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In Vitro Study of the Effect of Tooth Displacement and Vibration on Frictional Force and Binding-and-Releasing Phenomenon

치아변위와 진동적용이 마찰력과 구속-풀림 현상에 미치는 효과에 관한 연구

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서유진

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ABSTRACT

In Vitro Study of the Effect of Tooth Displacement and Vibration on Frictional Force and Binding-and-Releasing Phenomenon

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Objective: The purpose of this *in vitro* study was to evaluate the effect of tooth displacement and vibration on frictional force and binding-and-releasing phenomenon (BRP) in conventional bracket (CB) and passive-type self-ligating bracket (PSLB) when used with leveling/alignment wire, respectively.

Materials and Methods: Two types of bracket [CB (Victory, 3M-Unitek, Monrovia, CA, USA) and PSLB (Damon-Q, Ormco, Orange, CA, USA)] were tested under two conditions: tooth displacement [2 mm lingual displacement of the maxillary right lateral incisor (LD); 2 mm gingival displacement of the maxillary right canine (GD); no displacement (control)] and vibration [presence and absence (30 Hz and 0.25 N)] (N = 10/group). A stereolithographically-made typodont system was used. After artificial saliva was applied to the bracket slot, static/kinetic frictional forces (SFF/KFF) and frequency/amplitude of BRP were measured during drawing of 0.018 inch Copper-NiTi archwire at a speed of 0.5 mm/min for 5 minutes at 36.5 ℃. Two-way analysis of variance and *post hoc* Bonferroni test were performed.

Results:

(1) SFF and KFF significantly increased in order of control, LD, and GD groups among tooth displacement types in both CB and PSLB (all $p < 0.001$). SFF and KFF under vibration condition significantly decreased compared to non-vibration condition in PSLB (all $p < 0.001$), but they did not show significant differences in CB.

(2) The effect of vibration to increase BRP frequency was generally reduced according to tooth displacement in both CB ($p < 0.01$) and PSLB ($p < 0.001$).

(3) The effect of vibration to decrease BRP amplitude was generally reduced according to tooth displacement in CB ($p < 0.001$). However, in PSLB, BRP amplitude significantly increased in order of control, LD, and GD groups among tooth displacement types ($p < 0.001$) and significantly decreased under vibration condition than that under non-vibration condition ($p < 0.001$).

Conclusions: The effect of tooth displacement to increase the frictional force showed similar tendency in both CB and PSLB. However, the effect of vibration to decrease the frictional force and BRP amplitude was more prominent in PSLB than that in CB. Therefore, these results might suggest a possibility that the change in BRP by vibration indirectly induced decreases in frictional force in PSLB.

Keywords: vibration, frictional force, binding-and-releasing phenomenon, passive-type self-ligating bracket, conventional bracket

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I. INTRODUCTION

The resistance-to-sliding of a bracket along an archwire arises from two sources: the force of ligation and the force of binding in the absence of extreme forces that cause physical notching of the archwire.[1,2] Although frictional force or resistance-to-sliding has been well investigated,[3-11] the effect of binding on frictional properties has also received attention.[1,12-16]

The effect of binding on resistance-to-sliding is important at the leveling/alignment stage because misaligned teeth due to crowding, rotation, angulation, and vertical discrepancy result in wire deflection in contact with the edges of the bracket slots.[17,18] In an active configuration where the contact angle (θ) is greater than the critical contact angle (θ_c), the binding-and-releasing phenomenon (BRP) may be more significant than the frictional component of resistance-to-sliding.[12,13] Therefore, how to release the binding between bracket slot and wire is important in orthodontic tooth movement.

Vibration generated by mastication or swallowing in the intraoral environment can force an archwire to be released from the binding, which is suggested as a walking effect or stick-slip behavior.[19,20] To date, vibration in orthodontics has been studied in terms of two aspects - biological and mechanical effects. Vibration has been suggested to stimulate the periodontal tissue, resulting in acceleration of tooth movement.[21-24] Meanwhile, vibration has been reported to reduce resistance-to-sliding compared to non-vibration condition.[20,25-28]

Although previous studies [20,25-28] emphasized the intraoral dynamic factor, they had limitations in the standardization of vibration and simulation of the intraoral environment.

Therefore, the purpose of this *in vitro* study was to evaluate the effect of tooth displacement and vibration on frictional force and BRP in conventional bracket (CB) and passive-type self-ligating bracket (PSLB) when used with leveling/alignment wire, respectively. The null hypothesis was that there were no significant differences in the effect of tooth displacement and vibration on frictional force and BRP in CB and PSLB when used with leveling/alignment wire, respectively.

II. REVIEW OF LITERATURE

1. Friction in orthodontics

Friction is defined as a force that resists motion when one object moves tangentially against another. Friction in orthodontics occurs when the archwire slides through the bracket slot during tooth movement, which is called resistance-to-sliding. The resistance-to-sliding of a bracket along an archwire is ever present in orthodontics during initial leveling and alignment as well as space closure in sliding mechanics.[17] For orthodontic tooth movement, the bracket or archwire should overcome this resistance-to-sliding.

1-1. Contributing factors of friction in orthodontics

Factors that may influence resistance-to-sliding have been reported as follows: (1) material of the bracket and archwire [1,7,8,11,17,29-33], (2) bracket design and slot size [4,6,7,18,33-37], (3) archwire size and dimension [4,6,7,11,30,33,38], (4) type of ligation [9,19,31,39-41], (5) angulation, torque or rotation at the bracket/wire interface [4,13,15,16,37,39,42,43], (6) interbracket distance [6,8,38], (7) saliva [1,3,6,18,35,36,44], (8) temperature [18], and (9) vibration condition.[20,25-28]

1-2. Binding issue in orthodontics

Kusy and Whitley [1] and Burrow [2] divided the resistance-to-sliding into three components: (1) classical friction by contact between wire and bracket slot surfaces, (2) binding created when the tooth tips or the wire flexes so that there is contact between the wire and the corners of the bracket, and (3) notching, when permanent deformation of the wire occurs at the wire-bracket corner interface.

In a passive configuration, where the contact angle (θ) between archwire and bracket slot is less than critical contact angle (θ_c), only classical friction is important because binding and notching are not existed.[1,12] In an active configuration where θ is greater than θ_c due to misaligned or tipped teeth during sliding, binding increasingly restricts the sliding as classical friction becomes only a small part of binding.[1,12,13] When θ is much greater than θ_c, both classical friction and binding become negligible relative to notching.[12]

2. Vibration issue in orthodontics

2-1. Binding-and-releasing phenomenon (BRP) between the bracket slot and archwire

Tooth movement along an archwire occurs as a series of small tipping and uprighting movements.[45] Binding between the bracket and archwire increases during tooth tipping until equilibrium reaches between the applied force and the couple produced at the bracket-archwire interface, and eventually disturbs further tooth movement.[12,13,45] However, this binding is released by tooth uprighting produced by wire displacement, tooth mobility within the periodontium, or subsequent alveolar bone remodeling.[27,46] Therefore, Articolo and Kusy [13] suggested that the components of BRP may be more significant than the classical frictional component of resistance-to-sliding between bracket and wire.

Swartz [47] described that the binding between archwire and bracket is intermittently released as a result of the mobility of the teeth, the flexure of the archwire, and the yielding of ligatures and that the frequency of intermittent contact between archwire and bracket is highly variable.

Braun et al.[26] reported that perturbations by random finger touch (a mean force of 87.2 grams) resulted in frictional resistance to momentarily become zero. Although they did not relate these results to BRP, they suggested that the relative frequency of frictional resistance approaching zero would be important in resistance-to-sliding.

Although Olson et al.[20] reported that the stick-slip behavior at bracket-archwire interfaces was more affected by amplitude than frequency of vibration, they studied only the frequency and amplitude of vibration itself, not BRP. They used terms as follows: the frequency meant how fast the wire is moving up and down and the amplitude, the amount of vertical displacement of the wire.

2-2. Vibration in the oral environment

Vibration can be generated by mastication, swallowing, or speaking in oral environment. Normal mastication forces are in range 3-9 kg[48] and chewing contact frequencies are 145 cycles per minute.[49] Since the periodontal ligament and alveolar bone become more flexible during tooth movement, tooth mobility has been investigated to increase during orthodontic treatment.[50]

These oral environment factors can produce perturbation or vibration at the bracket/archwire interface, which makes an archwire released from the binding and affects the frictional forces at the interfaces.[19,20,26]

2-3. Effects of vibration in orthodontics

2-3-1. Biologic effect of vibration in orthodontics

Vibration is known to stimulate the periodontal tissue, to promote osteogenesis by inducing expression of bone regulators and differentiation of periodontal ligament stem cells, and to induce activation of osteoclasts at the compression site and resorption of alveolar bone, resulting in acceleration of tooth movement.[21-24]

Zhang et al.[24] evaluated the effect of vibration on proliferation, differentiation, and osteogenic potential of human periodontal ligament stem cell (PDLSC). After human PDLSCs were isolated from the premolar teeth and exposed to low-magnitude, high-frequency mechanical vibration (magnitude: 0.3 g; frequency: 10-180 Hz; 30 min/24 h), they found that low-magnitude, high-frequency mechanical vibration promoted osteogenic differentiation of human PDLSCs. Alikhani et al.[23] investigated the effect of high-frequency acceleration on osteogenesis. The experimental group underwent localized accelerations at different frequencies for 5 min/day on the occlusal surface of the maxillary right first molar at a very low magnitude of loading (4 $\mu\varepsilon$). They found that application of high-frequency acceleration significantly increased alveolar bone formation. These studies proposed that a simple mechanical therapy might play a significant role in alveolar bone formation and maintenance.

2-3-2. Mechanical effect of vibration in orthodontics

Several studies have reported that vibration significantly reduced the resistance-to-sliding compared to non-vibration condition.[20,25-28] These results suggested that resistance-to-sliding in dynamic oral environment might be much lower than that in non-vibrated laboratory model.

Braun et al.[26] studied the effect of finger tapping on resistance-to-sliding in the simulated dynamics of the oral environment. They reported that resistance-to-sliding was effectively reduced to zero each time minute with relative movements occurred at the bracket/archwire interfaces. Factors such as the degree of dental tipping, relative archwire/slot clearances, and method of tying, did not have a measurable effect on resistance-to-sliding. However, since their study was limited to the examination of the effects of random perturbations on one bracket/archwire interface, multiple interfaces should be evaluated to simulate the dynamics of the intraoral environment.

O’Reilly et al.[27], in an *ex vivo* study with oscillation of the bracket to release the binding between bracket and archwire while measuring resistance-to-sliding, investigated the effect of repeated bracket displacement on resistance-to-sliding. The results showed that the reduction in resistance-to-sliding depended on the kinds of archwire material. Over the range of displacements tested, there were 80 percent and 27 percent reduction associated with 0.019 x 0.025 inch stainless steel wire and 0.019 x 0.025 inch beta-titanium wire, respectively. They suggested that the *in vivo* influence of friction between bracket and archwire may have significantly less clinical importance than previously stressed.

Olson et al.[20] evaluated the stick-slip behavior under the several vibration conditions [frequency of low (60 Hz), medium (100 Hz), and high (140 Hz); amplitude of 110 mV (0.12 mm), 150 mV (0.16 mm), and 190 mV (0.20 mm); Damon Q (Ormco, Orange, CA, USA), Victory (3M Unitek, Monrovia, CA, USA) with active ligation by using an elastomeric ligature]. The results showed that resistance-to-sliding was significantly reduced by medium and high amplitudes of vibration, not by the frequency of vibration. However, either the normal force created during bracket tipping or the normal force from ligation was too great to be overcome by approximately 146 cN of retraction force or the vibrational energy input for both bracket types.

Iwasaki et al.[51] examined the effects of ligation force and mastication on friction when sliding a bracket along an archwire. Ten subjects chewed gum with the device in place to determine whether vibration eliminated friction. The results suggested that vibration introduced by mastication did not eliminate friction, which was different from other studies.

3. Limitations of experimental design in the previous studies

Too much simplification of the complex biomechanical interactions may have resulted in an over-estimation of the clinical significance of friction.[47] Previous studies have limitations in their experimental setups as follows:[20,25-28,51] First, they drew a straight wire through one to four brackets aligned in a straight row. However, in human dentition, an archwire contacts with multi-surfaces of brackets aligned in arch-form dentition. Second, they bonded the brackets to the stiff materials. However, the teeth are surrounded by periodontal ligament which can allow some mobility. Third, oral condition has consistent saliva and a temperature at 36.5 ℃. However, they did not include these intraoral factors which might influence the bracket-archwire interfaces and nickel-titanium properties. Fourth, since tooth, bracket, and archwire are simultaneously affected by vibration, it is necessary to apply vibration to the whole complex in the test design.

III. MATERIALS AND METHODS

Two types of bracket were tested [CB (Victory, 3M-Unitek, Monrovia, CA, USA) and PSLB (Damon-Q, Ormco, Orange, CA, USA)]. All brackets were made of stainless steel (SS) and had a 0.022 inch slot.

For each bracket, the samples consisted of six groups according to combinations of two experimental conditions: (1) three types of tooth displacement [2 mm lingual displacement of the maxillary right lateral incisor (LD), Fig. 1-A; 2 mm gingival displacement of the maxillary right canine (GD), Fig. 1-B; and no displacement (control)] and (2) the presence and absence of vibration. Each group was tested 10 times with a new wire each time.

Vibration was applied by an electronic vibratory device with one mode of vibration (AcceleDent®, OrthoAccel Technologies Inc., Bellaire, TX, USA; 30 Hz, 0.25 N). The device was placed between the maxillary and mandibular typodonts that represented a patient biting the device. To reproduce consistent and passive bite condition for each test, the complex of the typodonts and the AcceleDent system (OrthoAccel Technologies Inc.) was hold together using silicone bites and two metal fixation frames per side (Fig. 1-C).

Among leveling/alignment archwires used in clinical situation, 0.018 inch copper nickel-titanium (Cu-NiTi) archwire (Damon, Ormco) was selected as a test wire. For CB, elastic ligatures (Unistick Ligatures, American Orthodontics, Sheboygan, WI, USA) were used. A three-minute waiting period was given to allow for a reproducible amount of ligature force and stress relaxation of the elastic ligatures.[6-8,11]

A custom-designed typodont system previously used [11] was refabricated. This typodont system had the full maxillary dentition fixed to arch-shaped metal frame which could allow each tooth to move individually. At the zero position, all teeth were aligned in the ideal position according to the ovoid arch form (OrthoForm III-Ovoid, Reference No. 701-723, 3M-Unitek). For accurate and reproducible bracket positioning, the indirect bonding jigs for all brackets were fabricated at the zero position. Each tooth had its artificial periodontal ligament (PDL) space filled with a silicone impression material (Imprint™ II Garant™ Light Body Vinyl Polysiloxane Impression Material, 3M ESPE, Seefeld, Germany) emulating PDL and the mobility of human tooth. Since the stress-absorbing mechanism of PDL might affect the resistance-to-sliding, it is important to emulate PDL.[11,52]

Artificial saliva (Taliva, Hanlim Pharm. Co., Ltd., Seoul, Korea) was applied to the bracket slots (Fig. 1-D). Prior to every test, the archwire was wiped with an alcohol sponge. After each test, the typodont system was washed out and dried thoroughly. Tests were conducted in a chamber at 36.5 ± 0.3 ℃ (Fig. 1-E).

Static/kinetic frictional forces (SFF/KFF) and frequency/amplitude of BRP were measured during drawing of 0.018 inch Cu-NiTi archwire at a speed of 0.5 mm/min for 5 minutes using a mechanical testing machine (Model 4466, Instron, Canton, MA, USA). A custom-designed adaptor gripped one distal end of the archwire, which was extruded from the maxillary right second molar tube. The definitions of SFF, KFF, and frequency and amplitude of BRP are listed in Fig. 2.

The sample size was determined by a power analysis using a sample size determination program Ver. 2.0.1 (Seoul National University Dental Hospital, Registration number

2007-01-122-004453, Seoul, Korea). The values of mean and standard deviation derived from a previous study [11] were used for the power analysis.

Two-way analysis of variance (ANOVA) and *post hoc* Bonferroni test were performed to evaluate the effect of tooth displacement and vibration on SFF, KFF, and frequency and amplitude of BRP. The level of significance for all of the tests was set at $p < 0.05$.

IV. RESULTS

1. Effect of tooth displacement and vibration in conventional bracket (CB)

SFF and KFF significantly increased in order of control, LD, and GD groups among tooth displacement types (all $p < 0.001$, Table 1, Fig. 3-A and B). However, they did not show significant differences between vibration and non-vibration conditions (Table 1).

Interaction effect between tooth displacement types and vibration conditions was observed at both frequency and amplitude of BRP ($p < 0.01$, $p < 0.001$, respectively, Table 1, Fig. 3-C and D). The effect of vibration on the frequency and amplitude of BRP was generally reduced in LD and GD groups compared to control group, respectively (Table 1, Fig. 3-C and D): BRP frequency under vibration condition was increased than that under non-vibration condition ($p < 0.001$, Table 1). Among tooth displacement types, BRP frequency in LD and GD groups was decreased compared to control group ($p < 0.01$, Table 1) especially under vibration condition, while there was no difference under non-vibration condition (Fig. 3-C). BRP amplitude under vibration condition was decreased than that under non-vibration condition ($p < 0.001$, Table 1). Among tooth displacement types, under vibration condition BRP amplitude was increased in LD and GD groups compared to control group (Fig. 3-D), while under non-vibration condition it was decreased in LD and GD groups compared to control group (Fig. 3-D).

2. Effect of tooth displacement and vibration in passive-type self-ligating bracket (PSLB)

SFF and KFF significantly increased in order of control, LD, and GD groups among tooth displacement types (all $p < 0.001$, Table 2, Fig. 4-A and B) and significantly decreased under vibration condition than those under non-vibration condition (all p <

0.001, Table 2). BRP amplitude significantly increased in order of control, LD, and GD groups among tooth displacement types ($p < 0.001$, Table 2, Fig. 4-D) and significantly decreased under vibration condition than that under non-vibration condition ($p < 0.001$, Table 2, Fig. 4-D).

Interaction effect between tooth displacement types and vibration was found only in BRP frequency ($p < 0.001$, Table 2, Fig. 4-C). The effect of vibration on BRP frequency was generally reduced in LD and GD groups compared to control group (Table 2, Fig. 4-C): BRP frequency under vibration condition increased than that under non-vibration condition ($p < 0.001$, Table 2). BRP frequency in LD and GD groups was decreased compared to control group ($p < 0.001$, Table 2, Fig. 4-C) especially under vibration condition, while there was no difference under non-vibration condition (Fig. 4-C).

V. DISCUSSION

Although this study was an *in vitro* one, the authors tried to assess the effect of tooth displacement and vibration on frictional force and BRP in CB and PSLB when used with leveling/alignment wire, respectively. The experimental design was set to simulate clinical conditions as much as possible, including full dentition aligned in arch-shaped form, artificial viscoelastic alternatives to PDL, occlusion state with the maxillary and mandibular dentition, application of artificial saliva, maintenance of body temperature, and vibration generated by the appliance used in clinics.

The findings that SFF and KFF significantly increased in order of control, LD, and GD groups in both CB and PSLB (all $p < 0.001$, Tables 1 and 2, Figs. 3-A and B and 4-A and B) imply that an active configuration occurs between bracket slot and archwire in LD and GD groups and consequently the binding increases in both CB and PSLB. These results were in accordance with previous studies.[1,12,13,15,16,35,36]

When compared to non-vibration condition, CB and PSLB showed different responses in SFF and KFF under vibration condition: no difference in CB (Table 1, Fig. 3-A and B) and significant decrease in PSLB (all $p < 0.001$, Table 2, Fig. 4-A and B). Therefore, the effect of vibration to decrease the frictional forces might be more remarkable in PSLB than that in CB. However, this result was not in accordance with the previous studies which compared PSLB with CB [20] or reported decrease in frictional force in CB.[26,27] These differences might be derived from different test designs using different wires, alignment of brackets, and vibrating condition.

Although BRP frequency was more increased under vibration condition than that under non-vibration condition, the effect of vibration on BRP frequency was generally reduced in LD and GD groups compared to control group in both CB ($p < 0.01$) and PSLB ($p < 0.001$) (Tables 1 and 2, Figs. 3-C and 4-C). These mean that as the binding increased with tooth displacement, the effect of vibration to increase BRP frequency was reduced in both CB and PSLB. An increase in BRP frequency represents an increase in the number of BRP and decrease in the duration of binding in each cycle.

The changes in BRP amplitude showed a similar pattern with SFF and KFF in PSLB (Table 2, Figs. 4-A, B, and D). BRP amplitude in PSLB significantly increased in order of control, LD, and GD groups among tooth displacement types ($p < 0.001$, Table 2, Fig. 4-D) and significantly decreased under vibration condition than that under non-vibration condition ($p < 0.001$, Table 2, Fig. 4-D). As the binding increased with tooth displacement, BRP amplitude increased. Vibration can decrease BRP amplitude, which means a decrease in the maximum frictional force at the binding-release point. In other words, vibration would decrease the threshold of BRP and facilitate the release of binding. It might be considered as a ‘threshold-decreasing effect’ of vibration on BRP.

In PSLB, both vibration and non-vibration groups demonstrated increases in BRP amplitude from control group to LD and GD groups ($p < 0.001$, Table 2, Fig. 4-D). However, in CB, BRP amplitude showed a different pattern of change from control group to LD and GD groups between vibration and non-vibration groups (an increase under vibration condition and a decrease under non-vibration condition, Table 1, Fig. 3-D). This decrease in BRP amplitude of CB under non-vibration condition (Fig. 3-D) seemed to occur as follows: Although there were higher values of SFF and KFF in CB than those in PSLB (Tables 1 and 2, Figs 3-A and B, 4-A and B), the archwire could be drawn through CB without complete release of binding by the testing machine due to flexibility of 0.018 inch Cu-NiTi. Therefore, BRP amplitude in CB might be decreased in tooth displacement under non-vibration condition due to incomplete release of strong binding. However, it is necessary to test with round or rectangular SS wires to verify this assumption.

Bracket slot configuration and ligation methods have been reported to affect frictional force and critical contact angle.[4,11,12,17,18,35,36,54] When an archwire is engaged in the bracket slot, the effective slot dimension is mainly determined by the fourth slot wall (or ligation method) and type of tooth displacement. Since the fourth slot wall of CB is an elastomeric ligature, the effective slot width can be increased by a ligature surrounding the bracket wings. Also, the effective slot depth and height can be changed by a ligature pushing the archwire to the bracket slot (Fig. 5). However, the fourth slot wall of PSLB is a passive buccal slide, which can create a rectangular tube and maintain the original slot depth and height. However, due to the smaller effective buccal slot width of PSLB compared to the slot base width, the effective slot dimension for horizontal displacement of wire is smaller than that for vertical displacement of wire. These factors can determine the amount of clearance between archwire and bracket slot which affects the size of room for archwire to move and release the binding and explain why SFF and KFF were increased in LD and GD groups with different amounts between CB and PSLB.

The CB group exhibited apparently higher SFF and KFF than the PSLB group (Tables 1 and 2, Figs. 3-A and B and 4-A and B), which was in accordance with previous studies.[8,10,11,13,53] Since CB with elastic ligature has a smaller critical contact angle (θ_c) than PSLB due to larger effective slot width and smaller effective slot height and depth, the same amount of tooth displacement may result in stronger binding in CB than that in PSLB. Moreover, because the elastomeric ligature itself in CB generates high frictional force, the binding between a wire and CB seems to be more difficult to be released than that between a wire and PSLB. Therefore, bracket type, ligation method, and effective slot dimension of the bracket might result in higher SFF and KFF in CB than those in

PSLB. And these could explain why PSLB demonstrated prominent decreases in SFF, KFF and BRP amplitude under vibration condition compared to CB.

In terms of the bracket configuration, Chang et al.[18] reported that the frictional force was reduced by increasing the bevel angle. Thorstenson and Kusy [54] found that different designs of CB and types and methods of ligation influenced the contact between bracket, archwire, and ligature, and then affected frictional forces. However, this study tested one type of CB with elastomeric ligature and PSLB, respectively. Therefore, it will be necessary to compare various designs of CB, and active-type and passive-type self-ligating bracket with various ligation methods.

Although this was an *in vitro* study, the results of this study showed a possibility that the vibratory device could affect frictional properties. Further *in vitro* and *in vivo* studies are needed to investigate the optimal condition of vibration and its application method which can efficiently reduce the binding-release point. Since there are few studies focusing on BRP yet, the results from this study were difficult to directly compare with other studies. The authors hope that this study could be regarded as a preliminary study for designing more sophisticated test before conducting *in vivo* studies.

VI. CONCLUSIONS

1. The null hypothesis that there were no significant differences in the effect of tooth displacement and vibration on frictional force and BRP in CB and PSLB when used with leveling/alignment wire was rejected.
2. The effect of tooth displacement to increase the frictional force showed similar tendency in both CB and PSLB. However, the effect of vibration to decrease the frictional force and BRP amplitude was more prominent in PSLB than that in CB.
3. Therefore, these results might suggest a possibility that the change in BRP by vibration indirectly induced decreases in frictional force in PSLB.

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FIGURE LEGENDS

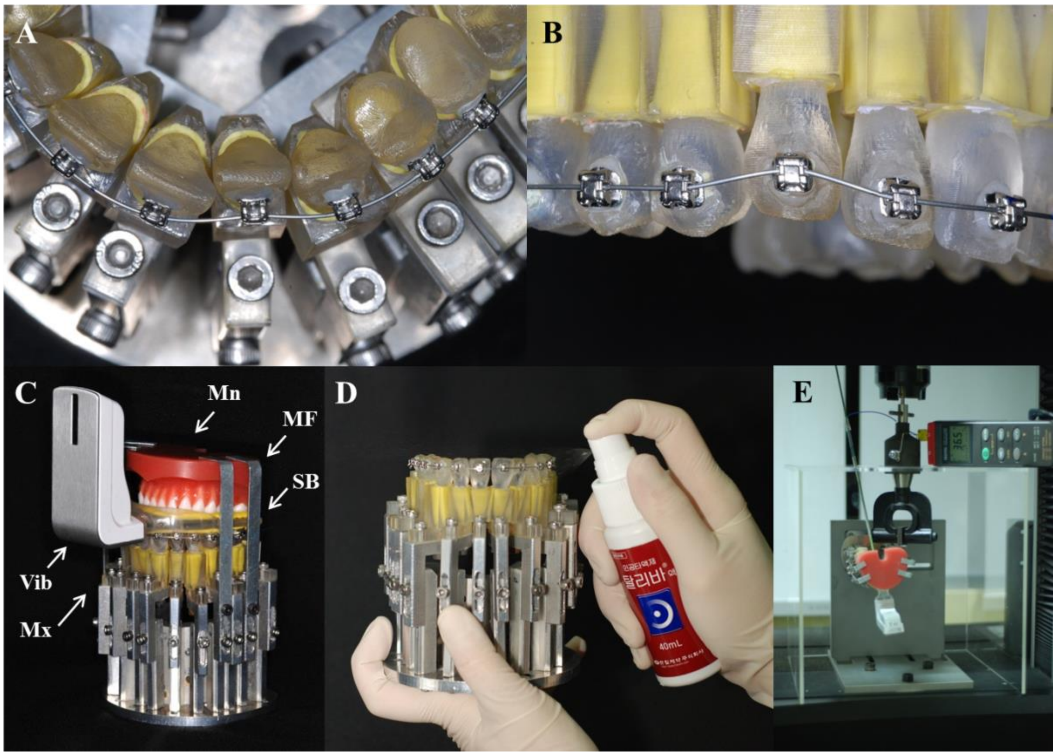
Figure 1. Experimental condition. **A.** 2 mm lingual displacement of the maxillary right lateral incisor (LD), **B.** 2 mm gingival displacement of the maxillary right canine (GD), **C.** Complex of the stereolithographically-made maxillary typodont system (Mx), the mandibular typodont (Mn), and the vibratory device (Vib; AcceleDent®, OrthoAccel Technologies, Inc., Bellaire, TX, USA). Silicone bites (SB) and two metal fixation frames (MF) per side were used to hold the complex consistently and passively. **D.** Artificial saliva (Taliva, Hanlim Pharm. Co., Ltd. Seoul, Korea) was applied into the bracket slots, **E.** The entire device was placed in a chamber at 36.5 ± 0.3 ℃.

Figure 2. Definition of the variables. Static frictional force (SFF) was measured at the maximal point of the initial rise; Kinetic frictional force (KFF), calculated by averaging the frictional forces from 0.2 mm (24 seconds) after the SFF point to the end of the test; Frequency of the binding-and-releasing phenomenon (BRP), the number of peaks divided by the time (minute) of the KFF phase; BRP amplitude, measured by averaging the differences between peak and trough of each BRP cycle within the KFF phase.

Figure 3. Comparison of the variables according to tooth displacement type and vibration condition in conventional bracket (CB). **A.** SFF (cN), **B.** KFF (cN), **C.** BRP frequency (cpm), **D.** BRP amplitude (cN).

Figure 4. Comparison of the variables according to tooth displacement type and vibration condition in passive-type self-ligating bracket (PSLB). **A.** SFF (cN), **B.** KFF (cN), **C.** BRP frequency (cpm), **D.** BRP amplitude (cN).

Figure 5. Comparison of effective slot dimensions of brackets in tooth displacement state (solid line - original slot dimension, dotted line - effective slot dimension). **A.** LD in CB (left) and PSLB (right), **B.** GD in CB (left) and PSLB (right), **C.** CB in LD (left) and GD (right), **D.** PSLB in LD (left) and GD (right).



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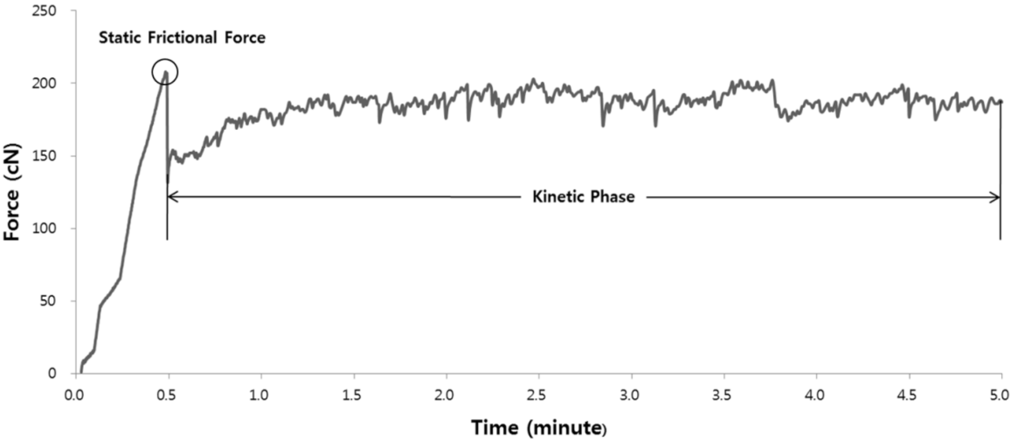

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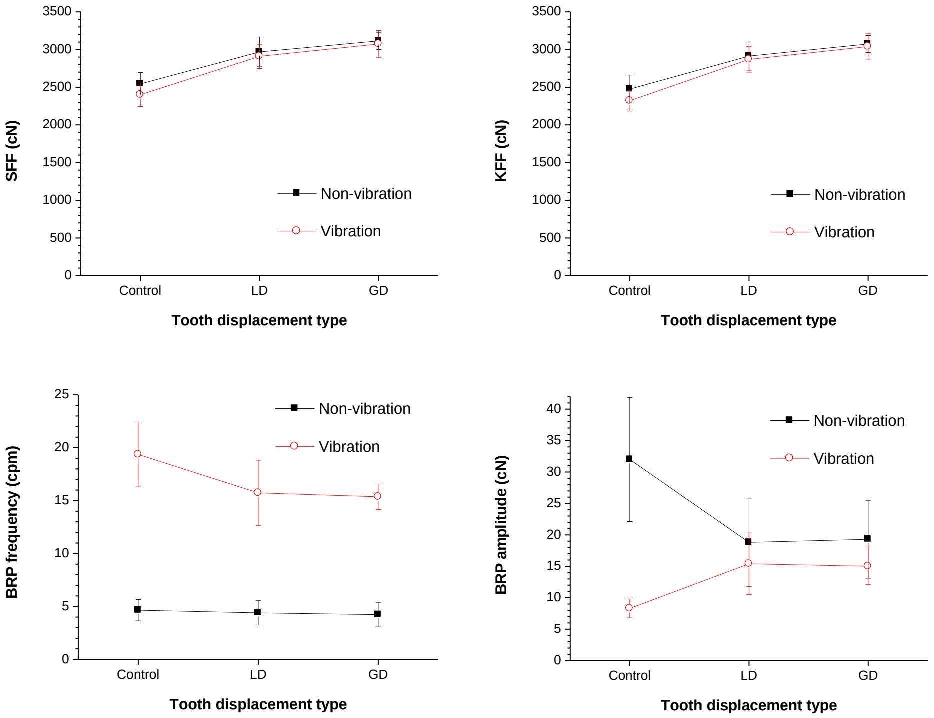

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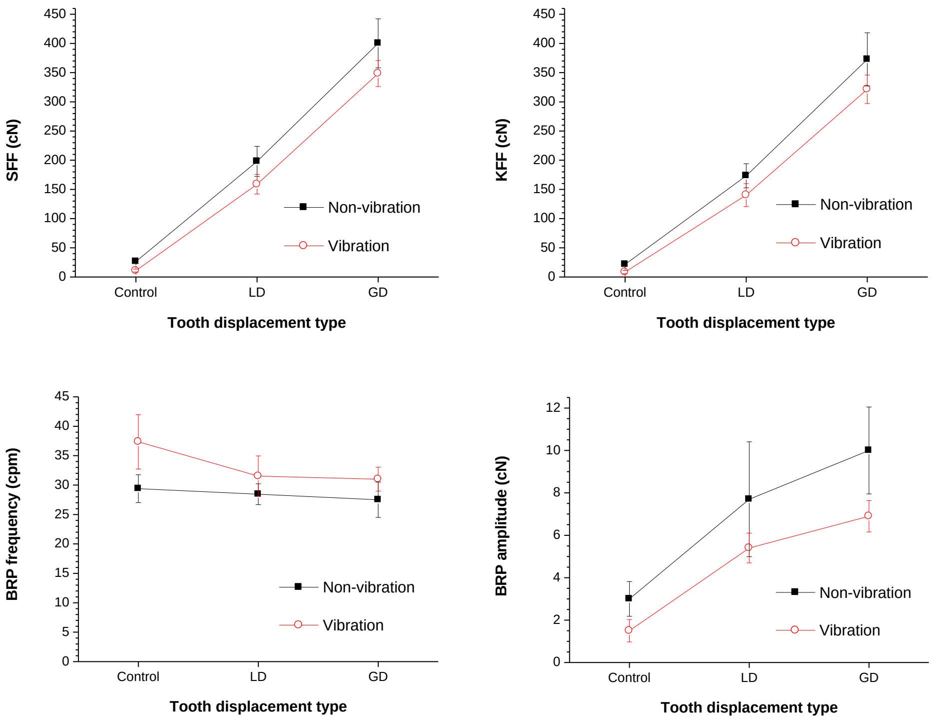

Figure 4. Comparison of the variables according to tooth displacement type and vibration condition in passive-type self-ligating bracket (PSLB). **A.** SFF (cN), **B.** KFF (cN), **C.** BRP frequency (cpm), **D.** BRP amplitude (cN).

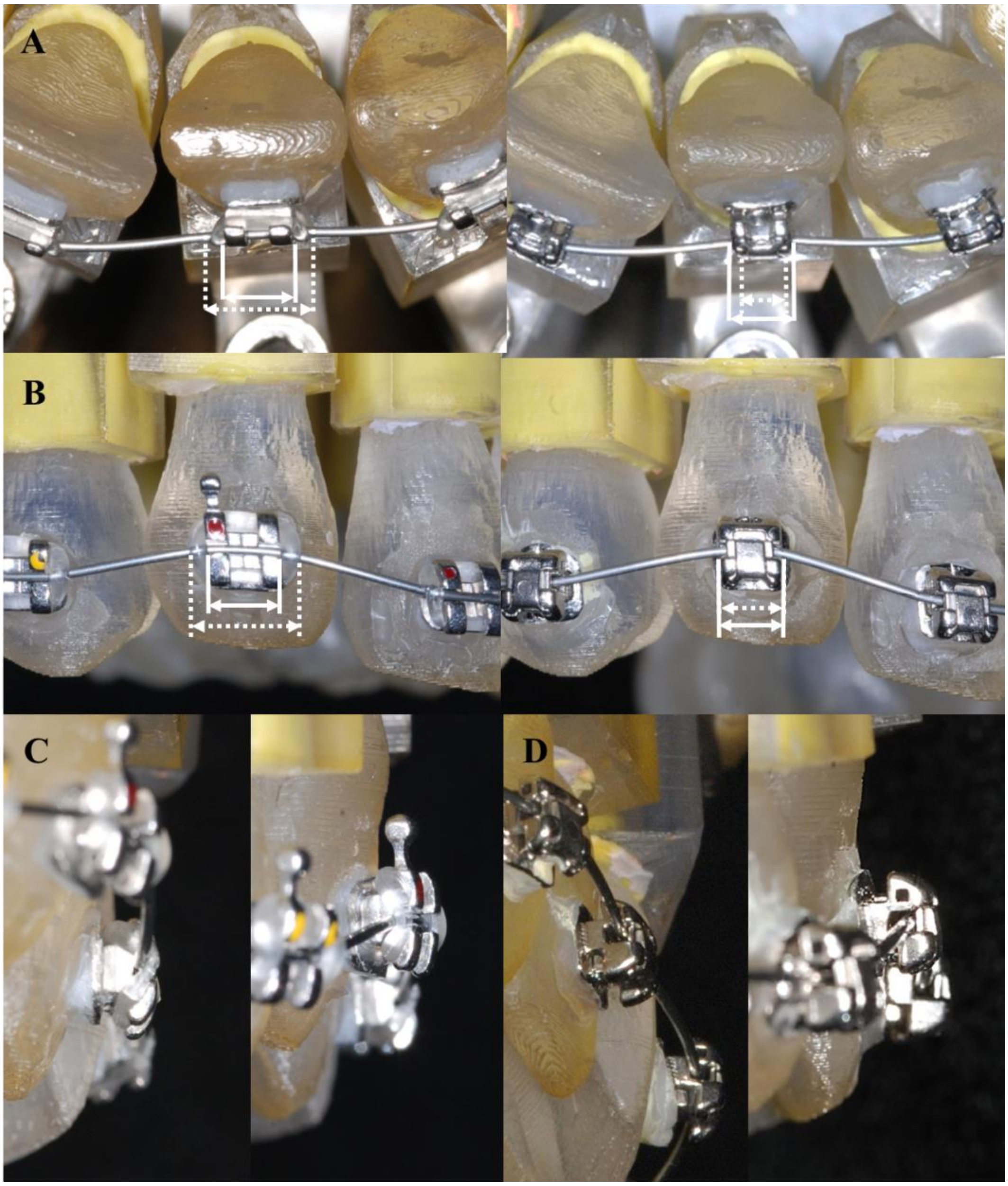

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Table 1. Comparison of the variables according to tooth displacement types and vibration conditions in conventional bracket (CB) (n = 10/group).

Variables	Displacement	Non-vibration		Vibration		Significance (p-value)		
		Mean	SD	Mean	SD	Displacement	Vibration	Displacement x Vibration
SFF (cN)	Control	2544.90	149.31	2400.30	156.76	< 0.001 *** Control < LD < GD	0.055	0.560
	LD	2969.00	196.97	2909.20	160.94			
	GD	3115.20	114.18	3074.50	178.73			
KFF (cN)	Control	2475.74	185.38	2320.81	137.28	< 0.001 *** Control < LD < GD	0.070	0.442
	LD	2913.45	187.61	2868.89	169.71			
	GD	3074.18	113.05	3039.28	176.49			
BRP frequency (cpm)	Control	4.65	1.01	19.37	3.06	0.002 ** Control > (LD, GD)	< 0.001 *** Non-vibration < Vibration	0.009 **
	LD	4.40	1.15	15.73	3.09			
	GD	4.23	1.16	15.37	1.20			
BRP amplitude (cN)	Control	32.00	9.87	8.30	1.50	0.199	< 0.001 *** Non-vibration > Vibration	< 0.001 ***
	LD	18.80	7.04	15.40	4.90			
	GD	19.30	6.20	15.00	2.91			

Two-way analysis of variance (ANOVA) and *post hoc* Bonferroni test were performed. **, $p < 0.01$; ***, $p < 0.001$

BRP represents the binding-and-releasing phenomenon; LD, 2 mm lingual displacement of the maxillary right lateral incisor; GD, 2 mm gingival displacement of the maxillary right canine; SD, standard deviation.

Table 2. Comparison of the variables according to tooth displacement types and vibration conditions in passive-type self-ligating bracket (PSLB) (n = 10/group).

Variables	Displacement	Non-vibration		Vibration		Significance (p-value)		
		Mean	SD	Mean	SD	Displacement	Vibration	Displacement x Vibration
SFF (cN)	Control	26.50	3.24	10.90	2.47	< 0.001 *** Control < LD < GD	< 0.001 *** Non-vibration > Vibration	0.052
	LD	198.00	25.81	158.90	16.78			
	GD	400.20	41.95	348.50	22.39			
KFF (cN)	Control	21.57	2.82	8.45	2.80	< 0.001 *** Control < LD < GD	< 0.001 *** Non-vibration > Vibration	0.051
	LD	173.35	20.62	140.25	19.68			
	GD	372.78	45.52	321.41	24.46			
BRP frequency (cpm)	Control	29.39	2.37	37.35	4.62	< 0.001 *** Control > (LD, GD)	< 0.001 *** Non-vibration < Vibration	< 0.001 ***
	LD	28.45	1.77	31.52	3.44			
	GD	27.51	3.00	31.00	2.04			
BRP amplitude (cN)	Control	3.00	0.82	1.50	0.53	< 0.001 *** Control < LD < GD	< 0.001 *** Non-vibration > Vibration	0.251
	LD	7.70	2.71	5.40	0.70			
	GD	10.00	2.05	6.90	0.74			

Two-way ANOVA and *post hoc* Bonferroni test were performed. ***, $p < 0.001$

국문 초록

치아변위와 진동적용이 마찰력과 구속-풀림 현상에 미치는 효과에 관한 연구

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목적: 본 연구의 목적은 일반 브라켓 (conventional bracket, CB)과 수동형 자가결찰 브라켓 (passive-type self-ligating bracket, PSLB)에서 레벨링과 배열용 나이타이 호선을 사용하였을 때 치아변위와 진동적용이 마찰력 (frictional force) 과 구속-풀림 현상 (binding-and-releasing phenomenon, BRP) 에 미치는 효과를 평가하기 위함이다.

연구재료 및 방법: 브라켓 종류는 CB (Victory, 3M-Unitek, Monrovia, CA, USA) 와 PSLB (Damon-Q, Ormco, Orange, CA, USA) 를 사용하였다. 실험 변수는 치아변위 유형과 진동적용 유무의 두 가지로 구성되었으며 변수별 조건은 다음과 같았다. (1) 치아변위 유형은 상악 우측 측절치의 2 mm 설측 변위 (lingual displacement, LD), 상악 우측 견치의 2 mm 치은측 변위 (gingival displacement, GD), 비변위 (대조군, control) 로 하였다. (2) 진동은 30 Hz 와 0.25 N 의 조건을 사용하거나 사용하지 않은 것으로 나누었다. 각 군당 10 번의 실험을 수행하였다. 치아의 치관, 치근, 치주인대의 형태를 Stereolithography apparatus (SLA) 공법으로 재현한 타이포돈트를 실험에 이용하였다. 브라켓 슬롯에 인공타액을 첨가하고 0.018 inch Copper-NiTi 호선을 삽입한 후, 36.5 °C 에서 인스트론 (Model 4466, Instron, Canton, MA, USA) 을 이용하여 호선을 0.5 mm/min 의 속도로 5 분간 당기는 동안 정지/운동 마찰력 (static/kinetic frictional force, SFF/KFF) 과 BRP 빈도/크기 (frequency/amplitude) 를 측정하였다. 이원배치 분산분석 및 사후검정으로 Bonferroni 방법을 사용하여 통계처리 하였다.

결과: 이로부터 다음과 같은 결과를 얻었다.

(1) SFF 와 KFF 는 치아변위 조건에서 CB 와 PSLB 모두에서 control, LD, GD 순으로 유의하게 증가하였다 (all $p < 0.001$). SFF 와 KFF 는 진동 조건 하에서 비진동 조건에 비하여 PSLB 에서 유의하게 감소하였으나 (all $p < 0.001$), CB 에서는 유의한 차이를 보이지 않았다.

(2) 진동적용이 BRP frequency 를 증가시키는 효과는 CB ($p < 0.01$) 와 PSLB ($p < 0.001$) 모두에서 치아변위에 따라 감소하였다.

(3) CB 에서 진동적용이 BRP amplitude 를 감소시키는 효과는 치아변위에 따라 감소하였다 ($p < 0.001$). 그러나 PSLB 에서는 치아변위 조건에서 control, LD, GD 순으로 유의하게 증가하였으며 ($p < 0.001$), 진동 조건 하에서 비진동 조건에 비하여 유의하게 감소하였다 ($p < 0.001$).

결론: 치아변위가 마찰력을 증가시키는 효과는 PSLB 와 CB 에서 같은 양상을 보였으나, 진동적용이 마찰력과 BRP amplitude 를 감소시키는 효과는 PSLB 에서 CB 보다 현저하게 나타났다. 따라서 PSLB 에서 진동에 의한 BRP 변화가 마찰력의 감소를 간접적으로 유도하였을 가능성을 보였다고 생각된다.

주요어: 진동, 마찰력, 구속-풀림 현상, 수동형 자가결찰브라켓, 일반 브라켓

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