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Effect of the vertical position of the canine on the frictional/orthodontic force ratio of Ni-Ti archwires during the levelling phase of orthodontic treatment

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Abstract: This study investigated the effect of the vertical position of the canine on changes in the frictional/orthodontic (F/O) force ratio of nickel-titanium (Ni-Ti) archwires during the initial levelling phase of orthodontic treatment. Frictional and orthodontic forces were measured by using low-friction brackets and Ni-Ti archwires with three different cross-sectional sizes and force types. To simulate canine malocclusion (first premolar extraction case), the upper right canine was displaced gingivally by 1 to 3 mm and the inter-bracket distance between the upper right lateral incisor and second premolar was set at 15 mm or 20 mm. A three-point bending test was performed to measure the orthodontic force of each Ni-Ti archwire. Frictional forces were measured with a universal testing machine and dental arch models by pulling parallel to the end of the archwire at a crosshead speed of 0.5 mm/min. F/O force ratio was calculated and analysed statistically. At a displacement of 3 mm, few archwires had F/O force ratios of less than 1.0, at which orthodontic force overcame frictional force, thus ensuring extrusion of the canine. For effective tooth movement, orthodontists should use Ni-Ti archwires with an F/O force ratio of less than 1.0.

Keywords: orthodontics; friction; Ni-Ti.

Introduction

During the initial levelling phase of orthodontic treatment, nickel-titanium (Ni-Ti) archwires are commonly used because of their advantageous mechanical properties, including shape memory, excellent springback and superelasticity, high elastic limit, and low elastic modulus (1). These mechanical properties of Ni-Ti archwires allow for application of continuous force, to correct vertical and horizontal displacements of teeth in the dental arch.

Effective tooth movement requires that orthodontic forces applied on a given tooth are sufficient to overcome the frictional force generated at the interface between the bracket slot and archwire. Previous studies have shown that the degree of tooth malalignment can affect the frictional force between the bracket slot and archwire (2-8). Vertical displacement of the upper canine is one of the most common types of vertical displacement in clinical practice (9,10), and extrusion of a high upper canine is

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influenced by friction and factors such as elastic binding and physical notching (2,11,12). When frictional force exceeds the orthodontic force produced by the archwire, a canine is less likely to extrude, but the dental arch will expand since the orthodontic force in the labial direction is applied to all teeth in the arch (7,13). In particular, expansion of the dental arch in cases of extraction leads to teeth jiggling and a need for prolonged treatment (13). However, the effects of the vertical position of the canine on the relationship between the frictional and orthodontic forces generated by Ni-Ti archwires and brackets remain unclear.

To investigate frictional force between archwires and brackets, the experimental conditions should mirror the oral environment during orthodontic treatment (14). Therefore, we constructed a model of the whole dentition and ensured that the archwire could slide through the brackets and tubes in the arch curvature (5). We also used artificial saliva in our study, to decrease friction between the archwires and brackets, where lubrication is an important factor in any study of friction (14).

The study objective was to determine the effects of the vertical position of the canine on changes in the frictional/orthodontic (F/O) force ratio of Ni-Ti archwires during the initial levelling phase. We used Ni-Ti archwires with three different cross-sectional sizes and force types, in the presence of artificial saliva, to identify the optimal archwires for efficient canine extrusion.

Materials and Methods

A conventional low-friction bracket with a unique design (Synergy, 0.022" slot; Rocky Mountain Orthodontics, Denver, CO, USA) was used in this study, as it offers lower friction than do other conventional brackets (8). Synergy brackets have six tie wings, bosses between the outer and inner tie wings, bumps along the slot floor, and rounded slot walls. When the elastomeric ligation is tied on the inner tie wings of the brackets, the bosses prevent the ligation from contacting the archwire. Synergy brackets have a passive ligation design (i.e., no ligation force is exerted on the archwire) (2,15-17).

The brackets were combined with Ni-Ti archwires (Sentalloy; Tomy International, Tokyo, Japan) with three cross-sectional sizes (0.014", 0.016", and 0.018") and three force types (light, medium, and heavy).

Mucin-based artificial saliva was prepared as described previously by Christersson and colleagues (18). Briefly, it was composed of porcine mucin (3.5 g), xylitol (2.0 g), methylparaben (100 mg), ethylenediaminetetra-acetic acid (50 mg), benzalkonium chloride (2.0 mg), and sodium fluoride (0.42 mg) in 100 mL of aqueous solution.

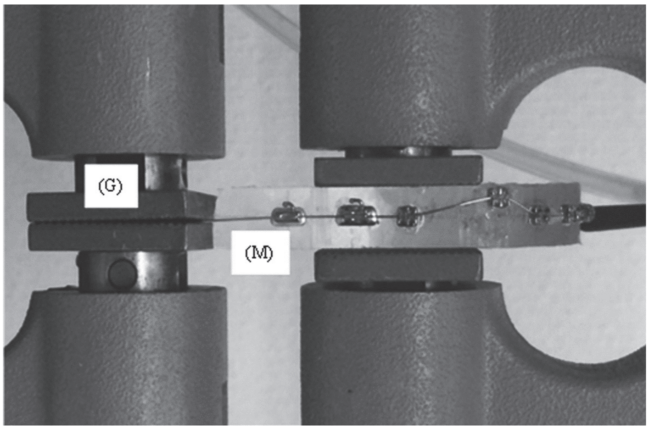

Fig. 1 The dental arch model (M) and distal end of the archwire are held in place by a pneumatic grip in a universal testing machine (G).

Three-point bending test

To examine the association between the force and deflection of Ni-Ti wires, we performed a three-point bending test by using a universal testing machine (5567; Instron, Norwood, MA, USA) with a 1-kN load cell. The bending test was performed with a straight 30-mm length of wire at the end of the archwire, in accordance with International Organization for Standardization (ISO) standard 15841, and an inter-fulcrum distance of 10 mm (to investigate the mechanical properties of archwires) or an inter-fulcrum distance of 15 mm or 20 mm (to measure orthodontic force). All measurements were performed at a crosshead speed of 7.5 mm/min and at a temperature of 36 ± 1°C in a thermostatic chamber. Six Ni-Ti wires of each type were used. All orthodontic force (unloading force) was measured at deflections of 1, 2, and 3 mm in the unloading process of the load-deflection curve, to simulate the force that a wire exerts on a canine as it is moved into the dental arch from a position of malocclusion.

Friction test

All eight brackets and four tubes were bonded from the central incisors to the second molars, excluding the first premolars, by using a cyanoacrylate adhesive applied to the dental arch models. This imitated a maxillary arch such that all bracket and tube slots, except the right canine slot, were vertically aligned at the same height. To simulate high canine malocclusion, the upper right canine was displaced gingivally by 1, 2, or 3 mm. In addition, to imitate a first premolar extraction, the inter-bracket distance between the upper right lateral incisor and second premolar was set at 15 mm or 20 mm (Fig. 1). The archwire was placed in the bracket slots and tied to the inner tie wings by using elastomeric rings with an

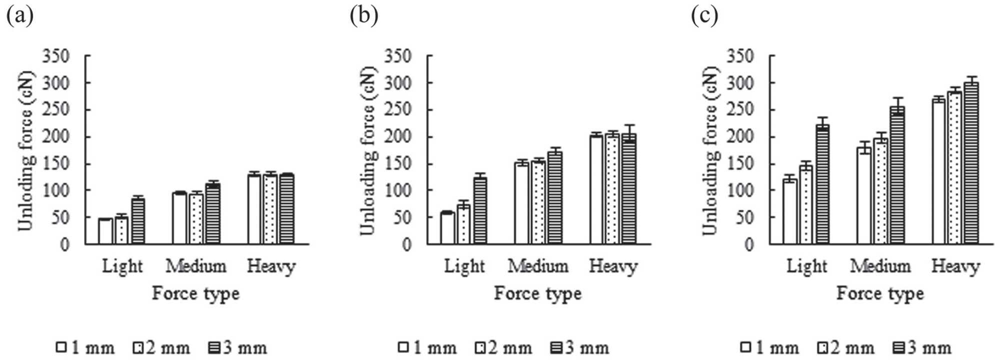

Fig. 2 Unloading force (orthodontic force) in the three-point bending test at an inter-fulcrum distance of 10 mm (ISO 15841). (a) 0.014”, (b) 0.016”, and (c) 0.018” nickel-titanium (Ni-Ti) wires.

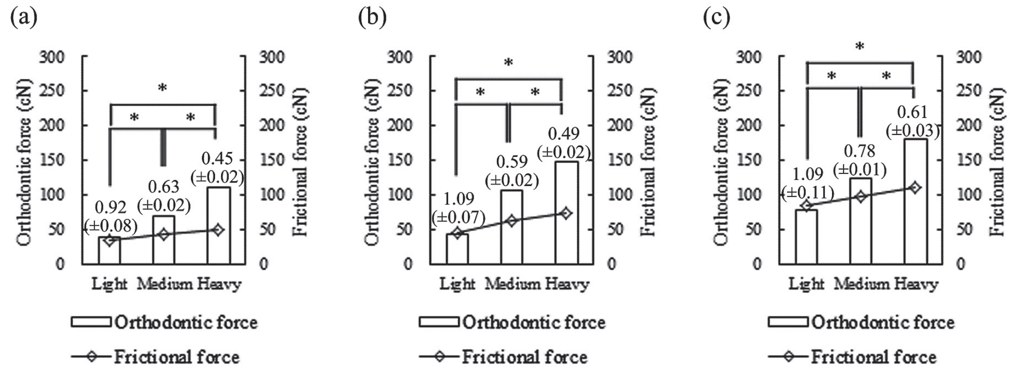

Fig. 3 Orthodontic force, frictional force, and frictional/orthodontic (F/O) force ratio with an inter-bracket distance of 15 mm for a vertical displacement of 1 mm. (a) 0.014”, (b) 0.016”, and (c) 0.018” Ni-Ti archwires.

outer diameter of 0.12” (Shofu, Kyoto, Japan). In total, 1 mL of mucin-based artificial saliva was applied to the archwire, bracket, tube slots, and elastomeric rings with a needleless syringe. Before the friction test, the assay was incubated for 3 min to allow for a reproducible amount of stress relaxation, as suggested by Henao and Kusy (19).

For the friction test, the dental arch model was held firmly by using the crosshead pneumatic grip of the universal testing machine (Fig. 1). The distal end of the archwire was held in place by the other grip and was pulled parallel to the end of the archwire and brackets at a crosshead speed of 0.5 mm/min. Each run was approximately 5 min. The maximum load during the process was recorded as the friction force. New archwires and elastomeric rings were used for each test. In total, nine types of archwire were tested across three different canine bracket positions. Each assay was performed six times, yielding a total of 54 assays. The temperature of the thermostatic chamber was maintained at 36 ± 1°C during testing.

Statistical analysis

Descriptive statistics, including means and standard deviations, were calculated for the F/O force ratio. The Shapiro-Wilk and Levene tests were applied to all data, which were found to be normally distributed and showed homogeneity of variance between groups. Therefore, parametric tests were used for subsequent analysis. Three-way analysis of variance (ANOVA) was used to evaluate the main effects of force type, cross-sectional size, and inter-bracket distance, as well as the interactions between these factors. The Scheffé test for multiple comparisons and pairwise comparisons adjusted with the Bonferroni method for the simple main effects test were used. The results were analysed with SPSS statistical software (ver. 16.0; SPSS, Chicago, IL, USA). A P value of less than 0.05 was considered statistically significant.

Results

The means and standard deviations of the forces generated during the unloading process, with 1-, 2-, and 3-mm deflections and an inter-fulcrum distance of 10 mm (ISO 15841), were used in the statistical comparison of the mechanical properties of Ni-Ti archwires, as shown in Fig. 2. The unloading force increased with a larger wire cross-sectional size, “heavier” force, and larger deflection.

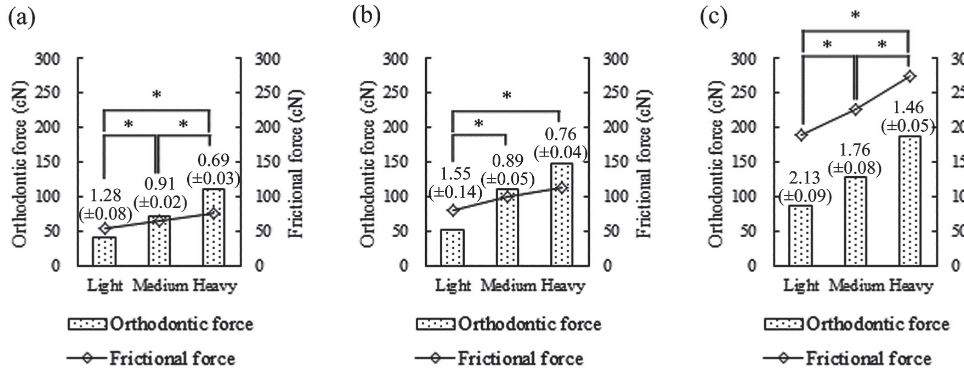

Fig. 4 Orthodontic force, frictional force, and F/O force ratio with an inter-bracket distance of 15 mm for a vertical displacement of 2 mm. (a) 0.014", (b) 0.016", and (c) 0.018" Ni-Ti archwires.

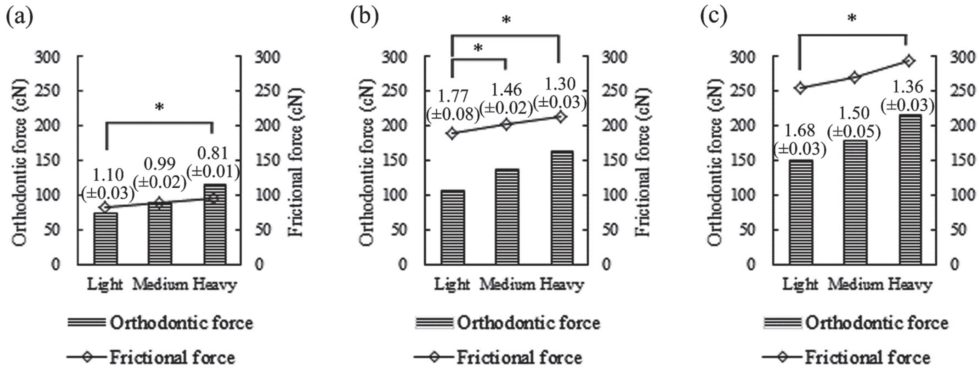

Fig. 5 Orthodontic force, frictional force, and F/O force ratio with an inter-bracket distance of 15 mm for a vertical displacement of 3 mm. (a) 0.014", (b) 0.016", and (c) 0.018" Ni-Ti archwires.

ANOVA of the F/O force ratio showed no significant interactions between force type, cross-sectional size, and inter-bracket distance at a vertical displacement of 3 mm, although interactions among the three factors were detected at vertical displacements of 1 and 2 mm (Tables 1-3). Regarding the main effects at a vertical displacement of 3 mm, force type, cross-sectional size of the archwire, and inter-bracket distance were significantly associated with F/O force ratio (Table 3, $P < 0.05$).

The mean values for frictional and orthodontic forces at an inter-bracket distance of 15 mm, and the F/O force ratios for vertical displacements of 1, 2, and 3 mm are shown in Figs. 3-5. F/O force ratio decreased as the wire became heavier for all vertical displacements at each size. For a 1-mm vertical displacement, F/O force ratios were less than 1.0 for all archwires except light archwires with 0.016" and 0.018" cross-sections (Fig. 3, $P < 0.05$). For a 2-mm vertical displacement, F/O force ratios were less than 1.0 for medium and heavy archwires with 0.014" and 0.016" cross-sections (Fig. 4, $P < 0.05$). For a 3-mm vertical displacement, F/O force ratios were less than 1.0 for medium and heavy archwires with a 0.014" cross-section (Fig. 5, $P < 0.05$).

The mean values for frictional and orthodontic forces at an inter-bracket distance of 20 mm, and F/O force ratios for vertical displacements of 1, 2, and 3 mm, are shown in Figs. 6-8 and are similar to the results obtained with an inter-bracket distance of 15 mm, i.e., F/O force ratio decreased as the wire became heavier for all vertical displacements at each size. For a 1-mm vertical displacement, the F/O force ratios were less than 1.0 for all archwires (Fig. 6, $P < 0.05$). For a 2-mm vertical displacement, the F/O force ratios were less than 1.0 for medium and heavy archwires with 0.014" and 0.016" cross-sections (Fig. 7, $P < 0.05$). For a 3-mm vertical displacement, the F/O force ratios were less than 1.0 for medium and heavy archwires with a 0.014" cross-section (Fig. 8, $P < 0.05$).

Regardless of the degree of tooth displacement, F/O force ratios were less than 1.0 for medium and heavy archwires with a 0.014" cross-section.

Discussion

To identify the conditions required for effective tooth movement, we investigated the F/O force ratio under six experimental conditions. With an F/O force ratio of

Table 1 Results of 3-way ANOVA of F/O force ratios for different combinations of force type, wire size, and inter-bracket distance
Dependent variable: F/O force ratio at a vertical displacement of 1 mm

Source	Type III Sum of squares	*df*	Mean square	*F*	*P* value
force type	2.734	2	1.367	404.721	0.000*
size	0.117	2	0.058	17.277	0.000*
inter-bracket distance	0.002	1	0.002	0.652	0.422
force type × size	0.135	4	0.034	9.975	0.000*
force type × inter-bracket distance	0.396	2	0.198	58.613	0.000*
size × inter-bracket distance	0.123	2	0.062	18.270	0.000*
force type × size × inter-bracket distance	0.160	4	0.040	11.816	0.000*
Error	0.304	90	0.003		
Total	63.669	108			

*Significant at $P < 0.05$

Table 2 Results of 3-way ANOVA of F/O force ratios for different combinations of force type, wire size, and inter-bracket distance
Dependent variable: F/O force ratio at a vertical displacement of 2 mm

Source	Type III Sum of squares	*df*	Mean square	*F*	*P* value
force type	5.384	2	2.692	269.730	0.000*
size	14.958	2	7.479	749.413	0.000*
inter-bracket distance	0.053	1	0.053	5.357	0.023*
force type × size	0.315	4	0.079	7.881	0.000*
force type × inter-bracket distance	0.437	2	0.218	21.894	0.000*
size × inter-bracket distance	0.007	2	0.003	0.328	0.721
force type × size × inter-bracket distance	0.089	4	0.022	2.222	0.073
Error	0.898	90	0.010		
Total	202.648	108			

*Significant at $P < 0.05$

Table 3 Results of 3-way ANOVA of F/O force ratios for different combinations of force type, wire size, and inter-bracket distance
Dependent variable: F/O force ratio at a vertical displacement of 3 mm

Source	Type III Sum of squares	*df*	Mean square	*F*	*P* value
force type	2.323	2	1.161	66.091	0.000*
size	8.295	2	4.147	235.997	0.000*
inter-bracket distance	0.584	1	0.584	33.223	0.000*
force type × size	0.138	4	0.035	1.966	0.106
force type × inter-bracket distance	0.025	2	0.012	0.711	0.494
size × inter-bracket distance	0.064	2	0.032	1.831	0.166
force type × size × inter-bracket distance	0.058	4	0.014	0.821	0.515
Error	1.582	90	0.018		
Total	225.764	108			

*Significant at $P < 0.05$

less than 1.0, the orthodontic forces generated on the teeth by the Ni-Ti archwire overcame frictional forces. The archwire could therefore easily slide through the brackets, thereby resulting in extrusion of the high canine. Conversely, with an F/O force ratio greater than 1.0, excessive frictional force impeded the sliding motion of the archwire through the brackets, and the high canine did not extrude. To level and align misaligned teeth, the F/O force ratio must be less than 1.0.

However, even if the F/O force ratio slightly exceeds 1.0, it might drop below 1.0 within a few hours, thereby allowing for extrusion of a high canine. Because the intraoral environment strongly influences the frictional forces produced by aging of elastomeric modules (20), and because the ligation force of elastomeric modules is affected by moisture and heat, rapid loss of between

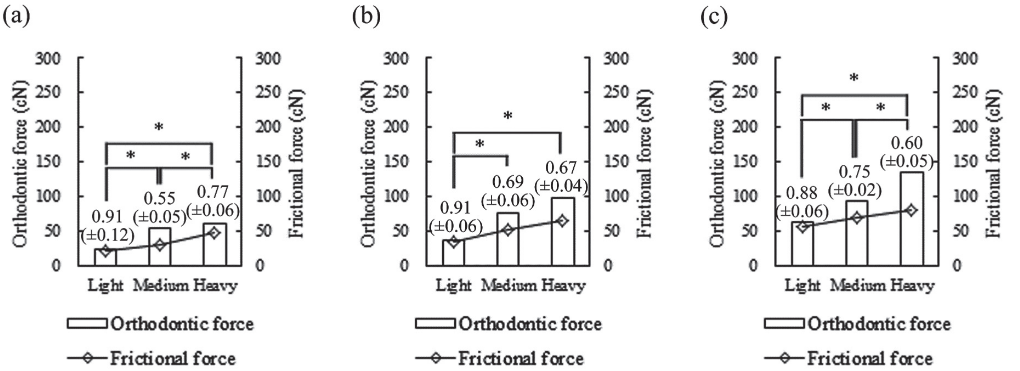

Fig. 6 Orthodontic force, frictional force, and F/O force ratio with an inter-bracket distance of 20 mm for a vertical displacement of 1 mm. (a) 0.014”, (b) 0.016”, and (c) 0.018” Ni-Ti archwires.

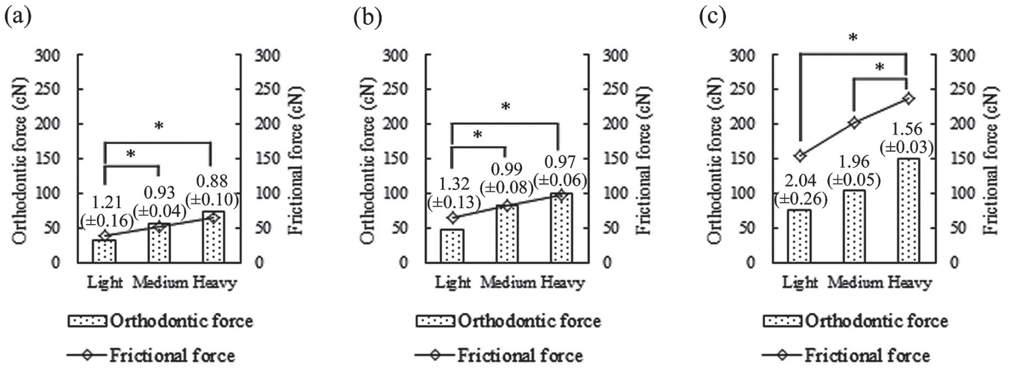

Fig. 7 Orthodontic force, frictional force, and F/O force ratio with an inter-bracket distance of 20 mm for a vertical displacement of 2 mm. (a) 0.014”, (b) 0.016”, and (c) 0.018” Ni-Ti archwires.

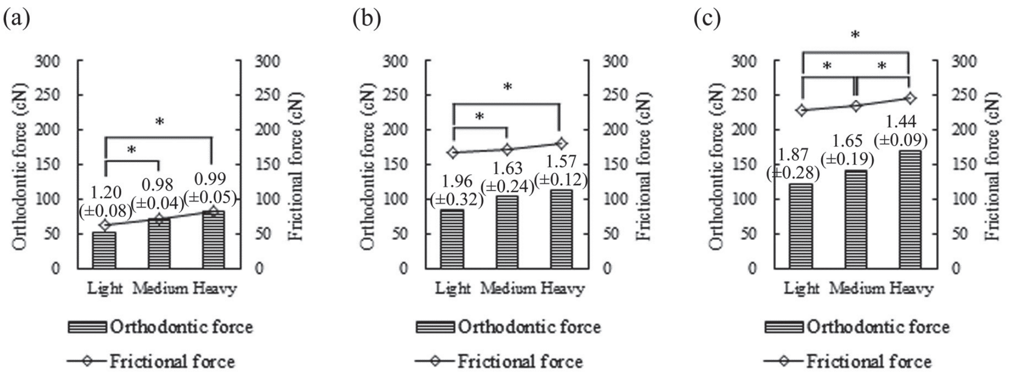

Fig. 8 Orthodontic force, frictional force, and F/O force ratio with an inter-bracket distance of 20 mm for a vertical displacement of 3 mm. (a) 0.014”, (b) 0.016”, and (c) 0.018” Ni-Ti archwires.

53% and 68% of force occurs within 24 hours (21). Thus, all archwires are available at a vertical displacement of 1 mm, 0.014” and 0.016” archwires are available for all force types at a vertical displacement of 2 mm, and 0.014” archwires are available for all force types at a vertical displacement of 3 mm, regardless of the distance between the lateral incisor and second premolar (Figs. 3-8). However, because the F/O force ratio is far greater than 1.0 (~1.96) at a displacement of 3 mm, it may not decrease to below 1.0, even if frictional force decreases because of aging of elastomeric modules. Therefore, archwires should be carefully selected so that they extrude the canine but do not expand the dental arch.

In this study, we used an experimental model to simulate high canine malocclusion. Although the effects of tooth malalignment on frictional forces have been investigated in various experimental models (2-8), few studies have examined the whole dentition and included artificial

saliva to reflect clinical conditions. When the canine is in a more periapical position relative to the occlusal plane, phenomena such as elastic binding (BI) and physical notching (NO) are more likely to occur and contribute to resistance to sliding (RS) (11), which is defined as (11):

RS = FR + BI + NO

Classical friction (FR) results from the ligation force that presses the archwire into the base and wall of the bracket slot (22). The rounded arch slot walls of Synergy brackets, which were used in our study, reduce BI and FR, which is important for efficient management of sliding between the archwire and bracket during the levelling phase (22). In this study, when the elastomeric ligation was tied onto the inner tie wings of the Synergy brackets, free movement of the archwire in the bracket slot was enabled (passive ligation design) (2,15-17); consequently, frictional force was reduced. However, at high vertical displacements, such as 3 mm, the Synergy brackets had higher F/O force ratios. Conventional brackets had an average frictional force 9.67 times that of Synergy brackets in a test conducted under dry conditions that included five brackets and used a vertically displaced center bracket (vertical displacement: 0-4.5 mm) (8). In addition, we previously found that the total average frictional force of conventional brackets (Mesh Standard Edgewise bracket, 0.022” slot; Tomy International, Tokyo, Japan) was 4.31 times that in the present study, under the same experimental conditions (unpublished data). Thus, high frictional force results in a large F/O force ratio. Because conventional brackets are commonly used for orthodontic treatment, orthodontists should use Ni-Ti archwires with smaller cross-sectional sizes and heavier force types. Errors in archwire choice can lead to inhibition of canine extrusion and expansion of the dental arch. Thus, selection of appropriate archwires may minimize the influence of frictional forces and increase the efficiency of canine extrusion during levelling.

Although the use of dental arch models and artificial saliva closely reflects the oral environment during orthodontic treatment, some limitations warrant mention. First, differences in brackets, such as slot configuration and bracket size, yield different frictional properties. Thus, studies of multiple bracket types might yield useful information. Second, some researchers have proposed that experimental models that can simulate the periodontal ligament—a stress-absorbing mechanism in vivo (5)—permit the initial tipping and rotation that occurs clinically (23). Such models might reproduce vibration of teeth caused by occlusion and reduce frictional force, thus further improving archwire selection.

Acknowledgments

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Conflict of interest

The authors have no conflict of interest related to this study.

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