Original Article

In vitro evaluation of frictional force of a novel elastic bendable orthodontic wire

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ABSTRACT

Objectives: To determine the frictional force (FF) of the novel, elastic, bendable titanium-niobium (Ti-Nb) alloy orthodontic wire in stainless steel (SS) brackets and to compare it with those of titanium-nickel (Ti-Ni) and titanium-molybdenum (Ti-Mo) alloy wires.

Materials and Methods: Three sizes of Ti-Nb, Ti-Ni, and Ti-Mo alloy wires were ligated with elastic modules to 0.018-inch and 0.022-inch SS brackets. The dynamic FFs between the orthodontic wires and SS brackets were measured at three bracket-wire angles (0°, 5°, and 10°) with an Instron 5567 loading apparatus (Canton, Mass).

Results: FFs increased gradually with the angle and wire size. In the 0.018-inch-slot bracket, the dynamic FFs of Ti-Nb and Ti-Ni alloy wires were almost the same, and those of the Ti-Mo alloy wire were significantly greater ($P<0.05$). FF values were 1.5–2 times greater in the 0.022-inch-slot bracket than in the 0.018-inch-slot bracket, regardless of alloy wire type, and the Ti-Mo alloy wire showed the greatest FF. Scanning electric microscopic images showed that the surface of the Ti-Mo alloy wire was much rougher than that of the Ti-Ni and Ti-Nb alloy wires.

Conclusion: These findings demonstrate that the Ti-Nb alloy wire has almost the same frictional resistance as the Ti-Ni alloy wire, although it has a higher elastic modulus. (*Angle Orthod.* 2018;88:602–610.)

KEY WORDS: Frictional coefficient; Orthodontic wire; Ti-Nb alloy wire; Bendable wire; Dynamic frictional force

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INTRODUCTION

Several different alloy wires have been developed and used for orthodontic treatment, depending on the clinical purpose. Titanium-nickel (Ti-Ni) alloy wires are used most commonly for leveling and alignment because of their superelasticity and excellent spring-back characteristics.[1] However, these wires do not have suitable properties for loop bending or torque application. Titanium-molybdenum (Ti-Mo) alloy wires were originally developed as bendable elastic wires for patients with Ni allergy.[2] Their characteristics fall between those of Ti-Ni wires and stainless steel (SS) wires; they provide a combination of adequate bendability, average stiffness, and ideal formability, which means that they are not suitable for initial leveling, finishing, or detailing of treatment.[3,4]

Recently, superelastic alloys with useful characteristics have been developed.[5–8] These alloys are divided into types IVa and Va. Both types contain oxygen. Their composition is Ti 23, Nb 0.7, Ta 2, Zr O (mole percentage [mol%]), and each alloy has a cubic crystal structure, leading to super elasticity and enhanced

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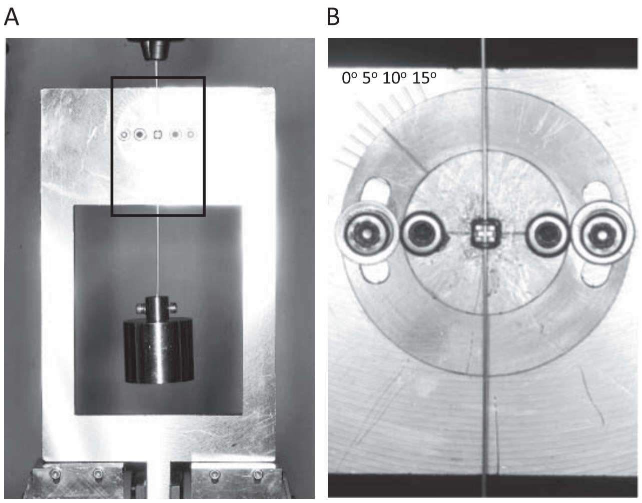

Figure 1. The testing machine, bracket-wire assembly, and force-measuring equipment. (A) Rotation fixture. (B) Inner aluminum block. (C) Outer aluminum block. (D) Anterior-posterior adjustable block. (E) Weight (150 g). (F) Horizontal adjustable joint. (G) Anterior-posterior adjusting handle.[11]

stiffness.[5,6] This alloy contains niobium (Nb) but not Ni. Ni allergy is the most common allergy, documented in up to 17% of women and 3% of men.[6] Cobalt and chromium allergies follow, with 1%–9% of populations having allergic responses.[6] In contrast, no clinical symptom of Nb allergy has been reported. Thus, this novel Ti-Nb alloy wire is suitable for use as an orthodontic wire. Recently, it has been marketed for use during orthodontic treatment (Gummetal; RMMC Inc, Tokyo, Japan).

We previously determined that the torque moment delivered by Ti-Nb alloy wire was smaller than that delivered by Ti-Mo and Ti-Ni alloy wires at $>20°$ applied torque.[7] Torque expression can be achieved by filling the bracket slot, and the torque built into the bracket depends not only on the play between the wire and bracket slot but also on the physical characteristics of the wire material. Frictional resistance has also been found to be influenced by the physical characteristics of the materials, such as surface roughness, hardness, yield strength, and elastic modulus.[9,10] However, the frictional force (FF) is not related directly to the torque moment, and information about the level of friction resistance of the Ti-Nb alloy wire during orthodontic tooth movement is lacking. Thus, the objective of this study was to investigate the effects of wire size and alloy type on the frictional resistance generated between the bracket and wire during in vitro translator displacement of the bracket relative to the wire.

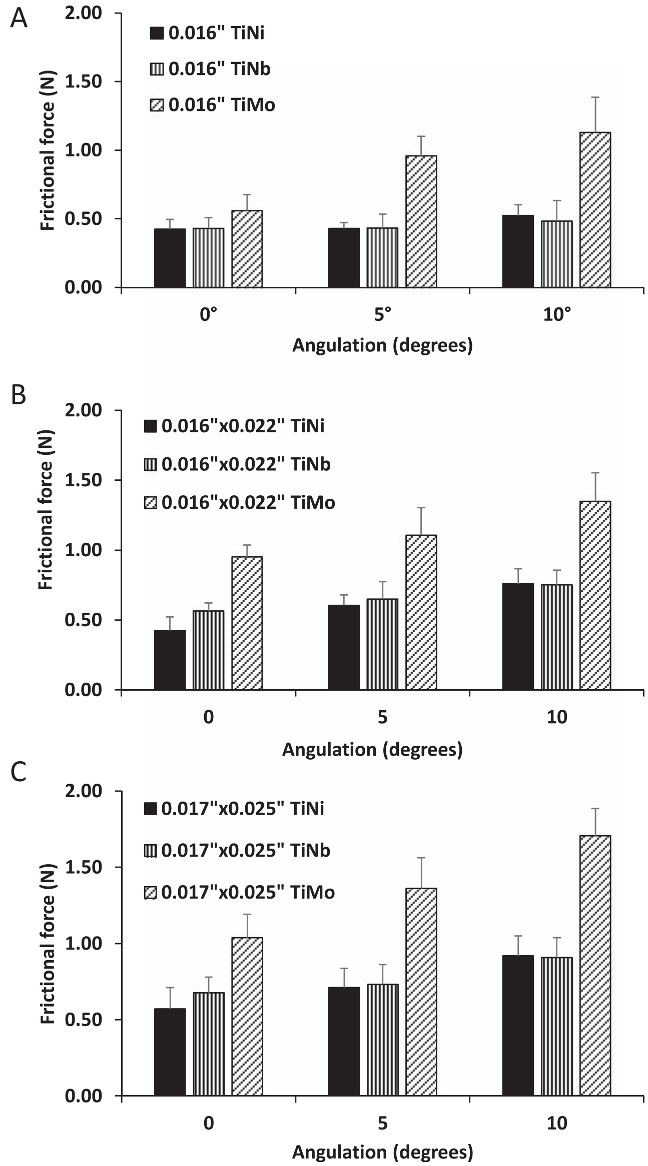

Figure 2. Frictional forces produced by orthodontic alloy wires in the 0.018-inch-slot bracket. (A) A 0.016-inch round wire, (B) 0.016 × 0.022-inch rectangular wire, (C) 0.017 × 0.025-inch rectangular wire (n = 15 per group).

MATERIALS AND METHODS

Two standard edgewise SS brackets (declared slot sizes of 0.018 × 0.025 inch [0.018-inch slot] and 0.022 × 0.028 inch [0.022-inch slot], respectively) for the maxillary central incisor (width, 0.13 inch; Tomy International Co Ltd, Tokyo, Japan) were used in this study. Three types of Ti alloy wire were used: Ti-Ni alloy wire (Tinilloy; Dentsply-Sirona, Tokyo, Japan), Ti-Mo alloy wire (TMA; Ormco Co, Glendora, Calif), and Ti-Nb alloy wire (Gummetal; RMMC Inc). The wire sizes tested in the 0.018-inch slot brackets were 0.016-inch round wire and 0.016 × 0.022-inch and 0.017 × 0.025-inch rectangular wires; those tested in the 0.022-inch slot brackets were 0.018-inch round wire and 0.017 × 0.025-inch and 0.019 × 0.025-inch rectangular

Table 1. Frictional Force Means and Standard Deviations (SD)[a]

Bracket Slot	Wire	0°		5°		10°	
		Mean	SD	Mean	SD	Mean	SD
0.018-inch slot	0.016-inch TiNi	0.426	0.070	0.430	0.044	0.525	0.077
	0.016-inch TiNb	0.431	0.077	0.433	0.101	0.484	0.150
	0.016-inch TiMo	0.560	0.116	0.958	0.143	1.130	0.256
	0.016 × 0.022-inch TiNi	0.426	0.098	0.605	0.075	0.759	0.108
	0.016 × 0.022-inch TiNb	0.565	0.057	0.650	0.124	0.753	0.105
	0.016 × 0.022-inch TiMo	0.950	0.086	1.106	0.198	1.348	0.205
	0.017 × 0.025-inch TiNi	0.571	0.140	0.710	0.128	0.919	0.132
	0.017 × 0.025-inch TiNb	0.677	0.102	0.732	0.129	0.907	0.130
	0.017 × 0.025-inch TiMo	1.038	0.153	1.360	0.203	1.705	0.179
0.022-inch slot	0.018-inch TiNi	0.382	0.083	0.537	0.059	0.542	0.072
	0.018-inch TiNb	0.492	0.049	0.505	0.050	0.534	0.053
	0.018-inch TiMo	0.665	0.066	0.750	0.075	1.194	0.099
	0.017 × 0.025-inch TiNi	0.451	0.096	0.656	0.176	0.813	0.161
	0.017 × 0.025-inch TiNb	0.527	0.155	0.739	0.145	0.843	0.170
	0.017 × 0.025-inch TiMo	0.735	0.172	1.235	0.126	1.540	0.119
	0.019 × 0.025-inch TiNb	0.625	0.075	0.665	0.094	0.798	0.093
	0.019 × 0.025-inch TiNb	0.682	0.052	0.693	0.247	0.818	0.037
	0.019 × 0.025-inch TiMo	0.999	0.158	1.346	0.274	1.832	0.271

[a] n = 15; unit: N.

Table 2. Comparison of Statistical Analysis of Frictional Force Between TiNi, TiNb, and TiMo Alloy Wires[a]

	0.016-inch TiNi			0.016 × 0.022-inch TiNi			0.017 × 0.025-inch TiNi			0.016-inch TiNb			0.016 × 0.022-inch TiNb		
	0°	5°	10°	0°	5°	10°	0°	5°	10°	0°	5°	10°	0°	5°	10°
0.016-inch TiNi															
0°	—	NS	NS	NS	NS	*	NS	NS	*	NS	NS	*	NS	*	*
5°	NS	—	*	*	NS	*	*	NS	*	NS	*	*	*	*	*
10°	NS	*	—	NS	*	*	NS	NS	*	NS	NS	*	NS	NS	*
0.016 × 0.022-inch TiNi															
0°	NS	*	NS	—	NS	*	NS	NS	*	NS	NS	*	NS	NS	*
5°	NS	NS	NS	NS	—	*	*	NS	*	NS	*	*	*	*	*
10°	*	*	*	*	*	—	*	*	NS	*	*	NS	*	*	NS
0.017 × 0.025-inch TiNi															
0°	NS	*	NS	NS	*	*	—	NS	*	NS	NS	*	NS	NS	*
5°	NS	NS	NS	NS	NS	*	NS	—	*	NS	*	*	*	*	*
10°	*	*	*	*	*	NS	*	*	—	*	*	NS	*	*	NS
0.016-inch TiNb															
0°	NS	NS	NS	NS	NS	*	NS	NS	*	—	NS	*	NS	*	*
5°	NS	*	NS	NS	*	*	NS	*	*	NS	—	*	NS	NS	*
10°	*	*	*	*	*	NS	NS	*	NS	NS	NS	—	NS	*	NS
0.016 × 0.022-inch TiNb															
0°	NS	*	NS	NS	*	*	NS	*	*	NS	NS	*	—	NS	*
5°	*	*	NS	NS	*	*	NS	*	*	*	NS	*	NS	—	*
10°	*	*	*	*	*	NS	*	*	NS	*	*	NS	*	*	—
0.017 × 0.025-inch TiNb															
0°	*	*	*	*	*	*	*	*	*	*	*	*	NS	NS	*
5°	*	*	*	*	*	*	*	*	*	*	*	*	NS	NS	*
10°	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
0.016-inch TiMo															
0°	NS	*	NS	NS	*	*	NS	*	*	NS	NS	*	NS	NS	*
5°	*	*	NS	NS	*	*	NS	*	*	*	NS	*	NS	NS	*
10°	*	*	*	*	*	NS	*	*	NS	*	*	NS	*	*	NS
0.016 × 0.022-inch TiMo															
0°	*	*	NS	*	*	*	*	*	*	*	NS	*	NS	NS	*
5°	*	*	NS	*	*	*	*	*	*	*	NS	*	NS	NS	*
10°	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
0.017 × 0.025-inch TiMo															
0°	*	*	*	*	*	NS	*	*	*	*	*	NS	*	*	*
5°	*	*	*	*	*	NS	*	*	*	*	*	NS	*	*	*
10°	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

[a] n = 15. NS indicates nonsignificant; * $P<0.05$.

wires. Three sizes of Ti-Nb, Ti-Ni, and Ti-Mo alloy wire and SS brackets with 0.018-inch and 0.022-inch slots were ligated with elastic modules. These three repeated evaluations for each bracket-wire combination were carried out at angulations of 0°, 5°, and 10°. The measurement condition was 37°C, as the simulated human oral temperature.

The angles between the bracket and wire were regulated using the modified method reported by Redlich et al.[11] The outer blocks were designed to fit the three angulations of each block. Each bracket was bonded with a cyanoacrylate adhesive (Aron Alpha; Toagosei Company, Tokyo, Japan) to an inner aluminum plate with a custom-made bracket-mounting apparatus (Figure 1), which enabled accurate placement of all brackets in similar positions. Then, each bracket was connected to an Instron 5567 testing machine (Canton, Mass). A 10-cm wire was tied to the bracket by elastomeric ligation. The upper end of the wire was connected to the tension-loading cell of a testing machine with a range of up to 1 KgN and was pulled through to a length of 5 mm at a crosshead speed of 10 mm/min. The lower end of the wire was fixed to a 150-g weight. The static FF was recorded as the maximum force exerted before the wire was pulled out of the bracket, and the dynamic FF was calculated by averaging the FF after measuring the static FF.

The surface topography and morphology of the archwires were evaluated by scanning electron microscopy (SEM; JEOL JSM 6400; Jeol Ltd, Tokyo, Japan). All wires were washed, fixed with 2% glutaraldehyde, post fixed with 1% osmic acid, and dehydrated through a graded series of ethanol solutions. After dehydration, the specimens were treated with t-butylalcohol and spattered with gold. The measurement of torque moment was performed 15 times for each bracket-wire combination and each angulation. The data were analyzed using the Statis-

Table 2. Extended

	0.017 × 0.025-inch TiNb			0.016-inch TiMo			0.016 × 0.022-inch TiMo			0.017 × 0.025-inch TiMo		
	0°	5°	10°	0°	5°	10°	0°	5°	10°	0°	5°	10°
0.016-inch TiNi												
	*	*	*	NS	*	*	*	*	*	*	*	*
	*	*	*	*	*	*	*	*	*	*	*	*
	*	*	*	NS	NS	*	NS	NS	*	*	*	*
0.016 × 0.022-inch TiNi												
	*	*	*	NS	NS	*	*	*	*	*	*	*
	*	*	*	*	*	*	*	*	*	*	*	*
	*	*	*	*	*	NS	*	*	*	NS	NS	*
0.017 × 0.025-inch TiNi												
	*	*	*	NS	NS	*	*	*	*	*	*	*
	*	*	*	*	*	*	*	*	*	*	*	*
	*	*	*	*	*	NS	*	*	*	*	*	*
0.016-inch TiNb												
	*	*	*	NS	*	*	*	*	*	*	*	*
	*	*	*	NS	NS	*	NS	NS	*	*	*	*
	*	*	*	*	*	NS	*	*	*	NS	NS	*
0.016 × 0.022-inch TiNb												
	NS	NS	*	NS	NS	*	NS	NS	*	*	*	*
	NS	NS	*	NS	NS	*	NS	NS	*	*	*	*
	*	*	*	*	*	NS	*	*	*	*	*	*
0.017 × 0.025-inch TiNb												
	—	NS	*	*	NS	*	NS	NS	*	NS	NS	*
	NS	—	*	*	NS	*	NS	NS	*	NS	NS	*
	*	*	—	*	*	*	*	*	NS	*	*	*
0.016-inch TiMo												
	*	*	*	—	NS	*	NS	NS	*	*	*	*
	NS	NS	*	NS	—	*	NS	NS	*	*	*	*
	*	*	*	*	*	—	*	*	*	NS	NS	*
0.016 × 0.022-inch TiMo												
	NS	NS	*	NS	NS	*	—	NS	*	*	*	*
	NS	NS	*	NS	NS	*	NS	—	*	*	NS	*
	*	*	NS	*	*	*	*	*	—	*	*	*
0.017 × 0.025-inch TiMo												
	NS	NS	*	*	*	NS	*	*	*	—	NS	*
	NS	NS	*	*	*	NS	*	NS	*	NS	—	*
	*	*	*	*	*	*	*	*	*	*	*	—

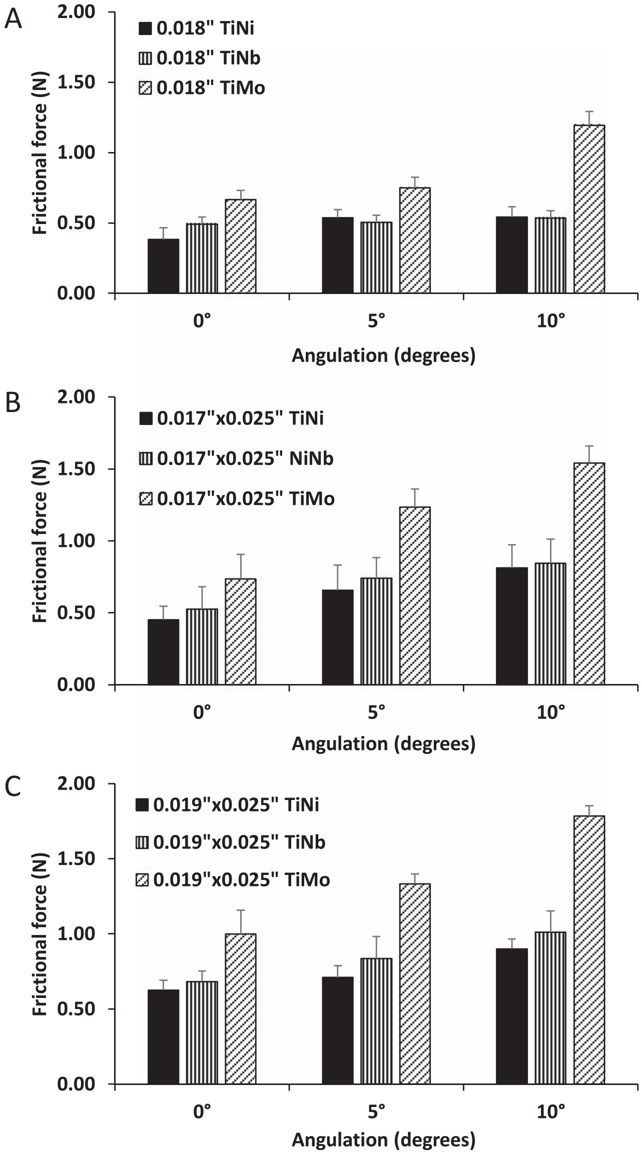

Figure 3. Frictional forces produced by orthodontic alloy wires in the 0.022-inch-slot bracket. (A) A 0.018-inch round wire, (B) 0.017 × 0.025-inch rectangular wire, (C) 0.019 × 0.025-inch rectangular wire (n = 15 per group).

tical Package for Social Sciences (version 8.0 for Windows; SPSS Japan Inc, Tokyo, Japan). Statistical analysis comparing each group was performed using multiple comparison tests of analysis of variance and, thereafter, Tukey's honestly significant difference test post hoc. $P<0.05$ was considered statistically significant.

RESULTS

Figure 2, Table 1, and Table 2 show the effect of wire alloy on bracket-wire friction in the 0.018 × 0.025-inch-slot bracket. In all bracket-wire combinations, the Ti-Mo alloy wire produced the highest level of friction, followed by the Ti-Nb and Ti-Ni alloy wires. Except for 0.016-inch round wires at 0° angulation, the FFs produced by the Ti-Mo alloy wire were significantly greater than those produced by the Ti-Nb and Ti-Ni alloy wires ($P<0.05$; Figure 2; Tables 1 and 2). The FFs produced by the Ti-Ni and Ti-Nb alloy wires were similar. The FFs produced by the 0.017 × 0.025-inch wires were greater than those produced by the 0.016-inch and 0.016 × 0.022-inch wires. Furthermore, the FFs in all bracket-wire combinations increased with angulation. The Ti-Mo alloy wires showed the greatest increase in FF, by 1.3- to 2.2-fold from 0° to 10°.

Figure 3, Table 1, and Table 3 show the effect of wire alloy on bracket-wire friction in the 0.022 × 0.028-inch-slot bracket. The effect of bracket slot size on the FF generated was not significant. At 0° angulation, the FF did not differ significantly among the three alloy wires. However, the Ti-Mo alloy wire produced more friction than the Ti-Nb and Ti-Ni alloy wires in all bracket-wire combinations. Furthermore, the FFs increased with angulation, regardless of wire size or material. The FFs produced by the 0.018-inch and 0.017 × 0.025-inch wires were slightly less than those produced by the 0.016-inch and 0.016 × 0.022-inch wires in the 0.018-inch-slot brackets. The FFs generated by the 0.019 × 0.025-inch wires in the 0.022-inch-slot brackets were greater than those produced by 0.017 × 0.025-inch wires in the 0.018-inch-slot brackets.

The FFs produced by the 0.017 × 0.025-inch Ti-Nb and Ti-Mo wires in the 0.018-inch-slot bracket were significantly greater than those produced in the 0.022-inch-slot bracket at 10° (Table 4). Values for the 0.018-inch slot were approximately 1.2-fold greater than those obtained with the 0.022-inch slot when the play between the wire and bracket slot was matched.

Figure 4 shows SEM images of the three 0.017 × 0.025-inch wires in the 0.018-inch slot bracket after the friction test. The surfaces of the Ti-Ni and Ti-Nb alloy wires were smoother than that of the Ti-Mo alloy wire. The surface of the Ti-Mo alloy wire was rough with abundant scratches.

DISCUSSION

Ti-Ni alloy wires were developed in the 1970s,[12,13] and they remain in common use as orthodontic wires for initial leveling and alignment because of their superelasticity, excellent ductility, good fatigue life, low elastic modulus, high spring back, and high weldability compared with conventional SS alloy wires.[14] Titanium is well known for its good mechanical properties, corrosion resistance, and excellent biocompatibility.[1] However, Ti-Ni alloy wire is not suitable for loop bending or torque application. Ti-Mo alloy wires

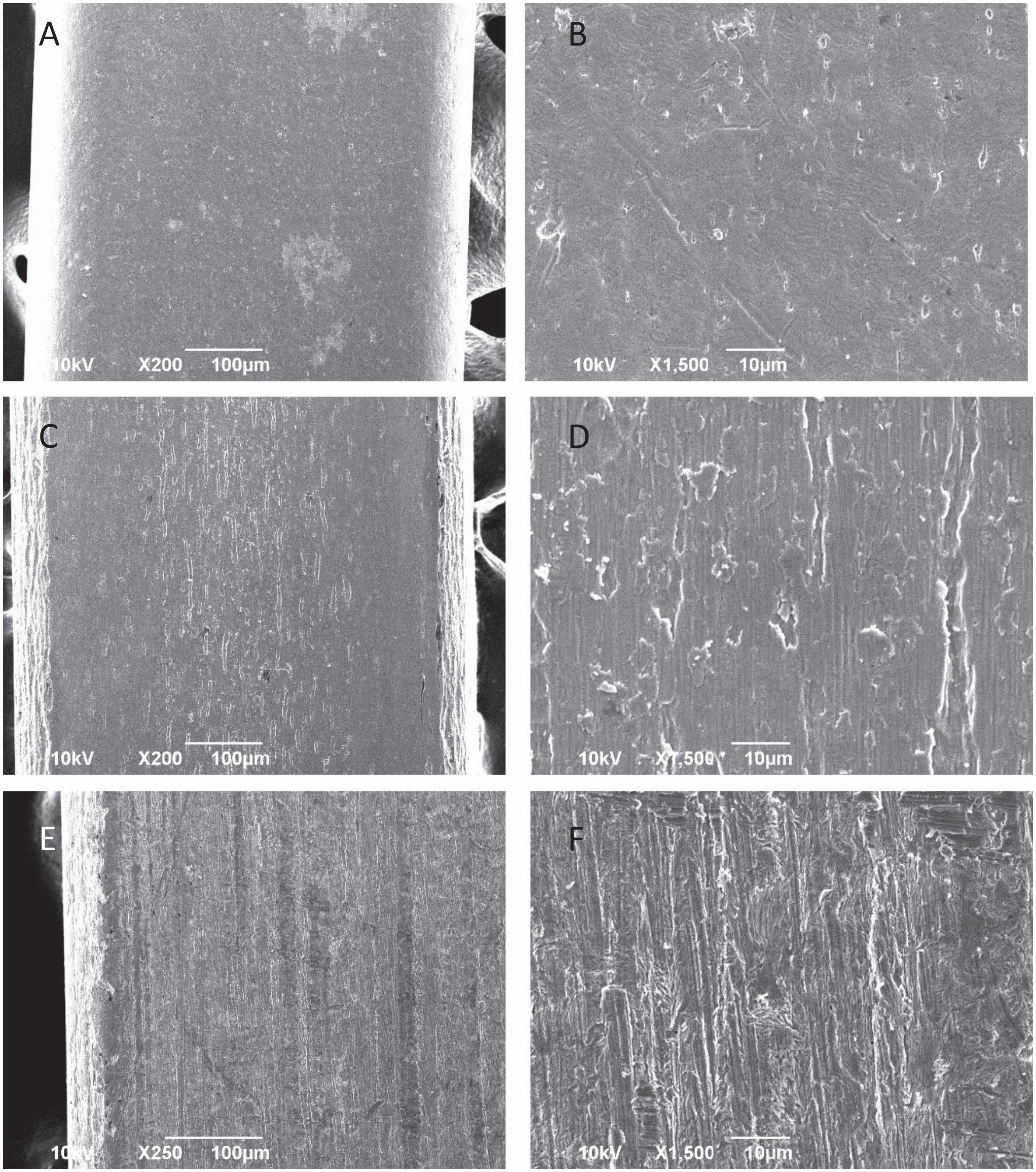

Figure 4. Scanning electron micrographs of orthodontic alloy wires. (A, B) Ti-Ni alloy wire, (C, D) Ti-Nb alloy wire, (E, F) Ti-Mo alloy wire. A, C, E: 250× magnification; B, D, F: 1500× magnification.

Table 3. Comparison of Statistical Analysis of Frictional Force Between TiNi, TiNb, and TiMo Alloy Wires in 0.022-inch Slot[a]

	0.018-inch TiNi			0.017 × 0.025-inch TiNi			0.019 × 0.025-inch TiNi			0.018-inch TiNb			0.017 × 0.025-inch TiNb		
	0°	5°	10°	0°	5°	10°	0°	5°	10°	0°	5°	10°	0°	5°	10°
0.018-inch TiNi															
0°	—	NS	NS	NS	NS	*	NS	NS	*	NS	NS	*	NS	*	*
5°	NS	—	NS	NS	NS	*	NS	NS	*	NS	NS	NS	NS	NS	*
10°	NS	NS	—	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	*
0.017 × 0.025-inch TiNi															
0°	NS	NS	NS	—	NS	NS	NS	NS	*	NS	NS	*	NS	NS	*
5°	NS	NS	NS	NS	—	NS	NS	NS	*	NS	NS	*	NS	NS	*
10°	*	*	NS	NS	NS	—	NS	NS	*	NS	NS	NS	NS	NS	NS
0.019 × 0.025-inch TiNi															
0°	NS	NS	NS	NS	NS	NS	—	NS	*	NS	NS	*	NS	NS	*
5°	NS	NS	NS	NS	NS	NS	NS	—	*	NS	NS	*	NS	NS	*
10°	*	*	*	*	*	*	*	*	—	*	*	*	*	*	NS
0.018-inch TiNb															
0°	NS	NS	NS	NS	NS	NS	NS	NS	*	—	NS	NS	NS	NS	*
5°	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	—	NS	NS	NS	*
10°	*	*	NS	*	*	NS	*	*	*	NS	NS	—	NS	NS	NS
0.017 × 0.025-inch TiNb															
0°	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	—	NS	*
5°	*	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	—	NS
10°	*	*	*	*	*	NS	NS	NS	NS	NS	NS	NS	*	NS	—
0.019 × 0.025-inch TiNb															
0°	*	*	NS	*	*	NS	*	*	*	NS	NS	NS	NS	NS	NS
5°	*	*	NS	*	*	NS	*	*	*	NS	NS	NS	NS	NS	NS
10°	*	*	*	*	*	NS	*	*	NS	*	*	NS	*	*	NS
0.018-inch TiMo															
0°	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	*
5°	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	*
10°	*	*	*	*	*	NS	*	*	NS	*	*	NS	*	*	NS
0.017 × 0.025-inch TiMo															
0°	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	*
5°	*	*		*	*	NS	*	*	*	NS	NS	NS	NS	NS	NS
10°	*	*	*	*	*	*	*	*	NS	*	*	*	*	*	*
0.019 × 0.025-inch TiMo															
0°	*	*		*	*	NS	*	*	*	*	NS	NS	NS	NS	NS
5°	*	*	*	*	*	*	*	*		*	*	NS	*	*	NS
10°	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

[a] n = 15. NS indicates nonsignificant; * $P<0.05$.

were developed as bendable elastic wires; they provide a combination of adequate spring back, average stiffness, and good formability compared with Ti-Ni alloy wires. However, the surface of the Ti-Mo alloy wire was found to be rough, and this wire exhibited very high friction values at the archwire-bracket interface compared with SS wire.[15] Therefore, a novel orthodontic alloy wire that is elastic and has a smooth surface and less frictional resistance has been desired in clinical orthodontics.

For efficient tooth movement in the presence of bracket-wire friction, the total force applied to the tooth is determined by the optimal force necessary to move the tooth and the magnitude of friction.[16] As the magnitude of frictional resistance depends on the bracket-wire combination, the amount of force required to overcome friction also depends on the bracket-wire combination used. Especially when using sliding mechanics, the frictional resistance of an orthodontic wire is an important counterbalancing element to tooth movement, and it must be controlled to allow the application of light continuous forces. In vivo, the FF of an archwire-bracket system increases with the surface roughness of the archwire. This positive correlation suggests that surface roughness can be used as an evaluation marker, in place of the direct measurement of FF, when estimating the efficiency of orthodontic treatment.[17]

The SEM evaluation showed that the Ti-Ni and Ti-Nb alloy wires had smoother surfaces than the Ti-Mo alloy wire, which had a rough surface with abundant scratches. These results were consistent with those for the FF of the three alloy wires. The FFs of the Ti-Nb alloy wires were very similar to FFs of the Ti-Ni alloy wires, whereas the FFs of the Ti-Mo alloy wires were approximately 1.3- to 2.0-fold greater than those of the Ti-Nb and Ti-Ni alloy wires.

The hardness of alloy wires also affects frictional resistance.[18] Torque moments delivered by various wire-

Table 3. Extended

	0.019 × 0.025-inch TiNb			0.018-inch TiMo			0.017 × 0.025-inch TiMo			0.019 × 0.025-inch TiMo		
	0°	5°	10°	0°	5°	10°	0°	5°	10°	0°	5°	10°
0.018-inch TiNi												
	*	*	*	NS	NS	*	NS	*	*	*	*	*
	*	*	*	NS	NS	*	NS	*	*	*	*	*
	NS	NS	*	NS	NS	*	NS	NS	*	NS	*	*
0.017 × 0.025-inch TiNi												
	*	*	*	NS	NS	*	NS	*	*	*	*	*
	*	*	*	NS	NS	*	NS	*	*	*	*	*
	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	*	*
0.019 × 0.025-inch TiNi												
	*	*	*	NS	NS	*	NS	*	*	*	*	*
	*	*	*	NS	NS	*	NS	*	*	*	*	*
	*	*	NS	*	*	NS	*	*	NS	*	NS	*
0.018-inch TiNb												
	NS	NS	*	NS	NS	*	NS	NS	*	*	*	*
	NS	NS	*	NS	NS	*	NS	NS	*	NS	*	*
	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	*
0.017 × 0.025-inch TiNb												
	NS	NS	*	NS	NS	*	NS	NS	*	NS	*	*
	NS	NS	*	NS	NS	*	NS	NS	*	NS	*	*
	NS	NS	NS	*	*	NS	*	NS	*	NS	NS	*
0.019 × 0.025-inch TiNb												
	—	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	*
	NS	—	NS	NS	NS	NS	NS	NS	NS	NS	NS	*
	NS	NS	—	*	*	NS	*	NS	*	NS	NS	*
0.018-inch TiMo												
	NS	NS	NS	—	NS	*	NS	NS	*	*	*	*
	NS	NS	NS	NS	—	*	NS	NS	*	NS	*	*
	NS	NS	NS	*	*	—	*	NS	*	NS	NS	*
0.017 × 0.025-inch TiMo												
	NS	NS	*	NS	NS	*	—	NS	*	NS	*	*
	NS	NS	NS	NS	NS	NS	NS	—	*	NS	NS	*
	*	*	*	*	*	*	*	*	—	*	*	*
0.019 × 0.025-inch TiMo												
	NS	NS	NS	*	NS	NS	NS	NS	*	—	NS	*
	NS	NS	NS	*	*	NS	NS	NS	*	NS	—	*
	*	*	*	*	*	*	*	*	*	*	*	—

Table 4. Comparison of Statistical Analysis of Frictional Force Between of 0.017 × 0.025-inch Wire in 0.018-inch Slot and 0.022-inch Slot[a]

	0.018-inch Slot								
	TiNi			TiNb			TiMo		
0.022-inch Slot	0°	5°	10°	0°	5°	10°	0°	5°	10°
TiNi									
0°	NS	NS	*	NS	NS	*	*	*	*
5°	NS	NS	*	NS	NS	*	NS	NS	*
10°	NS	NS	NS	NS	NS	*	NS	NS	*
TiNb									
0°	NS	NS	*	NS	NS	*	NS	NS	*
5°	NS	NS	*	NS	NS	*	NS	NS	*
10°	*	*	NS	NS	NS	*	NS	NS	*
TiMo									
0°	NS	NS	NS	NS	NS	*	NS	NS	*
5°	NS	NS	NS	NS	NS	*	NS	NS	*
10°	*	*	NS	*	NS	*	NS	NS	*

[a] n = 15, NS indicates nonsignificant; * $P<0.05$.

bracket combinations were previously measured and showed that those of Ti-Nb wires were smaller than those of Ti-Mo and Ti-Ni wires.[7] This finding implies that Ti-Nb alloy wire has superelasticity and a lower elastic modulus than does Ti-Ni alloy wire. In the present investigation, the FFs observed in 0.018-inch-slot brackets ranged from 0.31 N with 0.016-inch round Ti-Nb wire at 0° angulation to 1.34 N with 0.017 × 0.025-inch rectangular Ti-Mo wire at 10° angulation. Similarly, for 0.022-inch-slot brackets, the FFs ranged from 0.49 N with 0.018-inch round Ti-Nb wire at 0° angulation to 1.16 N with 0.019 × 0.025-inch Ti-Mo wire at 10° angulation. The FFs of Ti-Nb alloy wires were almost the same or slightly greater than those of Ti-Ni alloy wires, regardless of wire and bracket slot sizes or angulation. Taken together, these findings suggest that the frictional resistance of Ti-Nb alloy wire is slightly increased because of its lesser hardness compared with Ti-Ni alloy wire.

In the 0.018-inch-slot bracket, the FFs of the Ti-Nb and Ti-Ni alloy wires were almost the same, regardless of wire size and angulation, although Ti-Nb is stiffer than Ti-Ni. Furthermore, the FFs were approximately 1.2-fold greater with the 0.022-inch-slot brackets than with the 0.018-inch-slot brackets, regardless of alloy wire type. Taken together, these findings suggest that 0.017 × 0.025-inch Ti-Nb alloy wire can be used in an 0.018-inch-slot bracket for canine and en masse retraction. For cases requiring strict torque control during en masse retraction, the use of 0.019 × 0.025-inch Ti-Nb alloy wire in a 0.022-inch-slot bracket may be suitable. Further investigations should be conducted to clarify the advantages and disadvantages of these wire-bracket combinations.

In the present study, the three alloy wires generated greater FFs in the 0.018-inch-slot bracket than in the 0.022-inch-slot bracket. A possible explanation for this difference in frictional resistance was the disparity in wire-bracket slot play. As the heights, widths, and cross sections of rectangular orthodontic wires affect the play between the wires and the bracket slot,[19] the degrees of play of 0.016-inch round and 0.016 × 0.022-inch and 0.017 × 0.025-inch rectangular wires in the 0.018-inch slots can be assumed to be greater than those of 0.018-inch round and 0.017 × 0.025-inch and 0.019 × 0.025-inch rectangular wires in a 0.022-inch slot.

In conclusion, frictional resistance should be investigated in the future to clarify the wire-slot combination for en masse movement or canine retraction in the clinical situation. The novel bendable orthodontic alloy wire that consists of Ti-Nb alloy may be shown to have almost the same characteristics of frictional resistance as Ti-Ni alloy wire with a smooth surface and lower frictional resistance compared with Ti-Mo alloy wire.

CONCLUSION

- The bendable Ti-Nb alloy orthodontic wire has almost the same frictional resistance as the Ti-Ni alloy wire, with a smoother surface and less frictional resistance than the Ti-Mo alloy wire. Orthodontists should be aware of the frictional resistance of wire-bracket combinations to achieve efficient tooth movement with appropriate orthodontic alloy wires as shown in this study.

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