Original Article

Friction properties according to vertical and horizontal tooth displacement and bracket type during initial leveling and alignment

Wook Heo[a]; Seung-Hak Baek[b]

ABSTRACT

Objective: To compare frictional properties according to the amounts of vertical displacement (VD) and horizontal displacement (HD) of teeth and bracket types during the initial leveling/alignment stage.

Methods: Combinations of self-ligating brackets (SLBs; two active type: In-Ovation-R and In-Ovation-C; four passive type: Damon-3Mx, Damon-Q, SmartClip-SL3, and Clarity-SL) and 0.014-inch nickel-titanium archwires (austenitic type, A-NiTi, and copper type, Cu-NiTi) were tested in a stereolithographically made typodont system that could simulate malocclusion status and periodontal ligament space. The upper canines (UCs) were displaced in the gingival direction and the upper lateral incisors (ULIs) in the lingual direction from their ideal positions by up to 3 mm, with 1-mm intervals, respectively. Two conventional brackets were used as controls. Static and kinetic frictional forces were measured. One-way analysis of variance test with post hoc test was performed for statistical analysis.

Results: In the gingival displacement of UCs, Clarity-SL produced significantly lower frictional force ($P < .001$), while Damon-3Mx, In-Ovation-R, and SmartClip-SL3 produced higher frictional force among SLBs. In the lingual displacement of ULIs, Damon-Q and Damon-3Mx produced significantly lower frictional force ($P < .01$), while Clarity-SL produced the highest frictional force among SLBs ($P < .001$). Clarity-SL combined with A-NiTi and C-NiTi, Damon-3Mx combined with A-NiTi, and In-Ovation-C combined with Cu-NiTi showed differences in frictional properties between VD and HD.

Conclusions: Since the frictional properties of SLBs would be different between VD and HD of teeth, it is necessary to develop SLBs with low friction in both VD and HD of teeth. (*Angle Orthod.* 2011;81:653–661.)

KEY WORDS: Friction properties; Displacement of teeth; Bracket type; Initial leveling and alignment

INTRODUCTION

Self-ligating brackets (SLBs) are known to show lower frictional force (FF) than conventional brackets.[1–16] Conventional brackets have three slot walls (gingival horizontal wall, occlusal horizontal wall, and vertical wall), while SLBs have an additional facial wall (sliding door/clip in passive type or clip in active type) that conventional brackets do not have. Metal or elastomeric ligatures play a role in conventional brackets that is similar to that played by the facial wall in SLBs.

SLBs can be divided into two groups: active (ASLB) and passive (PSLB) types. The major difference between ASLBs and PSLBs is the function and structure of the facial wall. ASLBs such as In-Ovation-R and In-Ovation-C (GAC International, Bohemia, NY) have an active clip and short gingival horizontal wall (0.0195 inch) compared to the conventional occlusal horizontal wall (0.0285 inch).[1] PSLBs exhibit structural differences. Damon-3Mx and Damon-Q (SDS Ormco, Glendora, Calif) incorporate a passive sliding door as a facial wall. However, SmartClip-SL3 and Clarity-SL (3M Unitek, Monrovia, Calif) have a unique clip structure without a solid facial wall.

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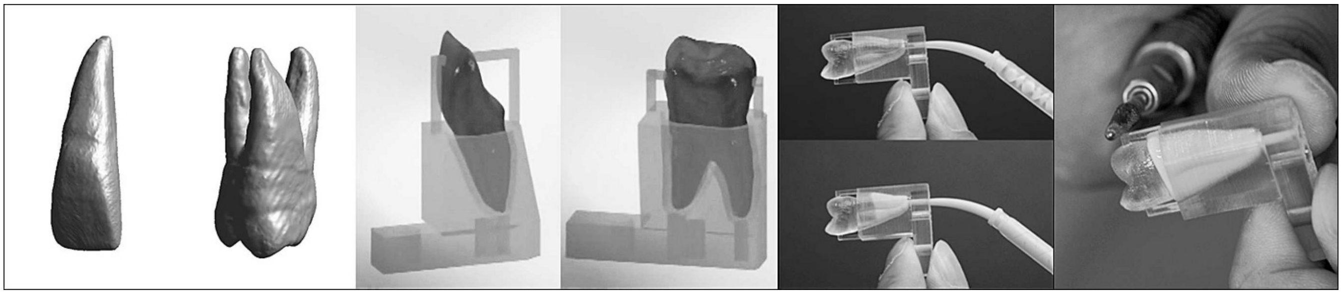

Figure 1. Three-dimensional (3D) virtual models of the upper central incisor (UCI) and the upper first molar (UFM) and 3D tooth virtual model block with the periodontal ligament space and its holding structure for the UCI and UFM (left). Procedure involves injection of vinyl polysiloxane light body into the periodontal ligament space of the SLA® product of the 3D model of the upper second premolar and cutting the bridge material for tooth holding (right).

In friction studies, study design can be categorized according to the number and alignment of the brackets tested. In previous studies,[2–13,17–19] five or fewer brackets were used to measure FF, and these brackets were aligned in a straight line rather than following the arch curvature. Only a few studies[14,15,20,21] examined entire dentitions aligned according to the arch curvature. Recently, Kim et al.[16] introduced a custom-designed typodont system that could include the whole dentition, align the dentition according to the arch curvature, and simulate malocclusion status. Therefore, for clinical relevance, the frictional values should be measured to check the ease with which the archwire is able to slide through the brackets in the whole dentition with the arch curvature.

In several studies[7,8,17,18] that assessed FFs generated between brackets and wires, the displacement direction of a single bracket was usually vertical (occluso-gingival) in relation to the direction of wire movement. However, malocclusion is a matter of three-dimensional (3D) displacement of individual teeth. When one tooth or bracket is displaced vertically, friction is generated between the gingival/occlusal walls, corners of the bracket slots, and wire. If one tooth or bracket is displaced horizontally to the labial or the lingual, friction is generated between the vertical/facial walls, corners of the bracket slots, and wire. Therefore, it is necessary to demonstrate that the frictional properties resulting from vertical displacement (VD) show the same characteristics as those resulting from horizontal displacement (HD). But there are no previous studies that compare these two kinds of frictional properties. Therefore, the purpose of this study was to compare the frictional properties according to VD and HD of teeth and the bracket types during the initial leveling/alignment stage.

MATERIALS AND METHODS

In this study, the custom-designed typodont system used in Kim et al.[16] was modified and upgraded using a stereolithographic technique. Using computed tomography data, 3D virtual tooth models with root and periodontal ligament (PDL) spaces were designed to emulate a stress-absorbing mechanism (Figure 1) and were fabricated into 3D structures using the Viper™ Pro SLA® System (3D Systems Corporation, Valencia, Calif). The PDL space was filled with Imprint™ II Garant™ Light Body Vinyl Polysiloxane Impression Material (3M ESPE, Seefeld, Germany), which effectively reproduces the mobility of human teeth (Figure 1). In this study, Periotest (Siemens AG, Bensheim, Germany) was used to test the mobility of the typodont teeth. The average Periotest value of the typodont teeth (6.9 ± 0.7, $n = 28$) was similar to the results obtained from previous studies of natural human teeth (-0.6 to $+13.6$).[22,23]

The metal frame holding the tooth structures could be moved in occluso-gingival (up and down) and labiolingual (forward and backward) directions from the ideal position to a maximum of 5 mm in displacement to produce arbitrary displacement of each tooth. At zero position, all teeth were aligned to the ideal position according to the ovoid arch form (OrthoForm III-Ovoid, reference no. 701-723, 3M Unitek) (Figure 2).

The SLBs tested in this study were as follows: (1) two ASLBs: In-Ovation-R and In-Ovation-C, and (2) four PSLBs: Damon-3Mx, Damon-Q, SmartClip-SL3, and Clarity-SL. As a control group, two conventional brackets, Clarity (3M Unitek) and Mini-Diamond (Ormco), were selected. All brackets tested had a .022-inch slot. As a typical archwire for the initial leveling/alignment stage, 0.014-inch austenitic nickel-titanium (A-NiTi) and copper nickel-titanium (Cu-NiTi) archwires (Ormco) were selected.

To simulate malocclusion, standardized displacements of the teeth were produced when all brackets were coupled with A-NiTi or Cu-NiTi wire. The upper canines on the right and left sides were displaced in the gingival direction, while the upper lateral incisors

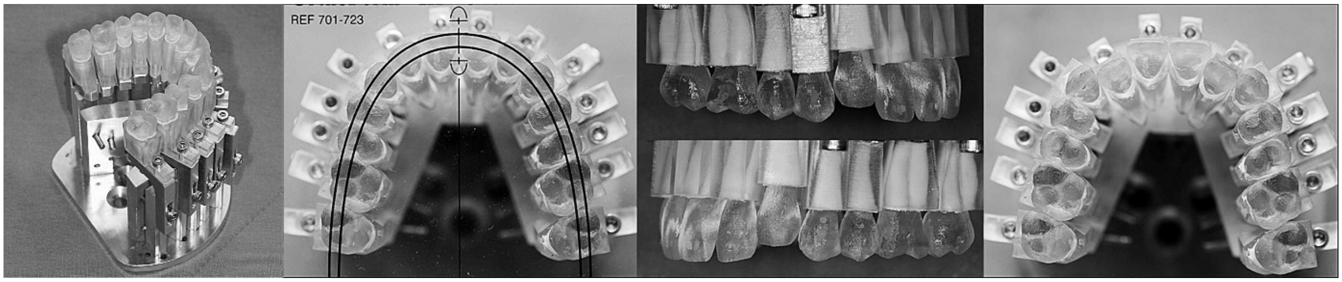

Figure 2. The stereolithographically made typodont system used in this study and its occlusal view (left); The upper teeth aligned according to the ovoid arch form; The upper canines are displaced in the gingival direction by 3 mm, with 1-mm intervals; The upper lateral incisors are displaced in the lingual direction by 3 mm, with 1-mm intervals (right).

on both sides were displaced in the lingual direction by 0, 1, 2, and 3 mm (Figure 2).

In this study, selections of the bracket-archwire combinations were made randomly. Once each combination was selected, the brackets were bonded in clinically appropriate positions according to the facial axis point using Transbond XT (3M Unitek) on stereolithographically fabricated typodont teeth. For the conventional brackets, after ligation with the elastic modules (Unistick Ligatures, American Orthodontics, Sheboygan, Wisc), a 3-minute waiting period allowed a reproducible amount of stress relaxation to occur. The typodont was then attached to a custom-made metal plate that was fixed to a mechanical testing machine

Table 1. Static and Kinetic Frictional Force (cN) According to Combinations of Bracket, Wire Alloy Type, and Vertical Displacement of the Upper Canines[a]

Type of Frictional Force	Bracket Type	Brackets	Wires	Vertical Displacement of the Upper Canines: 0 mm Mean	0 mm SD	1 mm Mean	1 mm SD	2 mm Mean	2 mm SD	3 mm Mean	3 mm SD
Static	Conventional	Mini-Diamond	A-Niti	2141.8	142.6	3269.2	116.2	3693.4	223.1	3838.2	62.9
			Cu-Niti	1905.6	26.5	1916.4	122.3	2619.6	61.7	2684.6	64.5
		Clarity	A-Niti	1964.4	81.2	2039.8	90.8	3564.4	138.7	3650.6	71.0
			Cu-Niti	1320.4	91.7	1545.8	48.5	1798.0	50.5	2286.8	61.1
	Active self-ligating	In-Ovation-R	A-Niti	57.3	7.5	278.8	24.1	734.8	56.0	912.2	32.7
			Cu-Niti	55.3	19.9	224.8	45.2	439.8	14.8	584.3	22.6
		In-Ovation-C	A-Niti	77.2	14.7	181.8	11.6	456.0	42.7	761.8	49.0
			Cu-Niti	88.9	17.8	246.4	12.1	514.8	58.0	890.8	61.1
	Passive self-ligating	Damon-3Mx	A-Niti	56.7	13.6	176.8	23.6	466.6	55.7	993.0	27.0
			Cu-Niti	52.1	9.0	155.6	12.1	316.6	12.1	477.6	22.6
		Damon-Q	A-Niti	50.1	14.7	203.2	14.8	456.0	19.1	729.6	48.0
			Cu-Niti	41.4	15.1	150.2	14.8	305.8	14.8	466.8	30.8
		SmartClip-SL3	A-Niti	40.5	12.2	139.4	12.1	541.6	29.3	906.8	51.6
			Cu-Niti	40.3	12.3	123.2	14.8	284.2	14.8	536.2	18.7
		Clarity-SL	A-Niti	56.4	13.4	176.8	23.6	332.4	14.2	579.2	24.1
			Cu-Niti	68.6	11.6	166.2	11.6	311.2	14.8	429.0	19.1
Kinetic	Conventional	Mini-Diamond	A-Niti	1920.1	32.9	2971.5	56.8	3427.9	140.8	3808.0	144.7
			Cu-Niti	1867.2	44.5	1892.9	45.8	2504.9	105.7	2619.7	24.1
		Clarity	A-Niti	1903.2	39.5	2021.5	34.3	3203.5	90.2	3572.4	104.8
			Cu-Niti	1149.5	30.3	1449.9	22.0	1662.5	37.3	2196.0	88.2
	Active self-ligating	In-Ovation-R	A-Niti	43.4	13.5	252.4	13.7	634.6	63.5	856.3	32.7
			Cu-Niti	38.3	13.6	169.3	12.5	367.1	30.9	536.0	45.9
		In-Ovation-C	A-Niti	66.3	13.5	160.2	9.9	392.0	14.5	631.2	29.2
			Cu-Niti	69.3	14.6	200.8	13.5	454.0	22.6	767.5	63.0
	Passive self-ligating	Damon-3Mx	A-Niti	46.4	15.1	145.8	13.4	406.7	15.2	840.2	57.3
			Cu-Niti	35.7	14.5	121.4	13.5	305.9	14.6	446.8	40.4
		Damon-Q	A-Niti	39.1	13.5	171.0	12.7	424.5	15.9	673.5	24.8
			Cu-Niti	28.0	15.3	118.8	13.4	268.5	16.7	417.1	18.7
		SmartClip-SL3	A-Niti	26.2	6.1	109.0	11.3	497.8	30.2	822.7	39.7
			Cu-Niti	26.0	7.2	99.9	12.3	257.3	13.4	491.4	24.2
		Clarity-SL	A-Niti	45.1	15.5	137.2	10.3	311.0	16.4	540.1	16.4
			Cu-Niti	48.0	15.3	137.0	11.8	277.0	21.2	389.8	17.3

[a] SD indicates standard deviation.

Table 2. Static and Kinetic Frictional Force (cN) According to Combinations of Bracket, Wire Alloy Type, and Lingual Displacement of the Upper Lateral Incisors[a]

Type of Frictional Force	Bracket Type	Brackets	Wires	Lingual Displacement of the Upper Lateral Incisors							
				0 mm		1 mm		2 mm		3 mm	
				Mean	SD	Mean	SD	Mean	SD	Mean	SD
Static	Conventional	Mini-Diamond	A-Niti	2141.8	142.6	2431.8	101.7	2330.0	81.4	3967.2	114.7
			Cu-Niti	1905.6	26.5	2302.8	137.4	2098.8	81.4	2415.6	68.3
		Clarity	A-Niti	1964.4	81.2	2131.2	106.8	2367.2	109.6	2464.0	69.4
			Cu-Niti	1320.4	91.7	1653.0	86.3	1707.2	56.0	2319.0	79.7
	Active self-ligating	In-Ovation-R	A-Niti	57.3	7.5	176.6	14.2	439.8	40.9	863.8	43.8
			Cu-Niti	55.3	19.9	171.4	14.2	337.6	14.2	499.0	30.5
		In-Ovation-C	A-Niti	77.2	14.7	176.8	23.6	300.0	47.8	584.8	72.1
			Cu-Niti	88.9	17.8	197.8	14.8	289.6	22.6	504.4	22.2
	Passive self-ligating	Damon-3Mx	A-Niti	56.7	13.6	144.8	24.1	284.2	30.8	600.8	40.9
			Cu-Niti	52.1	9.0	77.2	6.3	219.4	12.1	423.6	29.6
		Damon-Q	A-Niti	50.1	14.7	219.4	35.2	257.2	30.8	568.4	44.4
			Cu-Niti	41.4	15.1	176.6	14.2	230.2	24.1	412.8	36.2
		SmartClip-SL3	A-Niti	40.5	12.2	246.4	35.2	402.0	54.0	734.8	36.2
			Cu-Niti	40.3	12.3	257.2	14.8	337.6	30.3	552.2	24.1
		Clarity-SL	A-Niti	56.4	13.4	289.6	29.6	584.8	39.9	1309.4	99.2
			Cu-Niti	68.6	11.6	208.6	22.6	385.8	24.1	778.0	19.1
Kinetic	Conventional	Mini-Diamond	A-Niti	1920.1	32.9	2183.0	198.4	2291.0	63.7	3831.7	144.7
			Cu-Niti	1867.2	44.5	2017.7	80.1	2025.0	79.1	2358.9	92.5
		Clarity	A-Niti	1903.2	39.5	1906.1	41.9	2277.3	28.1	2380.1	88.3
			Cu-Niti	1149.5	30.3	1557.8	17.5	1662.1	37.6	2087.1	106.6
	Active self-ligating	In-Ovation-R	A-Niti	43.4	13.5	149.1	13.4	350.2	36.2	628.7	76.8
			Cu-Niti	38.3	13.6	140.9	12.8	276.7	32.7	424.6	40.5
		In-Ovation-C	A-Niti	66.3	13.5	122.5	14.3	229.5	13.9	453.1	27.2
			Cu-Niti	69.3	14.6	163.5	14.7	241.6	20.2	446.7	26.9
	Passive self-ligating	Damon-3Mx	A-Niti	46.4	15.1	85.5	12.5	228.6	13.7	525.8	23.1
			Cu-Niti	35.7	14.5	56.6	10.2	166.9	16.2	358.5	32.9
		Damon-Q	A-Niti	39.1	13.5	176.2	12.8	212.4	14.9	510.2	15.3
			Cu-Niti	28.0	15.3	139.2	14.4	189.3	15.2	319.4	30.4
		SmartClip-SL3	A-Niti	26.2	6.1	203.9	13.1	369.8	16.6	692.9	26.1
			Cu-Niti	26.0	7.2	203.7	19.2	253.7	30.1	402.3	52.3
		Clarity-SL	A-Niti	45.1	15.5	274.7	13.8	548.8	17.5	1221.0	79.2
			Cu-Niti	48.0	15.3	141.6	13.1	339.3	26.0	615.0	103.3

[a] SD indicates standard deviation.

(model 4466, Instron, Canton, Mass). A custom-designed adaptor gripped one distal end of the archwire, which was extruded from the upper second molar tubes.

Each combination was tested five times with different wires of the same type. Two and a half millimeters of wire was drawn through brackets and tubes at a crosshead speed of 0.5 mm per minute in the dry state and at room temperature. Both the static FF (SFF) and kinetic FF (KFF) were calculated by the same method used in Kim et al.[16] A total of 560 tests were conducted.

Descriptive statistics, including means and standard deviations, were calculated for each combination of brackets, type of wire alloy, type of malocclusion, and amount of displacement. A one-way analysis of variance test (ANOVA) was used to evaluate the effects of the variables on FF. If the assumption that the variances were equal was broken by the Levene test, the Welch variance weighted ANOVA test was used. The Duncan test was applied as a post hoc test. The level of significance for all of the tests was set at $P < .05$.

RESULTS

Conventional brackets showed significantly higher levels of SFF and KFF for each alloy type, type of malocclusion, and amount of displacement when compared with SLBs ($P < .001$; Tables 1 and 2).

Gingival Displacement of the Upper Canines by 3 mm

In the combinations of SLBs and A-NiTi, Clarity-SL produced significantly lower SFF and KFF levels ($P < .001$). Damon-3Mx produced significantly higher SFF ($P < .01$) and In-Ovation-R higher KFF ($P < .001$) (Table 3; Figure 3A,B).

In SLBs combined with Cu-NiTi, Clarity-SL, Damon-Q, and Damon-3Mx produced significantly lower SFF

Table 3. Multiple Comparisons According to Combinations of Self-Ligating Bracket, Wire Alloy Type, and Type of Malocclusion[a]

Deviation	Type of Frictional Force	Wires	*P*-Value	Multiple Comparison	Multiple Comparison (overall)
Zero position	Static	A-Niti	.006**	(SC, DQ, CS, D3, IR) < (IC)	(SC_c, SC_a, DQ_c, DQ_a, D3_c, IR_c, CS_a, D3_a, IR_a) < (DQ_a, D3_c, IR_c, CS_a, D3_a, IR_a, CS_c) < (CS_c, IC_a) < (IC_a, IC_c)
		Cu-Niti	.000***	(SC, DQ, D3, IR) < (D3, IR, CS) < (IC)	
	Kinetic	A-Niti[b]	.000***	(SC) < (DQ) < (IR, CS) < (CS, D3) < (IC)	(SC_c, SC_a, DQ_c) < (D3_c) < (IR_c, DQ_a) < (IR_a, CS_a) < (CS_a, D3_a) < (D3_a, CS_c) < (IC_a) < (IC_c)
		Cu-Niti[b]	.000***	(SC, DQ) < (D3) < (IR) < (CS) < (IC)	
Vertical displacement of the upper canines by 3 mm	Static	A-Niti	.000***	(CS) < (DQ, IC) < (SC, IR) < (D3)	(CS_c, DQ_c, D3_c) < (SC_c, CS_a, IR_c) < (DQ_a, IC_a) < (IC_c, SC_a, IR_a) < (D3_a)
		Cu-Niti[b]	.000***	(CS, DQ) < (DQ, D3) < (SC) < (IR) < (IC)	
	Kinetic	A-Niti[b]	.000***	(CS) < (IC) < (DQ) < (SC) < (D3) < (IR)	(CS_c) < (DQ_c) < (D3_c) < (SC_c) < (IR_c, CS_a) < (IC_a) < (DQ_a) < (IC_c) < (SC_a) < (D3_a) < (IR_a)
		Cu-Niti[b]	.000***	(CS) < (DQ) < (D3) < (SC) < (IR) < (IC)	
Lingual displacement of the upper lateral incisors by 3 mm	Static	A-Niti	.000***	(DQ, IC, D3) < (SC) < (IR) < (CS)	(DQ_c, D3_c) < (IR_c, IC_c, SC_c) < (SC_c, DQ_a, IC_a, D3_a) < (SC_a, CS_c) < (IR_a) < (CS_a)
		Cu-Niti	.000***	(DQ, D3) < (IR, IC) < (SC) < (CS)	
	Kinetic	A-Niti[b]	.000***	(IC) < (DQ) < (D3) < (IR) < (SC) < (CS)	(DQ_c) < (D3_c) < (SC_c) < (IR_c) < (IC_c, IC_a) < (DQ_a) < (D3_a) < (CS_c) < (IR_a) < (SC_a) < (CS_a)
		Cu-Niti[b]	.000***	(DQ) < (D3) < (SC) < (IR) < (IC) < (CS)	

[a] One-way analysis of variance (ANOVA) was done. IR, In-Ovation-R; IC, In-Ovation-C; D3, Damon-3Mx; DQ, Damon-Q; SC, SmartClip-SL3; CS, Clarity-SL; IR_a, In-Ovation-R with A-NiTi; IR_c, In-Ovation-R with Cu-NiTi; IC_a, In-Ovation-C with A-NiTi; IC_c, In-Ovation-C with Cu-NiTi; D3_a, Damon-3Mx with A-NiTi; D3_c, Damon-3Mx with Cu-NiTi; DQ_a, Damon-Q with A-NiTi; DQ_c, Damon-Q with Cu-NiTi; SC_a, SmartClip-SL3 with A-NiTi; SC_c, SmartClip-SL3 with Cu-NiTi; CS_a, Clarity-SL with A-NiTi; CS_c, Clarity-SL with Cu-NiTi.

[b] Welch variance weighted ANOVA was used. Multiple comparison test was done by Duncan test.

** $P < .01$; *** $P < .001$.

($P < .01$) and Clarity-SL lower KFF levels ($P < .001$). However, In-Ovation-C produced significantly higher SFF and KFF levels ($P < .001$).

Lingual Displacement of the Upper Lateral Incisors by 3 mm

In SLBs combined with A-NiTi, Damon-Q, In-Ovation-C, and Damon-3Mx produced significantly lower SFF ($P < .01$) and In-Ovation-C significantly lower KFF levels ($P < .001$). However, Clarity-SL produced significantly higher SFF and KFF levels ($P < .001$) (Table 3; Figure 3C,D).

In SLBs combined with Cu-NiTi, Damon-Q and Damon-3Mx produced significantly lower SFF ($P < .01$) and Damon-Q lower KFF levels ($P < .001$). However, Clarity-SL produced significantly higher SFF and KFF levels ($P < .001$).

In summary, there were significant differences in FF for each combination of brackets, type of wire alloy, type of malocclusion, and amount of displacement (Tables 1 through 3). Clarity-SL combined with A-NiTi and Cu-NiTi, Damon-3Mx combined with A-NiTi, and In-Ovation-C combined with Cu-NiTi showed differences in frictional properties between VD and HD (Figure 4).

DISCUSSION

In most of the frictional studies[9–11,17,18] using the conventional brackets, the brackets were either aligned straight or one bracket was displaced vertically in relation to the direction of wire movement. There were few friction studies about HD because ligature materials holding a wire, rather than the bracket itself, play a major role in terms of friction. Since SLBs have an innate facial wall or clip and do not need ligatures, the FF generated by either VD or HD is produced mainly from the SLB itself. Therefore, it is necessary to investigate the frictional properties in both HD and VD in SLBs.

Despite their similar structures, we detected a significant difference in frictional properties between In-Ovation-R and In-Ovation-C (Tables 1 and 2). Voudouris et al.[12] reported that In-Ovation-C demonstrated lower fictional force than In-Ovation-R when tested with stainless-steel wires. In this study, when these two SLBs were combined with A-NiTi, our

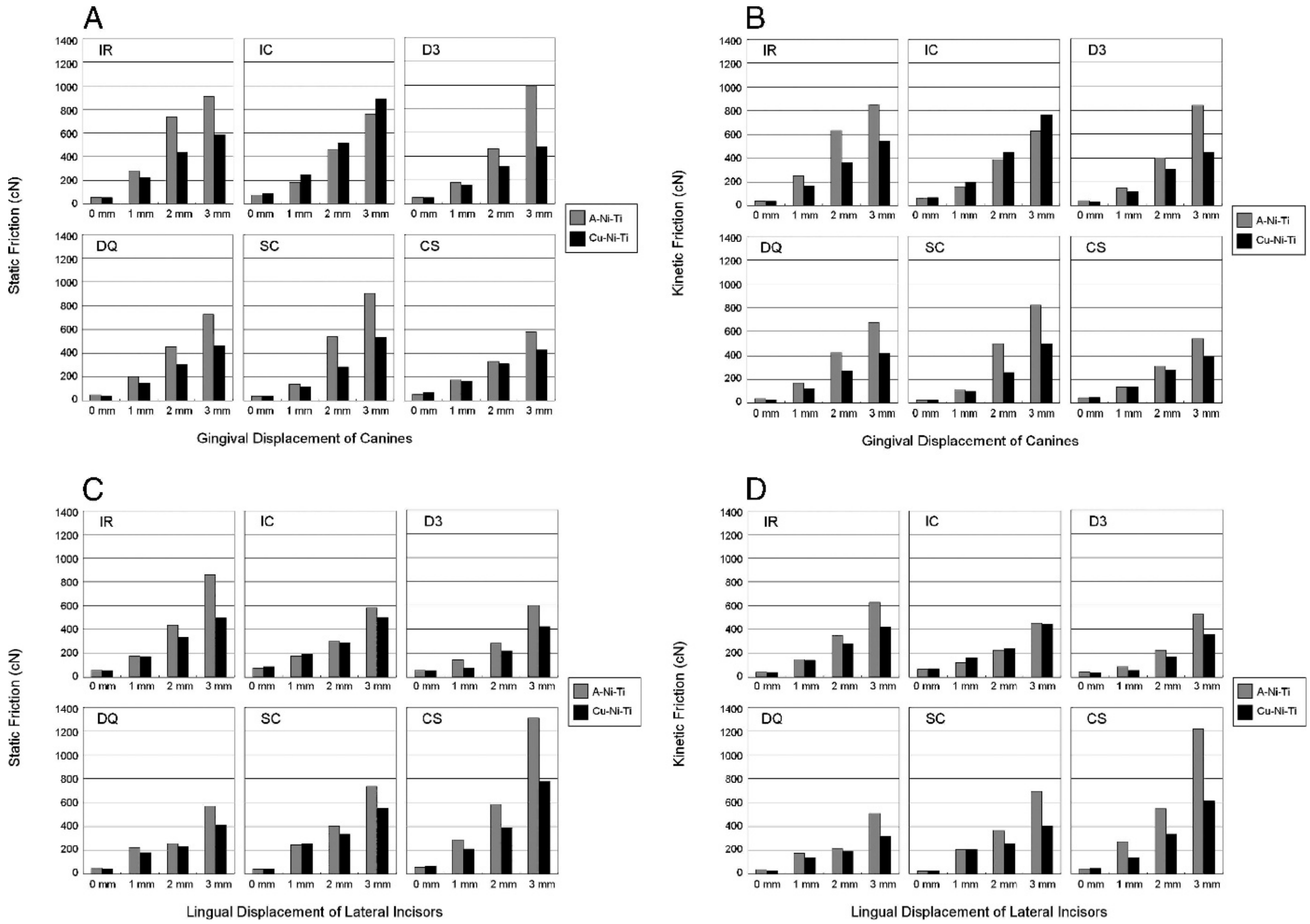

Figure 3. (A) Static frictional force (SFF, cN) of the self-ligating brackets (SLBs) according to the gingival displacement of the upper canines. (B) Kinetic frictional force (KFF, cN) of the SLBs according to the gingival displacement of the upper canines. (C) SFF (cN) of the SLBs according to the lingual displacement of the upper lateral incisors. (D) KFF (cN) of the SLBs according to the lingual displacement of the upper lateral incisors. IR indicates In-Ovation-R; IC, In-Ovation-C; D3, Damon-3Mx; DQ, Damon-Q; SC, SmartClip-SL3; CS, Clarity-SL; A-NiTi, austenitic nickel-titanium; and Cu-NiTi, copper nickel-titanium.

findings showed similar tendencies compared with those of Voudouris et al.[12] In-Ovation-C produced less FF in both VD and HD (by 3 mm) than In-Ovation-R ($P < .001$; Figures 3 and 4A,B). Voudouris et al.[12] explained that compared with In-Ovation-R, the Cr-Co clips within In-Ovation-C showed more freedom within the bracket slot and that the reduction in the curved shape of the In-Ovation-C clip may result in lower seating forces and lower friction.

When combined with Cu-NiTi, In-Ovation-C produced a higher FF than In-Ovation-R in VD of 3 mm ($P < .001$; Figures 3 and 4C,D). The reason why the Cu-Ni-Ti wire generated higher friction than the A-NiTi wire may be related to the differences in surface chemistry and chemical affinity between A-Ni-Ti and Cu-Ni-Ti archwires.[24] Further studies are needed to investigate the reasons for this result. In addition, In-Ovation-C in VD by 3 mm produced approximately 1.7 times more FF than in HD by 3 mm. This was the highest FF that we detected in SLBs combined with Cu-NiTi (Figure 4C,D). Therefore, it can be stated that different frictional properties existed between VD and HD in In-Ovation-C combined with Cu-NiTi.

When Damon-3Mx and Damon-Q were combined with Cu-NiTi, a lower FF was produced compared to other combinations of SLBs and archwires (Figure 4C,D). The manufacturer recommended that Cu-NiTi be used during the leveling/alignment phase with Damon bracket series.[25] This combination would be reasonable based on our findings from this study. In addition, Damon-Q with A-NiTi also exhibited good frictional properties compared to other SLBs with A-NiTi (Figure 4A,B).

Damon-3Mx with A-NiTi demonstrated different results. Damon-3Mx belonged to the lowest SFF group in HD by 3 mm but produced the highest SFF in VD by

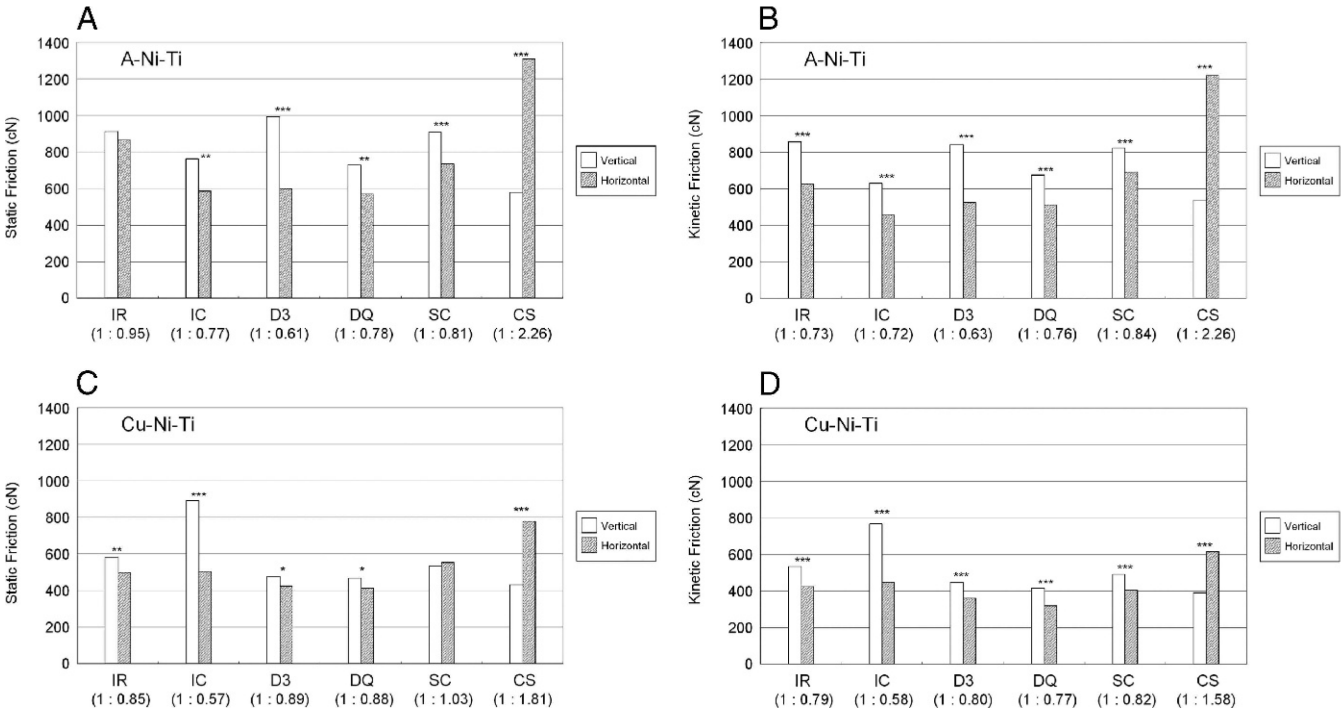

Figure 4. (A) Comparison of static frictional force (SFF; cN) in the vertical displacement (VD) and horizontal displacement (HD) by 3 mm when the self-ligating brackets (SLBs) were combined with A-NiTi. (B) Comparison of kinetic FF (KFF, cN) in VD and HD by 3 mm of SLBs with A-NiTi. (C) Comparison of SFF (cN) in VD and HD by 3 mm of SLBs with Cu-NiTi. (D) Comparison of KFF (cN) in VD and HD by 3 mm of SLBs with Cu-NiTi. * $P < .05$; ** $P < .01$; *** $P < .001$.

3 mm among SLBs (Table 3; Figure 4A). SFF of Damon-3Mx with A-NiTi was highly increased from 2 mm to 3 mm in VD (Figure 3A).

Thorstenson and Kusy[13,19] reported that for second-order angulations greater than the critical angle, binding increasingly contributed to resistance to sliding. In this case, it could be stated that binding forces increased in VD by 3 mm in combination with Damon-3Mx and A-NiTi. Therefore, it can be stated that different frictional properties existed between VD and HD in Damon-3Mx combined with A-NiTi.

As with In-Ovation-R and In-Ovation-C, there were differences in frictional properties between SmartClip-SL3 and Clarity-SL, despite their similar structure. When Clarity-SL was combined with A-NiTi, the lowest FF was produced in VD by 3 mm (Table 3; Figure 4A,B). However, this combination produced the greatest friction in HD by 3 mm among all SLBs (Table 3; Figure 4A,B). FF in HD by 3 mm was more than two times FF in VD by 3 mm (Tables 1 and 2; Figure 4A,B). Clarity-SL with Cu-NiTi also showed similar results when compared with A-NiTi (Figure 4C,D). However, there were no major discrepancies between VD and HD in SmartClip-SL3 (Figure 4).

If the upper lateral incisor is displaced lingually, friction will be generated between the vertical walls, corners of bracket slots, clips, and a wire (Figure 5). Therefore, clips of SmartClip-SL3 and Clarity-SL influence FF. Differences in friction between SmartClip-SL3 and Clarity-SL might be due to the differences in the clip force and shape between them. The manufacturer announced that the SmartClip-SL3 has more reduced clip force than the Clarity-SL and previous versions of SmartClip.[26] In addition, there were differences in bracket shape that influenced FF. SmartClip-SL3 and Clarity-SL commonly have vertical slot-wall extensions (VSEs) to hold clips (Figure 6). As VSE increased, the distance between the bracket margins decreased in both the mesial and distal sides of the horizontally displaced bracket (Figure 6). Eventually, FF in-

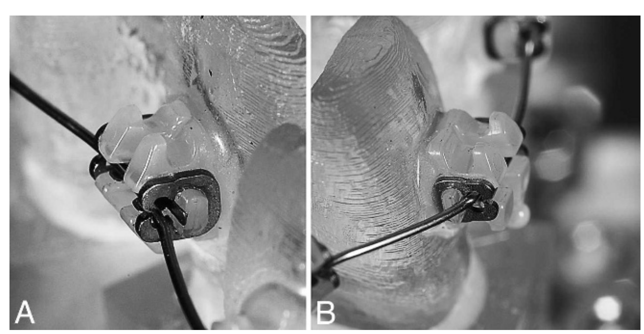

Figure 5. Lingual displacement of the upper lateral incisors by 3 mm with Clarity-SL. (A) Distal view of the upper right lateral incisor (#12) bracket. A wire mainly contacted the clip (=facial wall). (B) Mesial view of the upper right canine bracket. A wire mainly contacted the vertical slot wall.

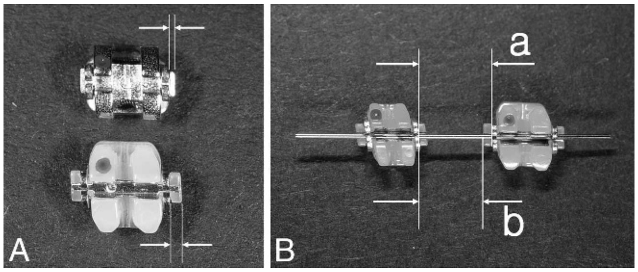

Figure 6. (A) Vertical slot-wall extension (VSE) of SmartClip-SL3 (upper one) and Clarity-SL (lower one) for the upper right central incisor (#11). (B) Clarity-SL for #12 (left one) and #11 (right one) brackets were aligned with archwire. When #12 was displaced to the lingual, the archwire contacted the distal margin of the VSE of the #11 bracket and the mesial clip of the #12 bracket. Eventually, the distance between the bracket margins decreased from A to B.

creased.[27] Since the VSEs of Clarity-SL are longer than those of SmartClip-SL3 (Figure 6), they would contribute to an increase in FF of Clarity-SL in HD.

From the clinical aspects, for the initial leveling/alignment with A-NiTi, Damon-Q and In-Ovation-C are recommended as a result of their lower FFs in both VD and HD, compared with the other combinations of SLBs and A-NiTi (Figures 3 and 4A,B). If the initial leveling/alignment is performed using Cu-NiTi, Damon-Q and Damon-3Mx are recommended for their lower FFs, compared to the other combinations of SLBs and archwires, all other factors being equal (Figures 3 and 4C,D).

The use of a stereolithographically made typodont system, which can simulate malocclusion status and the periodontal ligament space, still has some limitations. Further studies regarding rotation, mesiodistal tipping, and labiolingual inclination of individual teeth are needed.

CONCLUSIONS

- It is necessary to develop SLBs with low friction in both VD and HD of teeth since the frictional properties of SLBs would be different between VD and HD of teeth.

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