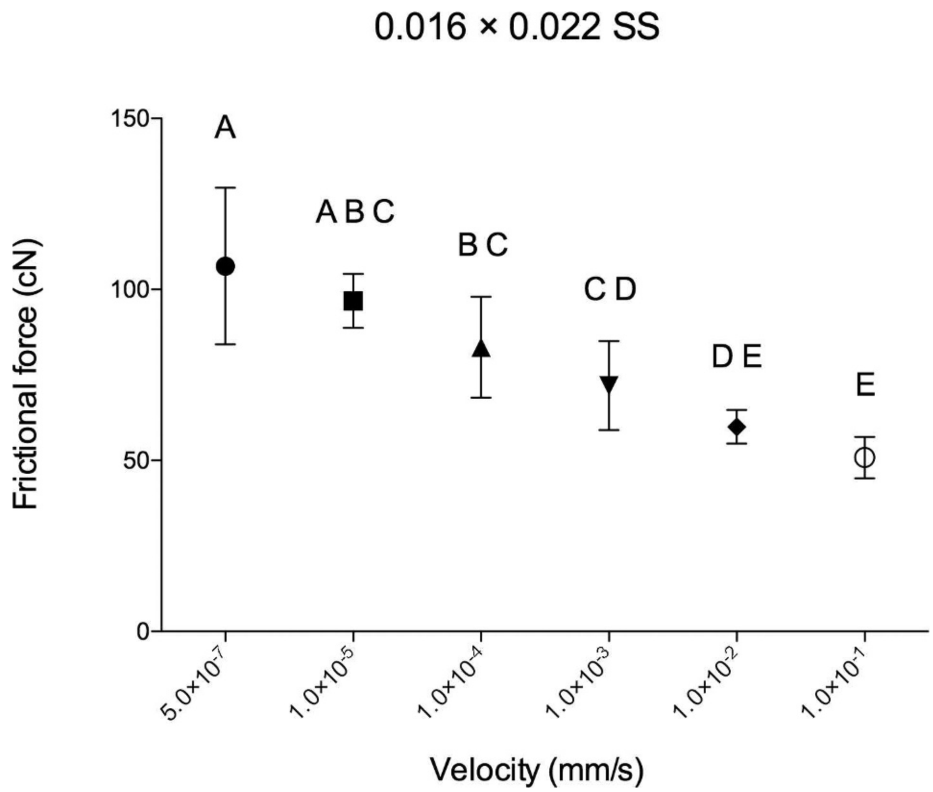

Figure 4. Means and standard deviations of the frictional forces produced by different sliding velocities in 0.016 × 0.022-inch stainless-steel (SS) wires. Tukey test results: different letters represent statistically significant differences at $P < .05$.

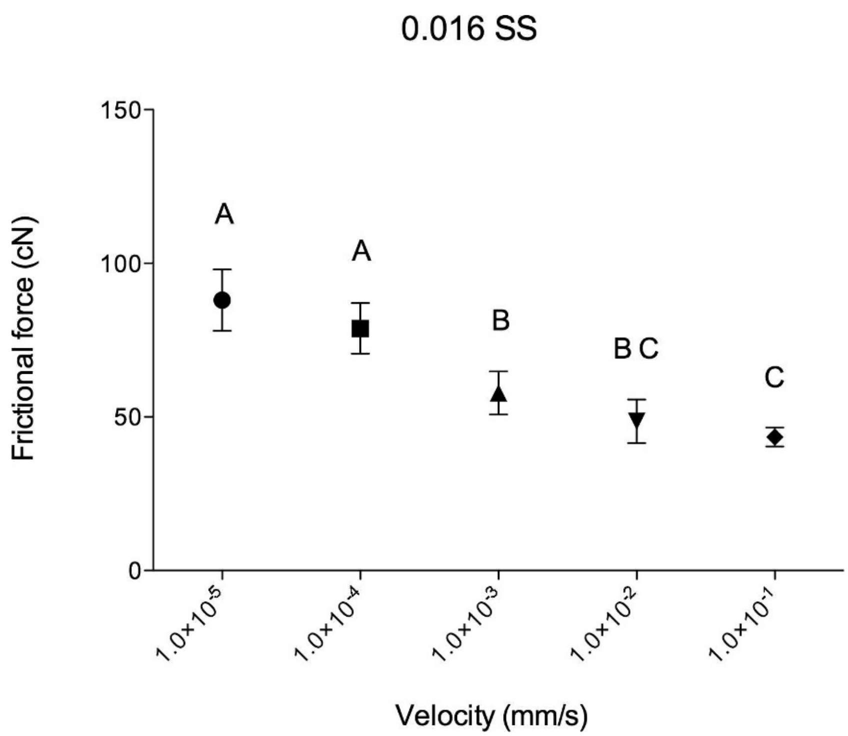

Figure 5. Means and standard deviations of the frictional forces produced by different sliding velocities in 0.016-inch stainless-steel (SS) wires. Tukey test results: different letters represent statistically significant differences at $P < .05$.

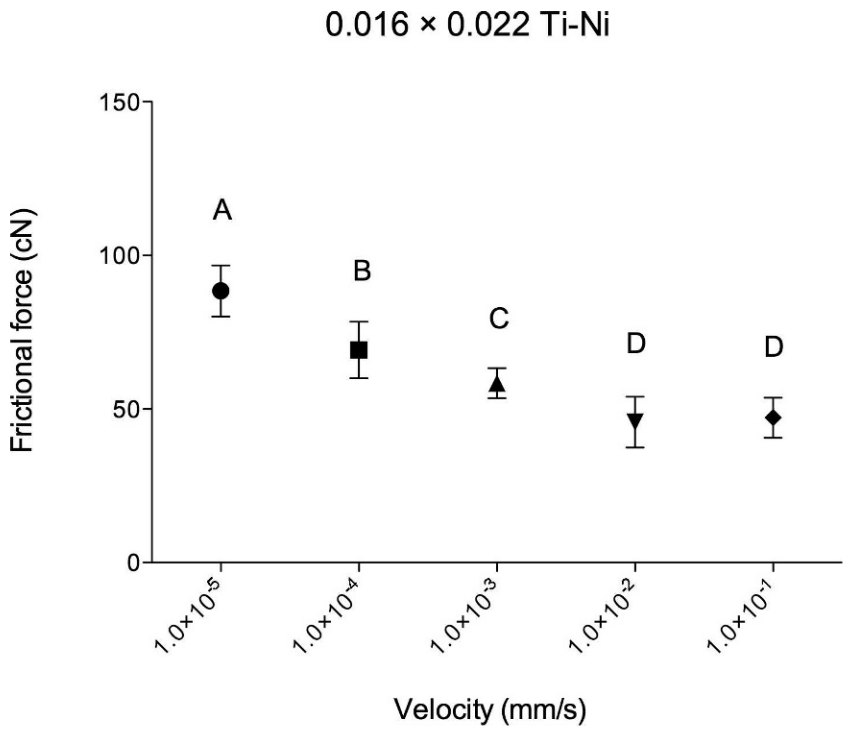

Figure 6. Means and standard deviations of the frictional forces produced by different sliding velocities in 0.016 × 0.022-inch nickel-titanium (Ni-Ti) wires. Tukey test results: different letters represent statistically significant differences at $P < .05$.

greater than 1.0×10^{-4} mm/s, the frictional forces of 0.016 × 0.022-inch SS wires were significantly larger than those of 0.016-inch SS wires or those of 0.016 × 0.022-inch Ni-Ti wires.

DISCUSSION

The main findings of this study are (1) the frictional forces between SS brackets and wires increased with the decrease of sliding velocity, and (2) the frictional forces tended to increase from 0 to 0.5 mm of pulling distance with increasing contact time between rubber and metal, particularly at low sliding velocities. No definite transition from static frictional resistance to kinetic frictional resistance was found with a velocity of 5.0×10^{-7} mm/s. These low sliding velocities would be closer to the clinical situation in orthodontic tooth movement. In this extremely low sliding velocity, we found no distinct larger static frictional resistance other than the kinetic frictional resistance. The frictional force after 0.2-mm traction maintained at approximately 100 cN at a velocity of 5.0×10^{-7} mm/s. These results implied that approximately 50% applied force was consumed by frictional resistance when the clinicians applied 200 g for canine retraction. Our results suggest that in the sliding mechanics, more than half of the applied force was not applied to the tooth movement but rather to the frictional forces. In fact, Iwasaki et al.[18] suggest that using vertical loop mechanics, the canine retraction of 1.27 mm/mo was achieved only with 60 g average retraction force. When clinicians use sliding mechanics in orthodontic tooth movement, it is very important to note the large amount of frictional force between the wire and

Table 1. Comparisons of the Mean Differences of Frictional Forces (cN) Among the Different Wire Shapes or Materials[a]

	0.016-inch SS		0.016 × 0.022-inch SS		0.016 × 0.022-inch Ni-Ti		
Velocity (mm/s)	Mean	SD	Mean	SD	Mean	SD	*P*-Value
5.0×10^{-7}	106.8	22.9					
1.0×10^{-5}	88.0	9.9	96.7	7.9	88.4	8.4	NS
1.0×10^{-4}	78.8	8.2	83.1	14.8	69.3	9.2	B
1.0×10^{-3}	57.8	6.9	71.9	13.0	58.4	4.9	A, B
1.0×10^{-2}	48.6	7.1	59.8	4.9	45.7	8.2	A, B
1.0×10^{-1}	43.5	3.1	50.9	6.1	47.2	6.5	A

[a] SS indicates stainless steel; Ni-Ti, nickel-titanium; SD, standard deviation; NS, not significant; A, significant between 0.016-inch SS and 0.016 × 0.022-inch SS; and B, significant between 0.016 × 0.022-inch SS and 0.016 × 0.022-inch Ni-Ti.

bracket tied with elastomeric modules. This study is the first to estimate the frictional forces between SS wires and SS brackets tied with elastomeric modules at extremely low sliding velocity approximating orthodontic tooth movement.

Our results appeared to contradict the Amontons-Coulomb law of friction, that is, the frictional force to the normal force during sliding is a constant, and the coefficient of kinetic friction is independent of relative velocity.[14] Although this law provides a simple phenomenological friction law, the estimates of frictional forces between wires and brackets tied with elastomeric modules are quite complicated and have not been clearly understood. Quoting the study of Baumberger,[19] Rossouw et al.[13] stated that within very low velocity ranges, most materials exhibit increasing coefficients of kinetic friction as the sliding velocity decreases. Kusy and Whitley[1] also reported that the coefficient of friction for cobalt-chromium (Co-Cr) wires increased with decreasing sliding velocity. These results could be explained by the adhesive theory of friction,[20] which gives a frictional force proportional to the real contact area. The real contact area will generally be much less than the apparent contact area, and the real contact area is proportional to the normal force. As the sliding velocity decreases, the shear fracture of the adhesive bridges occurs slowly and leads to an increase of the real contact area. Indeed, Rubinstein et al.[21] proved that 12% reduction in the net contact area signals the transition from static to dynamic friction due to the detachment process. Other possible explanations are the specific experimental system, that is, the frictional forces were measured not only between the wires and brackets but also as the total friction tied with the elastomeric modules. The elastomeric modules tend to stick to the wires and brackets, and the shear stress at the interface increases continuously with time.[22,23] In studies[24,25] of friction between rubber and rigid surfaces it has been found that the level of adhesion and friction rises over time for joined surfaces.

The brackets were configured passive to the wires in this study. Therefore, the materials composing the archwire and bracket would determine the coefficient of friction. In addition, in this wire-bracket configuration, the frictional forces relate to the ligation force. Straight-line traction might not simulate the clinical situation in which the actual bracket is tipped to and fro. In our study, however, we focused on evaluating the effects of extremely low sliding velocity approximating orthodontic tooth movement on the friction in vitro study. The results should be interpreted with caution since experimental conditions do not always accurately represent the clinical situation.

On the other hand, frictional resistance increases as the archwire shape enlarges from round to square to rectangular.[5,26] In the present study, we found that the frictional force of 0.016×0.022-inch SS wires was heavier than that of 0.016-inch SS wires, which is coincident with their findings.[5,26] It could be considered that the force generated by elastomeric modules would be heavier with a larger dimension of wires than with smaller wires, especially at higher pulling velocities. On the other hand, even at the same size, 0.016×0.022-inch SS and Ni-Ti wires had different frictional forces at higher sliding velocities. In a straight-line traction study, frictional resistance is generally ranked in order from lowest to highest friction, increasing with SS, Co-Cr, Ni-Ti, and beta-titanium, respectively, in order of increasing surface roughness[3,27–29]; however, surface roughness does not always correlate with frictional forces,[6,30] and surface chemistry and chemical affinity could play a significant role.[3] Vaughan et al.[8] reported that 0.016×0.022-inch Ni-Ti wires generated less friction than did the same-sized SS wires in sintered SS brackets ligated with polyurethane ligatures. Thus, it could be considered that the difference found in the frictional force in the present study was caused by the chemical surface properties of the wires tied with the elastomeric modules.

Interestingly, in the present study there was no significant difference between the different wire shapes and properties at 1.0×10^{-5} mm/s sliding velocity, in contrast to the other findings. Further investigations are required to explore frictional properties in orthodontic treatment in an extremely low velocity range, which is used in clinical orthodontics.

CONCLUSIONS

- We found that the frictional forces tended to increase as the sliding velocity decreased, and Coulomb's friction law was not applicable at an extremely low sliding velocity.
- These results suggest that the frictional forces between wires and brackets tied with the elastomeric modules would have a significant effect on tooth movement in clinical orthodontics.

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