Original article

Effect of self-ligating bracket type and vibration on frictional force and stick-slip phenomenon in diverse tooth displacement conditions: an in vitro mechanical analysis


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Summary

Objective: To evaluate the effects of self-ligating bracket (SLB) type and vibration on frictional force and stick-slip phenomenon (SSP) in diverse tooth displacement conditions when a levelling/alignment wire was drawn.

Materials and Methods: A total of 16 groups were tested (n = 10/group): Two types of SLBs [active SLB (ASLB, In-Ovation R) and passive SLB (PSLB, Damon Q)]; vibration (30 Hz and 0.25 N) and non-vibration conditions; and 4 types of displacement [2 mm lingual displacement of the maxillary right lateral incisor (LD), 2 mm gingival displacement of the maxillary right canine (GD), combination of LD and GD (LGD), and control]. After applying artificial saliva to the typodont system, 0.018 copper nickel–titanium archwire was drawn by Instron with a speed of 0.5 mm/min for 5 minutes at 36.5°C. After static/kinetic frictional forces (SFF/KFF), and frequency/amplitude of SSP were measured, statistical analysis was performed.

Results: ASLB exhibited higher SFF, KFF, and SSP amplitude (all $P < 0.001$) and lower SSF frequency (all $P < 0.05$) than PSLB in all displacement groups. Vibration decreased SFF, KFF, and SSP amplitude and increased SSP frequency in control and all displacement groups (all $P < 0.001$). ASLB exhibited lower SSP frequency than PSLB only under non-vibration condition ($P < 0.05$ in LD and GD, $P < 0.01$ in LGD). However, regardless of vibration conditions, ASLB demonstrated higher SSP amplitude than PSLB in all displacement groups (all $P < 0.001$ under non-vibration; all $P < 0.01$ under vibration).

Conclusion: Even in tooth displacement conditions, vibration significantly reduced SFF, KFF, SSP amplitude, and increased SPP frequency in both PSLB and ASLB. However, in vivo studies would be needed to confirm the clinical significance.

Introduction

Self-ligating brackets (SLBs) can be divided into active and passive types: Active SLB (ASLB) has a spring clip that encroaches into the bracket slot and presses the archwire, whereas passive SLB (PSLB) has a passive slide which covers the slot and does not encroach into the slot lumen, thus does not exert active force on the archwire (1–5).
As compared to a passive configuration, in an active configuration, binding becomes more significant than the classic frictional component of resistance-to-sliding (6, 7). Since the critical contact angle (θ) depends on the dimension of the bracket slot and the archwire, ASLB and PSLB may differ in binding and resistance-to-sliding due to the difference in the bracket slot dimension and the spring clip/slide design. Based on these assumptions, numerous studies have been performed to investigate the frictional properties of these brackets (3, 4, 8–15).

Since vibration can unbind the archwire from the bracket slot, several studies have reported the effects of vibration on resistance-to-sliding and stick-slip phenomenon (SSP) in conventional bracket (CB) and PSLB (16–19). However, to the authors’ knowledge, few studies have been performed to compare the vibration effect on frictional properties and SSP between ASLB and PSLB.

Therefore, the purpose of this in vitro mechanical study was to evaluate the effects of SLB type and vibration on frictional force and SSP in diverse tooth displacement conditions when a levelling/alignment wire was drawn. The null hypothesis was that there were no significant differences in the effects of SLB type and vibration on frictional forces in the effects of SLB type and vibration on frictional force and SSP in the horizontal and/or vertical tooth displacement conditions when a levelling/alignment wire was drawn.

Materials and methods
Experimental design
A total of 16 groups were tested (n = 10/group): 2 types of SLB, 2 states of vibration condition, and 4 types of tooth displacement.

Two types of SLBs, ASLB (In-Ovation R, Tomy, Tokyo, Japan), and PSLB (Damon-Q,Ormco, Orange, California, USA), were used. These brackets had a 0.022-inch slot and were made of stainless steel (SS), but the clip of ASLB was made of cobalt-chromium.

Two states of vibration condition (presence or absence) were used. Since standardization of vibration condition is important in investigating the mechanical effects of vibration on frictional force and SSP (19), we used a commercially available electronic device (AccelDeDent®, OrthoAccel Technologies Inc.; Bellaire, Texas, USA) which has fixed values of frequency and force of vibration (set at 30 Hz and 0.25 N).

Four conditions of tooth displacement (2 mm lingual displacement of the maxillary right lateral incisor (LD), 2 mm gingival displacement of the maxillary right canine (GD), combination of LD and GD (LGD), and no displacement (control)) were tested.

Experimental procedure
The experiment procedure consisted of typodont setup including bracket bonding and tooth displacement, placement of the vibration device, drawing of the archwire, and measurement of the variables (19).

Typodont setup including bracket positioning
The typodont system was comprised of a complete maxillary dentition fixed to an arch-shaped metal frame, which allowed individual tooth movement. The metal frame holding the tooth can be moved in the ocluso-gingival (up and down) and labio-lingual (forward and backward) directions from the zero position to a maximum of 5 mm to produce an arbitrary displacement of the individual resin tooth (3, 11, 19). After all the teeth were ideally aligned according to the ovoid arch form (OrthoForm III-Ovoid, Reference No. 701–723, 3M-Unitek) in the zero position, the maxillary right lateral incisor or canine were moved 2 mm lingually or gingivally. For accurate and reproducible bracket positioning, indirect bonding jigs were fabricated for all the brackets. Passive alignment of the brackets was ensured by inserting a 0.021×0.025 SS archwire. Then, as mentioned earlier, 4 types of tooth displacement (LD, GD, LGD, and control) were produced.

Each tooth had its periodontal ligament (PDL) space filled with a silicone impression material (Imprint™ II Garant™ Light Body Vinyl Polysiloxane Impression Material, 3M ESPE; Seefeld, Germany), which emulates human teeth mobility and functions as a stress-absorbing mechanism that can affect resistance-to-sliding (11, 19, 20).

Vibration device placement
The vibration device was placed between the maxillary and mandibular typodonts to simulate the condition of a patient biting the device. In order to consistently reproduce passive bite conditions, the typodonts and the AcceleDent® system were held together with silicone bites and 2 metal fixation frames on each side (19).

Drawing of the archwire
After spray of artificial saliva (Taliva®, Hanlim Pharm. Co., Ltd., Seoul, Korea) was applied to each bracket slot for 1 second, a 0.018 Cu-NiTi archwire was drawn at a speed of 0.5 mm/min for 5 minutes with a mechanical testing machine (Model 4466, Instron; Canton, Massachusetts, USA). The end of the archwire that extruded from the maxillary right second molar tube was gripped by a custom-designed adaptor.

Each group was tested 10 times and a new wire was used each time. Immediately after each test, the typodont system was washed with distilled water and alcohol to remove the artificial saliva and dried using air syringe. Tests were conducted in a chamber that was maintained at 36.5 ± 0.3°C (19).

Measurement of the variables
Static/kinetic frictional forces (SFF/KFF) and the frequency and amplitude of SSP were measured. The frictional force was defined as a resisting force against drawing a wire through bracket slots, which includes classic frictional component and binding of resistance-to-sliding. SSP frequency was defined as the number of peaks divided by the time of the KFF phase in minutes. SSP amplitude was measured by averaging the differences between the peak and trough of each SSP cycle within the KFF phase. Increase in SSP frequency represents an increase in the number of SSP and a decrease in the duration of binding in each SSP cycle (19). Decrease in SSP amplitude means a decrease in the maximum frictional force at the binding-release point (19).

Statistical analysis
Two-way analysis of variance (ANOVA) was performed to evaluate the interaction of SLB type and vibration condition with regard to SFF, KFF, SSP frequency, and SSP amplitude. The independent t-test was used to compare the effect of vibration on the variables between SLB types. The level of significance for all tests was set at P < 0.05.

Results
Interaction between SLB types and vibration conditions
There was no significant interaction between SLB types and vibration conditions with regard to SFF, KFF, SSP frequency, and SSP
amplitude in the control group (Table 1) and with regard to SFF, KFF, and SSP frequency in all displacement groups (Tables 2–4). However, SSP amplitude showed significant interaction between SLB types and vibration conditions in all displacement groups (all \( P < 0.001 \), Tables 2–4).

**Effect of SLB and vibration on SFF and KFF**

In the control group, there was no difference between ASLB and PSLB with regard to SFF and KFF (Table 1). However, ASLB exhibited significantly higher SFF and KFF than PSLB in all displacement groups (all \( P < 0.001 \), Tables 2–4). Application of vibration resulted in significantly

### Table 1. Comparison of variables according to self-ligating bracket types and vibration conditions in the control group.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Bracket</th>
<th>Non-vibration (n = 10)</th>
<th>Vibration (n = 10)</th>
<th>Significance (P value)</th>
<th>Bracket × Vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>SFF (cN)</td>
<td>PSLB</td>
<td>26.50</td>
<td>3.24</td>
<td>10.90</td>
<td>2.47</td>
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<tr>
<td></td>
<td>ASLB</td>
<td>29.50</td>
<td>6.72</td>
<td>13.20</td>
<td>3.49</td>
</tr>
<tr>
<td>KFF (cN)</td>
<td>PSLB</td>
<td>21.57</td>
<td>2.82</td>
<td>8.45</td>
<td>2.80</td>
</tr>
<tr>
<td></td>
<td>ASLB</td>
<td>26.18</td>
<td>6.57</td>
<td>9.27</td>
<td>3.76</td>
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<tr>
<td>SSP frequency (cpm)</td>
<td>PSLB</td>
<td>29.39</td>
<td>2.37</td>
<td>37.35</td>
<td>4.62</td>
</tr>
<tr>
<td></td>
<td>ASLB</td>
<td>28.75</td>
<td>6.56</td>
<td>36.32</td>
<td>4.37</td>
</tr>
<tr>
<td>SSP amplitude (cN)</td>
<td>PSLB</td>
<td>3.00</td>
<td>0.82</td>
<td>1.50</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>ASLB</td>
<td>3.40</td>
<td>1.35</td>
<td>2.10</td>
<td>0.74</td>
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</tbody>
</table>

Two-way analysis of variance (ANOVA) was performed. ASLB, active self-ligating bracket; control represents no displacement; SSP, stick-slip phenomenon; PSLB, passive self-ligating bracket; SD, standard deviation. *** \( P < 0.001 \).

### Table 2. Comparison of variables according to self-ligating bracket types and vibration conditions in the lingual displacement of the maxillary right lateral incisor (LD) group.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Bracket</th>
<th>Non-vibration (n = 10)</th>
<th>Vibration (n = 10)</th>
<th>Significance (P value)</th>
<th>Bracket × Vibration</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>SFF (cN)</td>
<td>PSLB</td>
<td>198.00</td>
<td>25.81</td>
<td>158.90</td>
<td>16.78</td>
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<td></td>
<td>ASLB</td>
<td>230.30</td>
<td>18.64</td>
<td>180.50</td>
<td>13.18</td>
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<td>KFF (cN)</td>
<td>PSLB</td>
<td>173.35</td>
<td>20.62</td>
<td>140.25</td>
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<td></td>
<td>ASLB</td>
<td>208.20</td>
<td>13.89</td>
<td>162.05</td>
<td>9.73</td>
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<td>SSP frequency (cpm)</td>
<td>PSLB</td>
<td>28.45</td>
<td>1.77</td>
<td>31.52</td>
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<td></td>
<td>ASLB</td>
<td>24.88</td>
<td>3.79</td>
<td>30.78</td>
<td>3.15</td>
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<td>SSP amplitude (cN)</td>
<td>PSLB</td>
<td>7.70</td>
<td>2.71</td>
<td>5.40</td>
<td>0.70</td>
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<tr>
<td></td>
<td>ASLB</td>
<td>19.90</td>
<td>5.49</td>
<td>6.70</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Two-way ANOVA was performed. LD represents 2 mm lingual displacement of the maxillary right lateral incisor. ASLB, active SLB; PSLB, passive SLB; KFF, kinetic frictional forces; SFF, static frictional forces; SSP, stick-slip phenomenon. * \( P < 0.05 \); *** \( P < 0.001 \).

### Table 3. Comparison of variables according to self-ligating bracket types and vibration conditions in the gingival displacement of the maxillary right canine (GD) group.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Bracket</th>
<th>Non-vibration (n = 10)</th>
<th>Vibration (n = 10)</th>
<th>Significance (P value)</th>
<th>Bracket × Vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>SFF (cN)</td>
<td>PSLB</td>
<td>400.20</td>
<td>41.95</td>
<td>348.50</td>
<td>22.39</td>
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<td></td>
<td>ASLB</td>
<td>459.90</td>
<td>40.17</td>
<td>375.30</td>
<td>33.25</td>
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<tr>
<td>KFF (cN)</td>
<td>PSLB</td>
<td>372.78</td>
<td>45.52</td>
<td>321.41</td>
<td>24.46</td>
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<tr>
<td></td>
<td>ASLB</td>
<td>431.20</td>
<td>34.04</td>
<td>357.20</td>
<td>31.54</td>
</tr>
<tr>
<td>SSP frequency (cpm)</td>
<td>PSLB</td>
<td>27.52</td>
<td>3.00</td>
<td>31.00</td>
<td>2.04</td>
</tr>
<tr>
<td></td>
<td>ASLB</td>
<td>24.30</td>
<td>2.57</td>
<td>29.99</td>
<td>3.93</td>
</tr>
<tr>
<td>SSP amplitude (cN)</td>
<td>PSLB</td>
<td>10.00</td>
<td>2.05</td>
<td>6.90</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>ASLB</td>
<td>25.90</td>
<td>4.48</td>
<td>8.70</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Two-way ANOVA was performed. GD represents 2 mm gingival displacement of the maxillary right canine. ASLB, active SLB; PSLB, passive SLB; KFF, kinetic frictional forces; SFF, static frictional forces; SSP, stick-slip phenomenon. * \( P < 0.05 \); *** \( P < 0.001 \).
lower SFF and KFF when compared with non-vibration condition in the control and all displacement groups (all $P < 0.001$, Tables 1–4).

Under both non-vibration and vibration conditions, the control group did not exhibit significant differences between ASLB and PSLB with regard to SFF and in KFF (Figure 1A and 1B). However, there were significant differences in SFF in all displacement groups (all $P < 0.01$ except $P < 0.05$ under vibration condition in GD group, Figure 1A) and in KFF in all displacement groups ($P < 0.001$ and $P < 0.01$ in LD and LDG groups; $P < 0.01$ and $P < 0.05$ in GD group, respectively, Figure 1B).

Effect of SLB and vibration on SSP frequency

Although there was no difference between ASLB and PSLB with regard to SSP frequency in the control group (Table 1), PSLB had significantly higher SSP frequency when compared with ASLB in all displacement groups (all $P < 0.05$, Tables 2–4). Application of vibration resulting in significantly higher SSP frequency compared to non-vibration condition in the control and all displacement groups (all $P < 0.001$, Tables 1–4).

When vibration was not applied, there was significant difference in SSP frequency between ASLB and PSLB ($\text{ASLB} < \text{PSLB}$, $P < 0.05$ in LD and GD, $P < 0.01$ in LDG, Figure 1C). However, when vibration was applied, there was no difference in SSP frequency between ASLB and PSLB (Figure 1C).

Effect of SLB and vibration on SSP amplitude

As with SSP frequency, there was no difference in SSP amplitude between ASLB and PSLB in the control group (Table 1). However, PSLB exhibited significantly lower SSP amplitude than ASLB in all displacement groups (all $P < 0.001$, Tables 2–4). Application of vibration significantly lowered SSP amplitude compared to non-vibration condition in the control and all displacement groups (all $P < 0.001$, Tables 1–4).

Under both non-vibration and vibration conditions, although the control group did not exhibit any significant differences between ASLB and PSLB with regard to the SSP amplitude, there were significant differences in SSP amplitude in all displacement groups (ASLB $> \text{PSLB}$, all $P < 0.001$ under non-vibration condition; all $P < 0.01$ under vibration condition, Figure 1D).

Discussion

In this study, ASLB showed higher SFF and KFF than PSLB in all displacement groups (all $P < 0.001$, Tables 2–4) but not in control group (Table 1). These findings are in accordance with previous studies, which reported higher frictional forces in ASLB than in PSLB in an active configuration and no significant differences between ASLB and PSLB in a passive configuration (3, 4, 8–15). When considering these differences between active and passive configurations, the bracket design may be one of the causes for difference in frictional forces between ASLB and PSLB in an active configuration. PSLB used in this study has a flat and rigid buccal slide made of SS, which makes the slot configuration as a rectangular tube and maintains slot dimension even in an active configuration. However, ASLB used in this study has a sloping and flexible buccal spring clip made of cobalt-chromium, which makes the trapezoidal tube. This clip begins to load the seating force on the archwire in an active configuration. Therefore, the difference between buccal slide and clip in SLBs becomes prominent in an active configuration, causing higher frictional forces in ASLB compared to PSLB (Tables 2–4). However, when a wire does not contact the buccal slide or clip and some clearance exists between them, difference in frictional force between ASLB and PSLB would be negligible (Table 1). In addition, according to previous studies which measured the actual slot configuration, ASLB is known to have wider width, shorter height, shallower depth, smaller bevel angle, and consequently smaller critical contact angle ($\theta$) when compared to PSLB (1, 9, 14, 15). Therefore, in an active configuration, ASLB exhibited higher frictional forces than PSLB, as observed in all displacement groups (Tables 2–4). However, it is needed to investigate the effects of alloy type of buccal spring clip in ASLB or slide in PSLB on frictional properties.

Vibration induced significant decrease in SFF and KFF compared to non-vibration condition in the control and all displacement groups (all $P < 0.001$, Tables 1–4), which was consistent with previous studies using PSLB (17, 18). Although vibration can change the contact status between archwire and bracket slot or between archwire and buccal clip and significantly reduce the frictional forces, ASLB showed higher SFF and KFF than PSLB in all displacement groups regardless of vibration condition (Tables 1–4; Figure 1). This may have occurred because the buccal clip in ASLB still contacts the wire and exerts a seating force on it even during the presence of vibration. These findings imply the possibility that the bracket design of SLBs might be more important for the difference in frictional forces between PSLB and ASLB in an active configuration than existence of vibration.

Since studies on frequency and amplitude of SSP in SLB are limited, it was not possible to directly compare the results of this study with previous studies, which measured the actual slot configuration, ASLB is known to have wider width, shorter height, shallower depth, smaller bevel angle, and consequently smaller critical contact angle ($\theta$) when compared to PSLB (1, 9, 14, 15). Therefore, in an active configuration, ASLB exhibited higher frictional forces than PSLB, as observed in all displacement groups (Tables 2–4). However, it is needed to investigate the effects of alloy type of buccal spring clip in ASLB or slide in PSLB on frictional properties.

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with other studies. However, an in vitro mechanical study using CB performed by Seo et al. (19) could be used for indirect comparison of data. According to them, although the application of vibrations increased SSP frequency both in the control and all displacement groups, it decreased SSP amplitude only in the control group, but not in displacement groups (19). These findings differ from the results of this study using SLB, which reported that vibration increased SSP frequency and reduced SSP amplitude in the control and all displacement groups (all \( P < 0.001 \), Tables 1–4). The difference could be explained by that the effect of vibration might be more significant in PSLB and ASLB than in CB.

The control group, wherein the archwire may not have contacted the buccal slide or clip, did not exhibit any significant difference between PSLB and ASLB in the frequency and amplitude of SSP (Figure 1C and 1D). In all displacement groups, when vibration was not applied, significant differences were observed between PSLB and ASLB (Figure 1C and 1D). However, when vibration was applied, these significant differences disappeared in SSP frequency (Figure 1C) and diminished in SSP amplitude (Figure 1D). In other words, the effects of vibration on increase in SSP frequency and decrease in SSP amplitude were greater in ASLB compared to PSLB in all displacement groups. ASLB with a flexible clip may be more sensitive to vibration when compared with PSLB with rigid buccal slide. When considering these findings, bracket design may be one of the major determinants for SSP features in SLBs. However, further studies would be needed to comprehensively analyse the differences in contact status between archwire and buccal slide/clip in the presence and absence of vibration.

Low frictional force during levelling/alignment stage has some advantage in terms of the ease in sliding. However, there could be some loss of control in angulation and rotation (1, 21, 22). Therefore, vibration-induced lower frictional force may not be clinically superior in all situations during orthodontic treatment.

Although this in vitro mechanical study found significant differences between PSLB and ASLB with regard to effects of vibration on frictional force and SSP, it was preliminary in nature as far as investigating the effects of vibration on the frictional properties of SLBs. Although we tried to reproduce the in vivo condition as previously described, one of the limitations of this study is an in vitro study in nature. Therefore, in vitro and in vivo studies with more sophisticated designs would be needed to confirm clinical significance of the effects of vibration on SLBs.

Conclusions
1. The null hypothesis was rejected.
2. Even in tooth displacement conditions, vibration significantly reduced SFF, KFF, SSP amplitude, and increased SPP frequency in both PSLB and ASLB.

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References


