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In-vitro investigation of the mechanical friction properties of a computer-aided design and computer-aided manufacturing lingual bracket system under diverse tooth displacement condition

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Objective: The purpose of this study was to compare the static (SFF) and kinetic frictional forces (KFF) of a computer-aided design and computer-aided manufacturing lingual bracket (CAD/CAM-LB) with those of conventional LB (Con-LB) and Con-LB with narrow bracket width (Con-LB-NBW) under 3 tooth displacement conditions. **Methods:** The samples were divided into 9 groups according to combinations of 3 LB types (CAD/CAM-LB [Incognito], Con-LB [7th Generation, 7G], and Con-LB-NBW [STb]) with 3 displacement conditions (no displacement [control], maxillary right lateral incisor with 1-mm palatal displacement [MXLI-PD], and maxillary right canine with 1-mm gingival displacement [MXC-GD]; n = 6/group). While drawing a 0.016-inch copper or super-elastic nickel-titanium archwire with 0.5 mm/min for 5 minutes in a chamber maintained at 36.5°C, SFF and KFF were measured. The Kruskal–Wallis method with Bonferroni correction was performed. **Results:** The Incognito group demonstrated the highest SFF, followed by the 7G and STb groups ([STb-control, STb-MXLI-PD, Stb-MXC-GD] < [7G-MXC-GD, 7G-MXLI-PD, 7G-control] < [Incognito-MXLI-PD, Incognito-control, Incognito-MXC-GD]; $p < 0.001$). However, there were no significant differences in SFF among the 3 displacement conditions within each bracket group. Within each displacement condition, the Incognito group demonstrated the highest KFF, followed by the 7G and STb groups ([STb-control, STb-MXLI-PD] < Stb-MXC-GD < 7G-MXLI-PD < [7G-control, 7G-MXC-GD] < [7G-MXC-GD, Incognito-MXLI-PD, Incognito-control] < [Incognito-control, Incognito-MXC-GD]; $p < 0.001$). MXC-GD exhibited higher KFFs than MXLI-PD in the same bracket group. **Conclusions:** The slot design and ligation method of the CAD/CAM-LB system should be modified to reduce SFF and KFF during the leveling/alignment stage.
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Key words: Lingual bracket, Wire, Frictional properties, Tooth displacement

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INTRODUCTION

Lingual orthodontic appliances have been evolving with respect to the design of brackets and archwires.[1-10] There are 3 concepts regarding development of lingual orthodontic treatment. The first concept is the use of computer-aided design and computer-aided manufacturing lingual bracket (CAD/CAM-LB). A customized base can be fabricated to match the anatomical variations of the lingual surfaces of each individual tooth, related to difficulties in precise bracket positioning and accurate finishing.[5] The first commercially available CAD/CAM-LB is Incognito (3M Unitek, Bad Essen, Germany), which is made by gold alloy casting; importantly, it demonstrates a lower wear resistance to fretting and sliding, compared with nickel-titanium or ferrous alloys.[11] Therefore, when an archwire made of nickel-titanium or ferrous alloy slides along these gold alloy brackets, it leaves an imprint and wear in the slot, resulting in increased friction.[12] In addition, there are several differences in the ligation method, archwire shape, and bracket slot orientation of the anterior tooth between CAD/CAM-LB and conventional LB (Con-LB) systems.[10,13] The second concept is the use of lingual straight wire. Mushroom archwires, which are used in conventional lingual orthodontic treatment, have several disadvantages, which include complicated archwire bending, vertical steps and bowing during leveling and alignment, and difficulty in arch coordination between maxillary and mandibular arches.[6,7] Therefore, a lingual straight wire is needed to make leveling and alignment more effective; moreover, this allows arch coordination to be less difficult, and the mechanics to be easy and simple.[6,7] The third concept is the application of sliding mechanics using LB with narrow bracket width.[6,7] To use sliding mechanics, the bracket width of the LB must be reduced to compensate for the decrease in interbracket distance at the lingual side, compared with that of the labial side; furthermore, the archwire shape should be changed from mushroom archwire to straight archwire.[6,7,10]

When measuring the frictional forces of the LB system, it is more appropriate to adopt an experimental design that uses the entire dentition set with an initial malocclusion condition, rather than 1 or several LBs lined up in a single row.[10,14-20] Moreover, there have been few studies involving comparison of the frictional properties of Con-LB, Con-LB with narrow bracket width (Con-LB-NBW), and CAD/CAM-LB.[17-20] Therefore, the objective of the present *in vitro* mechanical study was to compare the static (SFF) and kinetic frictional forces (KFF) of CAD/CAM-LB with those of Con-LB and Con-LB-NBW under 3 tooth displacement conditions when drawing a leveling/alignment wire. The null hypothesis was that there would be no significant differences in SFF and KFF according to LB types or tooth displacement conditions.

MATERIALS AND METHODS

The samples were divided into 9 groups based on combinations of 3 types of LBs and 3 conditions of tooth displacement (n = 6 per group, Figure 1).

Three types of LBs

The 3 LB systems were comprised of 1 Con-LB (7th Generation [7G]; Ormco, Orange, CA, USA), 1 Con-LB-NBW (STb; Ormco) and 1 CAD/CAM-LB (Incognito; 3M Unitek). The features of the LB systems are provided in Table 1. Three dimensional (3D) virtual tooth models with root (Orapix, Anyang, Korea) were fabricated using computed tomography data, volume rendering technique, and the Viper™ Pro SLA® System (3D Systems Corporation, Rock Hill, SC, USA).[10,21-23] Because of the complexity of the periodontal ligament (PDL) space, 0.7

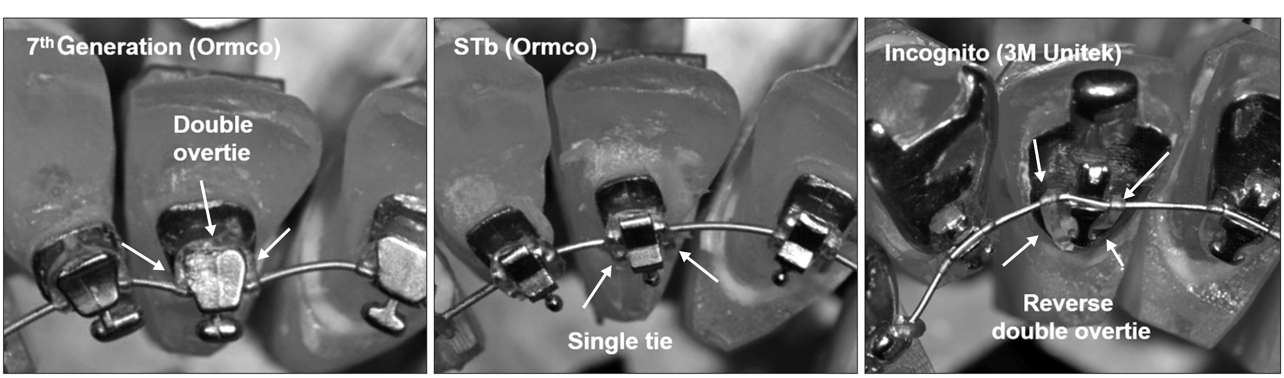

Figure 1. Double overtie in conventional lingual bracket (Con-LB) (7th Generation; Ormco, Orange, CA, USA), single tie in Con-LB with narrow bracket width (STb; Ormco), and reverse double overtie in computer-aided design and computer-aided manufacturing lingual bracket (Incognito; 3M Unitek, Bad Essen, Germany). Arrows indicate the ligation method.

Table 1. Features of the lingual bracket systems

	7th Generation	STb	Incognito
Bracket type	Conventional lingual bracket	Conventional lingual bracket with narrow bracket width	Computer-aided design and computer-aided manufacturing lingual bracket
Manufacturer	Ormco, Orange, CA, USA	Ormco, Orange, CA, USA	3M Unitek, Bad Essen, Germany
Bracket			
Slot	Edgewise slot	Edgewise slot	Ribbonwise slot
Slot size (inch)	0.018	0.018	0.018
Slot orientation			
Anterior	Horizontal	Horizontal	Vertical
Posterior	Horizontal	Horizontal	Horizontal
Base type	Conventional base	Conventional base	Customized base
Ligation			
Anterior	Double overtie (Clear Generation II Powerchain, 639-0002, Ormco)	Single tie (AlastiK Easy-To-Tie Ligature, 3M Unitek)	Reverse double overtie (Clear Generation II Powerchain, 639-0002, Ormco)
Posterior	Single tie (AlastiK Easy-To-Tie Ligature, 3M Unitek)	Single tie (AlastiK Easy-To-Tie Ligature, 3M Unitek)	Single tie (AlastiK Easy-To-Tie Ligature, 3M Unitek)
Wire			
Wire size (inch)	0.016 copper nickel-titanium	0.016 copper nickel-titanium	0.016 super-elastic nickel-titanium archwire
Wire shape	Preformed lingual straight (STb straight wire small, 204-2101, Ormco)	Preformed lingual straight (STb straight wire small, 204-2101, Ormco)	Customized bent (3M Unitek)

mm of space was evenly provided on the outside of the root surface.[10,21-23] We used the same typodont model to fabricate CAD/CAM-LBs (Incognito) and the other LBs (7G and STb). Following attainment of an alginate impression of ideally aligned typodont teeth, which was the same control condition used for other LBs, a white stone model was made and then sent to the company (3M Unitek, Bad Essen, Germany).

Three conditions of tooth displacement

The 3 displacement conditions were no displacement (control), maxillary right lateral incisor with 1-mm palatal displacement (MXLI-PD), and maxillary right canine with 1-mm gingival displacement (MXC-GD). Maxillary teeth replicated using a stereolithographic technique were fixed to an arch-shaped metal frame. After all maxillary teeth in this typodont system were ideally aligned at the origin position using the ovoid arch form (OrthoForm III-Ovoid, 701-723; 3M Unitek, Monrovia, CA, USA), the MXLI was moved 1 mm palatally, or the MXC was moved 1 mm gingivally.[10,21-23] During a pilot study, in the condition involving 2-mm gingival displacement of the maxillary canine, the Incognito group exhibited disengagement of wire from the bracket slot. Therefore, the 2-mm displacement condition was eliminated from the study design. Because the existence of a PDL can affect the degree of frictional properties, the PDL space of each tooth was made and filled with a vinyl polysiloxane impression material (Imprint™ II Garant™ Light Body; 3M ESPE, St. Paul, MN, USA). Its function was to absorb stress during drawing of the archwire.[10,21-23]

Archwire used in the experiment

A full-size preformed lingual straight archwire was used to align the 7G and STb brackets at the origin position; these brackets were then bonded to the lingual tooth surface by curing Transbond XT (3M Unitek, Monrovia, CA, USA).[7,10,24] Then, 0.016-inch copper nickel-titanium (Cu-NiTi) preformed straight lingual archwires (STb straight wire small, 204-2101; Ormco) were inserted for the experiment. After Incognito brackets were bonded using their own incisal or occlusal rest and Transbond XT, a customized bent 0.016-inch super-elastic NiTi archwire (SE-NiTi; 3M Unitek, Monrovia, CA, USA) was inserted for the experiment (Table 1 and Figure 2).[5]

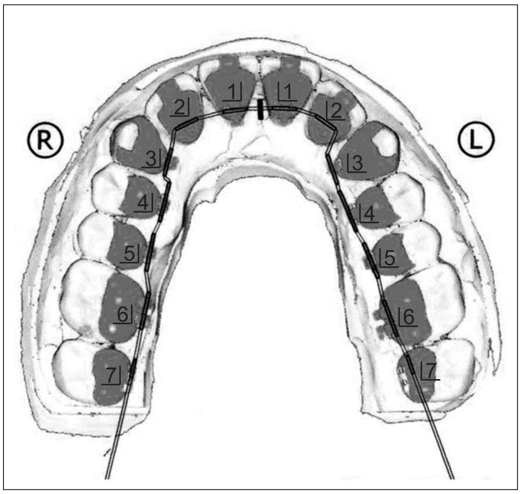

Figure 2. Screenshot of a customized bent archwire used in the computer-aided design and computer-aided manufacturing lingual bracket system (Incognito; 3M Unitek, Bad Essen, Germany).

Ligation method

To ligate the anterior tooth brackets with an elastic module, a single tie method was used for the STb group; a double overtie method was used for the 7G group; and a reverse double overtie method was used for the Incognito group (Figure 1 and Table 1).[5,7,10,25] To ligate the posterior brackets with an elastic module (7G, STb, and Incognito), a single tie method was used for all 3 LB groups (Table 1).[5,7,10,25] After ligation, a 3-minute waiting period was used to ensure similar conditions for stress relaxation and ligature force.[10,21-23,26-28]

Drawing condition

The typodont system was placed in a chamber, in which the temperature was maintained at 36.5 ± 0.3°C. After an adaptor gripped the archwire extruded from the tube of the maxillary right second molar, artificial saliva (Taliva®; Hanlim Pharm. Co., Ltd., Seoul, Korea) was sprayed onto the bracket slot. While drawing an archwire with a specific speed and duration (0.5 mm/minute for 5 minutes), SFF and KFF were measured using a mechanical testing machine (Model 4466; Instron, Norwood, MA, USA).[10,21-23] After the experiment, the bracket slots of maxillary dentition were immediately rinsed with distilled water and alcohol and then dried using an air syringe. Then, a new wire was inserted for the next experiment.

Variable measurement

The SFF was defined as the maximal point of the initial rise. The KFF was calculated as the average of the frictional forces, from the SFF point to the end of experiment (Figure 3).[10,21-23]

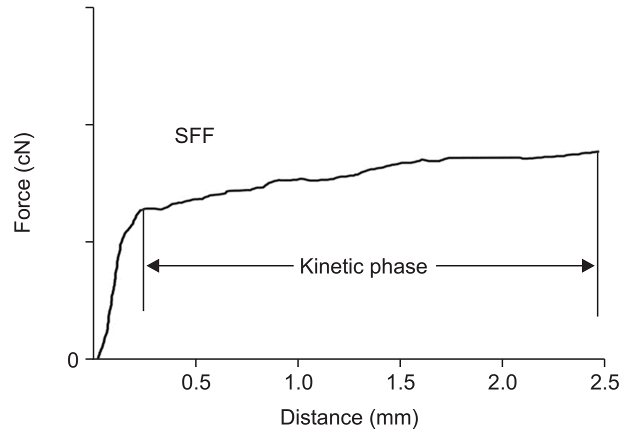

Figure 3. Definitions of static (SFF) and kinetic frictional forces (KFF) in this study. SFF was defined as the maximal point of the initial rise; KFF was calculated as the average of the frictional forces, from the SFF point to the end of experiment.

Statistical analysis

The Kruskal–Wallis method and Bonferroni correction were performed using SPSS Statistics for Windows, version 12.0 (SPSS Inc., Chicago, IL, USA). The levels of significance were set to $p < 0.05$ for the Kruskal–Wallis method and $p < 0.0055$ for the Bonferroni correction.

RESULTS

Comparison of SFF according to bracket type and displacement condition (Table 2 and Figure 4)

There was a significant difference in SFF among the 9 groups ([STb-control, STb-MXLI-PD, Stb-MXC-GD] < [7G-MXC-GD, 7G-MXLI-PD, 7G-control] < [Incognito-MXLI-PD, Incognito-control, Incognito-MXC-GD]; $p < 0.001$). The Incognito group exhibited the highest SFF, followed by the 7G and STb groups. However, there were no significant differences in SFF among the 3 displacement conditions within each bracket group.

Comparison of KFF according to bracket type and displacement condition (Table 2 and Figure 5)

There was a significant difference in KFF among the 9 groups ([STb-control, STb-MXLI-PD] < Stb-MXC-GD < 7G-MXLI-PD < [7G-control, 7G-MXC-GD] < [7G-MXC-GD, Incognito-MXLI-PD, Incognito-control] < [Incognito-control, Incognito-MXC-GD]; $p < 0.001$). Although the difference in KFF exhibited a more complex pattern than that of SFF, the Incognito group also demonstrated the highest KFF, followed by the 7G and STb groups within each displacement type. In addition, MXC with

Table 2. Comparison of static and kinetic frictional forces (cN) among the 9 experimental groups

Frictional force	Displacement	7th Generation	Incognito	STb	*p*-value	Bonferroni correction
Static	Control (no displacement)	808.6 ± 23.9	1,635.8 ± 70.5	256.5 ± 58.5	< 0.001***	(STb-control, STb-MXLI-PD, STb-MXC-GD) < (7G-MXC-GD, 7G-MXLI-PD, 7G-control) < (Inc-MXLI-PD, Inc-control, Inc-MXC-GD)
	1 mm PD of MXLI (MXLI-PD)	755.8 ± 80.5	1,630.7 ± 51.0	310.1 ± 14.0		
	1 mm GD of MXC (MXC-GD)	741.1 ± 85.1	1,750.3 ± 134.0	366.1 ± 51.7		
Kinetic	Control (no displacement)	1,602.6 ± 74.0	1,845.6 ± 49.1	358.0 ± 30.6	< 0.001***	(STb-control, STb-MXLI-PD) < STb-MXC-GD < 7G-MXLI-PD < (7G-control, 7G-MXC-GD) < (7G-MXC-GD, Inc-MXLI-PD, Inc-control) < (Inc-control, Inc-MXC-GD)
	1 mm PD of MXLI (MXLI-PD)	1,453.1 ± 62.8	1,747.7 ± 83.8	387.3 ± 31.7		
	1 mm GD of MXC (MXC-GD)	1,730.0 ± 78.1	1,957.7 ± 101.8	611.2 ± 72.7		

Values are presented as mean ± standard deviation.
PD, Palatal displacement; MXLI, maxillary right lateral incisor; GD, gingival displacement; MXC, maxillary right canine; 7G, 7th Generation; Inc, Incognito.
7th Generation: Ormco, Orange, CA, USA; STb: Ormco; Incognito: 3M Unitek, Bad Essen, Germany.
The Kruskal–Wallis method and Bonferroni correction were performed.
****p* < 0.001.

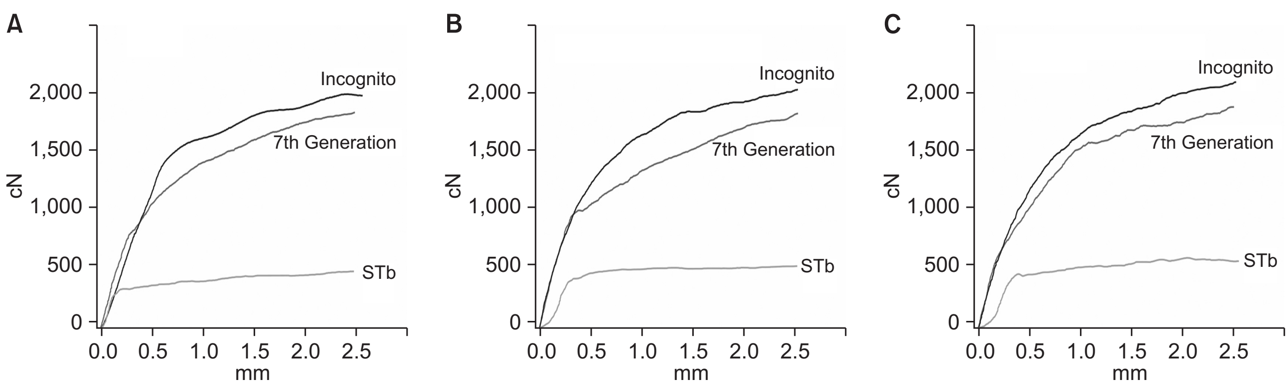

Figure 4. Comparison of frictional forces among the 3 lingual bracket types under the same displacement condition. **A**, Control, no displacement. **B**, 1-mm palatal displacement of the maxillary right lateral incisor. **C**, 1-mm gingival displacement of the maxillary right canine.
7th Generation: Ormco, Orange, CA, USA; STb: Ormco; Incognito: 3M Unitek, Bad Essen, Germany.

1-mm gingival displacement exhibited higher KFFs than did MXLI with 1-mm palatal displacement in the STb, 7G, and Incognito groups; it also showed higher KFFs than did the control in the STb group.

DISCUSSION

This study compared the frictional properties of the CAD/CAM-LB (Incognito) with those of Con-LB and Con-LB-NBW (7G and STb). The findings that the Con-LB-NBW (STb) group showed lower SFF and KFF than the Con-LB (7G) group and the CAD/CAM-LB (Incognito) group under the 3 displacement conditions ($p < 0.001$; Table 2 and Figure 5) were identical with the results of previous studies,[10,17,18] suggesting that differences in bracket type, bracket width, and ligation method are the main causes of differences in SFF and KFF among these LBs.

In the present study, the CAD/CAM-LB group (Incognito) produced higher SFF and KFF than did the conventional LB groups (7G and STb) under the 3 displacement conditions ($p < 0.001$; Table 2 and Figure 5). This divergence might be due to the following differences between the CAD/CAM-LB (Incognito) and conventional LBs (7G and STb). First, differences in the microstructural and elemental compositions of the alloys might contribute to higher SFF and KFF in the Incognito bracket. Second, because the slot size of the Incognito

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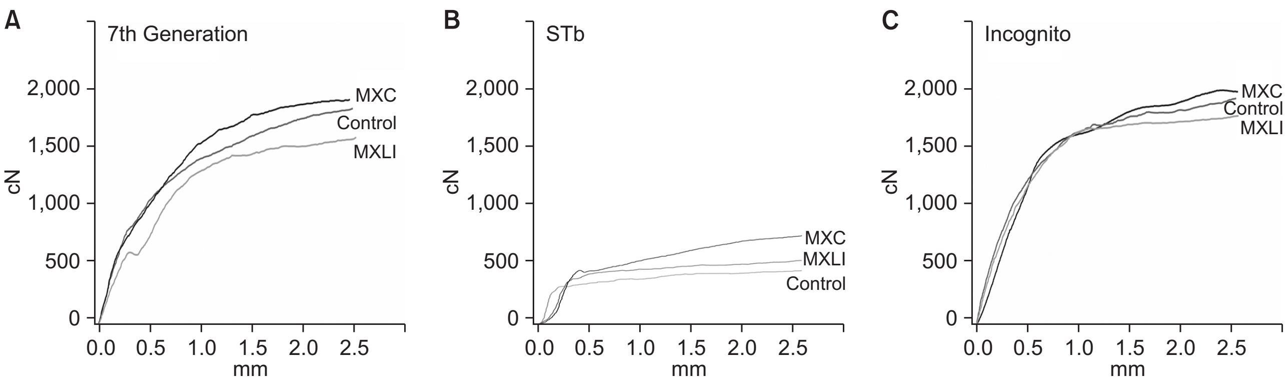

Figure 5. Comparison of frictional forces among the 3 displacement conditions within the same lingual bracket type. **A**, 7th Generation; **B**, STb; **C**, Incognito.
Control, No displacement; MXC, 1-mm gingival displacement of the maxillary right canine; MXLI, 1-mm palatal displacement of the maxillary right lateral incisor.
7th Generation: Ormco, Orange, CA, USA; STb: Ormco; Incognito: 3M Unitek, Bad Essen, Germany.

bracket is smaller than those of the STb and 7G brackets (0.0184 inch for the 7G bracket and 0.0183 inch for the STb bracket vs. 0.0181 inch for the Incognito bracket, $p < 0.05$),[13] the Incognito bracket could exhibit increased SFF and KFF. Third, regarding the bracket slot orientation of the maxillary anterior teeth, Incognito brackets use a vertical slot, whereas both STb and 7G brackets use a horizontal slot. Differences in the bracket slot orientation of the maxillary anterior teeth can affect the pattern of contact and degree of binding between the bracket slot and archwire, resulting in differences in frictional properties.[10] Because the Incognito anterior tooth bracket has a vertical slot, a wire can be inserted into bracket slot from the incisal side; it can then be ligated using the reverse double overtie method. When the maxillary canine is displaced in the gingival direction, a wire is deformed toward the occlusal side and contacts with an elastic ligature, resulting in increased friction. However, because the other anterior tooth brackets (7G and STb) have a horizontal slot, an occlusally deformed wire contacts with the slot wall, resulting in a relatively lower increase of friction, compared with contact with the elastic ligature of an Incognito anterior tooth bracket. Fourth, regarding the ligation method for maxillary anterior teeth, Incognito brackets use the reverse double overtie method, which can produce tighter binding between the archwire and bracket slot, relative to that of the single tie method used by STb brackets. To reduce frictional force in lingual brackets, in addition to modification of the bracket slot, it is also necessary to change the ligation method to a specifically designed single-tie ligature.[27,28] Fifth, because the Incognito system used a customized bent archwire, it can increase SFF and KFF more than the preformed straight lingual archwire used in the 7G and STb systems. In summary, the factors that can lead to differences between the Incognito system and other conventional LB systems appear to be the microstructural and elemental compositions of the alloys, slot sizes, bracket slot orientations of the anterior teeth, ligation methods, and archwire configurations.

Within the same bracket groups, there were no significant differences in SFF among the 3 displacement conditions (Table 2). This finding indicates that displacement conditions do not affect SFF significantly within the same bracket type; moreover, bracket types, ligation methods, and other factors might be more important for determining the amount of SFF. The present study shows that all LB groups had higher KFFs than SFFs (Table 2). However, previous frictional studies of conventional-ligating or self-ligating labial brackets have shown higher SFFs than KFFs.[10,21-23] This might be a result of mechanical differences between labial and lingual bracket systems, including interbracket distance, arch perimeter, and anterior curvature of the arch.[4,9,10] Notably, these differences might influence the load-deflection and stiffness of the archwire and produce tight binding between the bracket slot and wire during the drawing of an archwire, resulting in a greater increase in KFF than in SFF.[4,8]

This *in vitro* mechanical study demonstrated that the CAD/CAM-LB group (Incognito) exhibited higher SFF and KFF than the Con-LB and Con-LB-NBW groups (7G and STb) under the 3 displacement conditions. However, due to differences in experimental conditions, including bracket types, ligation methods, and archwire shapes, the results should be interpreted with caution. Because there are anatomical differences in the thickness and shape of PDL space between these model teeth and real teeth,[29] it is necessary to improve the experimental design, and to provide a more sophisticated 3D model[30] that resolves these limitations in further studies. In addition, it is necessary to improve the typodont design via incorporation of 3D sensors for measuring forces and moments along 6 axes in future studies.[29]

CONCLUSION

• The null hypothesis, that there would be no significant differences in SFF and KFF according to LB types or tooth displacement conditions, was rejected.

• The slot design and ligation method of the CAD/CAM-LB system (Incognito) should be modified to reduce SFF and KFF during the leveling/alignment stage.

CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

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